Growth, yield, fruit composition, and postharvest attributes of glasshouse tomatoes produced under deficit irrigation

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Abstract

Two experiments in 1994 and 1995 investigated the effects of deficit irrigation (DI) on growth and fruit attributes of tomato (*Lycopersicon esculentum* Mill. 'Virosa') grown in a glasshouse. Two treatments were applied: control which was watered daily and DI where watering was based on the measurement of leaf water potential and soil moisture. Due to the large reduction in plant growth and yield under the DI in the first experiment, a less severe DI was applied during the second experiment. Fruit yield, mineral concentration, colour, soluble sugars, and plant mass were measured in both experiments. Fruit production of ethylene and CO_2 were determined in the first experiment, while fruit total soluble solids (TSS), total acidity, sugar:acid ratio and shelf life were determined in the second experiment.

Plant growth, yield, fruit size and fruit number declined in DI plants. This was more pronounced in the first experiment than in the second. However, the percentage of fruit dry mass was higher in the DI than in the control treatment. Incidence of blossom-end rot was observed only in the DI fruit in the first experiment.

Sucrose, glucose and fructose concentrations were higher in DI fruit than in control fruit only in the first experiment. In the second experiment, TSS was higher in the DI than the controls. DI had no effect on fruit titratable acidity but the sugar:acid ratio was higher for the control fruit. Fruit concentration of Ca, Mg and K was the same for both treatments in the two experiments. The DI fruit had higher colour intensity than the control fruit only in the first experiment. The DI fruit produced higher quantities of CO_2 and ethylene than the control fruit. Cumulative weight loss and shelf life were the same in both treatments. Although DI may

improve certain fruit quality attributes such as colour and TSS, it should be applied with caution. Deficit irrigation should not be severe enough to generate a plant water potential of lower than -1.0 MPa.

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Glossary of abbreviations

Θ -Soil volumetric water content

ψ_l -Leaf water potential

ψ_f -Fruit water potential

ψ_m -Matric potential

ψ_p -Turgor potential

ψ_s -solute potential

AAS -Atomic absorption spectrometer

BER -Blossom-end rot

DAS -Days after sowing

DI -Deficit irrigation

EC -Electric conductivity

HPLC -High performance liquid chromatography

MPa -Mega Pascal (1 MPa = 10 bars)

PG -Polygalacturonase

RDI -Regulated deficit irrigation

SAS -Statistical analysis system

TDR -Time domain reflectometry

TSS -Total soluble solids

UK -United Kingdom

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Chapter One: General introduction

Tomato (*Lycopersicon esculentum* Mill) is a fruit crop from Solanaceae family. On a global scale, tomato continues to increase in importance as a fresh crop, as a major constituent in many prepared foods, and as a processed product. Over the last 15 years tomato production was higher than that of bananas and pome fruits in terms of weight of crop on an annual basis (Table 1.1). Recently, it has overtaken grapes so that tomato is second only to citrus production world wide (Hobson and Grierson, 1993). In the USA, it ranks number 1 in terms of contribution of nutrients to diet (Wills et al., 1981).

Table 1.1. Average world production of tomatoes in comparison with other popular fruits, 1979-1981 and 1990

Commodity	**Production in tonnes (000s)**		**Percentage change**
	1979-1981	**1990**	
Grapes	65991	59943	-9
Citrus	57026	73195	+28
Tomatoes	51907	69304	+34
Apples and pears	43140	50103	+16
Bananas	36849	45845	+24

Source: Hobson and Grierson (1993)

Success of a tomato grower used to be measured in terms of yield. Increasingly, quality of horticultural produce has become equally important to the expanding tomato industry. Producers and consumers are concerned about product appearance. Firmness, colour, and long storage life are important to market distributors. Consumers on the other hand prefer high quality products with the freshness, firmness, flavour, high nutritive value, and chemical-free inputs. Although most consumers buy on the basis of appearance and feel, their satisfaction and repeat purchases depend upon the edible quality of the fruit.

Water stress, either excess or deficit, is an important parameter influencing plant growth and development (Brown and Scott, 1984). Under field conditions, frequent and moderate soil drying is one of the most common stresses experienced by a plant during its life cycle (Saunders, 1991). Irrigation consumes 85% of the water used for all purposes (Van Schilfgaarde, 1994). In the recent years, growers have attempted to develop water management techniques that maintain yield and improve fruit quality (Mitchell et al., 1991a). Practices and technologies that maintain current productivity cannot be abandoned, but some modifications may be needed to promote agricultural sustainability (Poincelot, 1990). Water availability could be manipulated in a variety of ways to beneficially modify development processes in a plant. Regulated deficit irrigation (RDI) is an approach to irrigation management where water supply to the plant is reduced at specific growth stages to levels which cause the ψ of the plant to decline to a predetermined amount below the maximum ψ possible at that time (Chalmers, 1989). The application of RDI had been beneficial to perennial crops (Kilili, 1996) and processing tomatoes (Mitchell et al., 1991a). Reduced irrigation strategies in crop production can reduce leaching

of nutrients and pesticides into the ground water. Deficit irrigation (DI) could also help to conserve water and minimise the leaching. Establishment of DI as a management tool in tomatoes could be useful in water-limited production systems. However, before DI can be adopted as a management tool in tomatoes, its effect on fruit yield and quality needs to be examined.

So far, DI has mainly focused on processing tomatoes. Findings reveal that it increases the fruit's total soluble solids (TSS), but decreases its yield and water content (Mitchell et al., 1991a). A reduced water content is desirable in processing tomatoes where paste production is the objective. The few studies conducted on the effects of irrigation on the quality of fresh market tomatoes have included those on cracking (Abbott et al., 1985; Peet and Willits, 1995) and on TSS, pH, skin toughness and titratable acidity (Tüzel et al., 1994). DI could be an effective management tool for fresh market tomatoes grown in the field and in protected cultivation systems, provided yield reduction is within acceptable limits and fruit quality is improved.

Indeterminate glasshouse tomatoes, unlike processing tomatoes, have excess foliage which usually has more photosynthetic area than the fruit needs (Rudich and Luchinsky, 1986). Photosynthesis is less sensitive to water stress than translocation of assimilate or growth (Kramer, 1983). It could therefore be hypothesised that DI may not severely limit the yield of 'Virosa' tomato which is an indeterminate cultivar. Moreover, fruit quality could improve under DI as has been shown for processing tomatoes (Mitchell et al., 1991a). The objective of this study was to evaluate DI as a management tool. The effects of DI on plant growth, yield and fruit quality were investigated. Plant growth parameters studied included plant truss

number and flower development and fresh and dry mass. Fruit yield included the size and number of fruit per plant. Fruit quality attributes studied included concentration of soluble sugars, titratable acidity, sugar:acid ratio, TSS, concentration of mineral elements and shelf life; and rate of ripening as characterised by colour development, ethylene evolution and respiration which was measured in terms of CO_2 production.

Chapter Two: Review of literature

2.1. The tomato crop

Tomato is a member of the Solanaceae, the potato family. The crop is regarded as easy to grow, perennial, determinate or indeterminate (depending on the variety), very often self-fertile and tolerant to a wide range of environmental and nutritional conditions (Hobson and Grierson, 1993). Cultivated tomatoes can be grown for either processing or fresh market. They could be planted in the field or glasshouse. Most of the glasshouse tomato are indeterminate. The main stem of indeterminate plants may grow indefinitely and flower and fruit regularly and evenly (Picken et al., 1986). Glasshouse tomatoes frequently suffer from excessive vegetative growth (Araki, 1994). It may be due to the excess foliage of the indeterminate plant (Rudich and Luchinsky, 1986). Mild water stress on the plant creates a balance between the vegetative and reproductive which lead to a better fruit growth (Araki, 1994).

2.2. The concept of water stress

The water status of the plant depends on the combined effects of the soil, atmosphere and the plant (Rudich and Luchinsky, 1986). Figure 2.1 show the factors influencing plant water status. The gradient between ψ of the soil and the ψ of the plant roots is the driving force of water movement from the soil to the plant (Kramer, 1983 p. 235). Water potential describes the energy status of water and is the commonly-used terminology for studies in soil-plant-water relationship (Mengel and Kirkby, 1987 p. 193). It is commonly expressed as:

$$\psi=\psi_p + \psi_s + \psi_m$$

where: ψ_p is the pressure potential which is equal to the hydrostatic pressure and has a positive value, ψ_s is osmotic potential or solute potential and is always negative, and ψ_m is matric potential and also a negative value. Plant ψ is generally negative.

Plants lose water to the atmosphere through transpiration. The gradient between water vapour pressure of the atmosphere and the plant is the driving force of transpiration. Water stress occurs when transpiration exceeds water absorption.

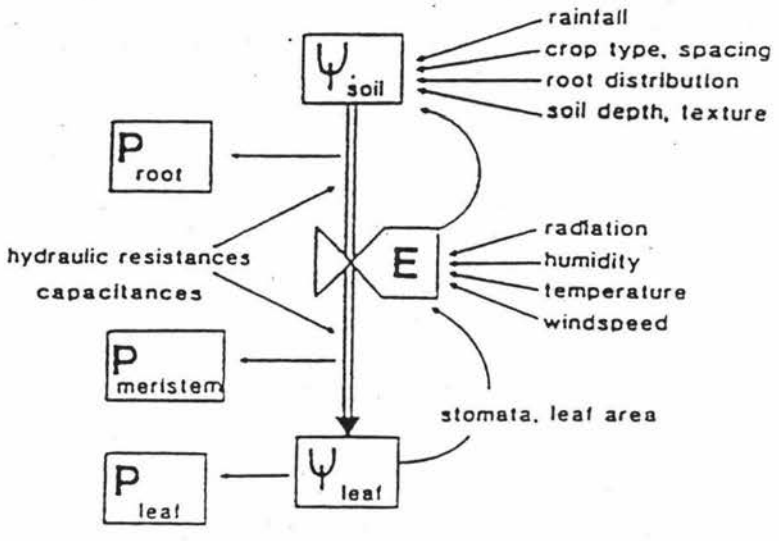

Fig. 2.1. Factors and processes involved in the control of plant water status (Jones, 1990).

2.3. Plant response to water stress

2.3.1. Leaf and fruit water potential

Water potential is a commonly used measure of plant water status (Jones, 1990). Water potential of water stressed plants is generally lower than in plants receiving adequate water. As water deficit develops the balance between the components of plant water potential is changed. All plants react to water stress by lowering their water potential which becomes more negative. Torrecillas et al. (1995) found that in a controlled environment leaf water potential of a deficit irrigated tomato plant was lower than the well watered plant. Similarly, Behboudian et al. (1994) reported fruit water potential in Asian pear to be lower in deficit irrigated than control fruit. Water potential is commonly measured predawn and at midday. Possibly because water potential is highest at predawn and lowest at midday (Kilili, 1996). Plant water status is variable as it is a function of environmental conditions and transpiration rate. Diurnal changes causes ψ_l fluctuation (Jones, 1990). Generally there is less fluctuation in ψ_l at predawn compared to midday (Katerji et al., 1987). Predawn ψ_l is a more sensitive measure of plant water status than midday ψ_l (Jones, 1990). Syvertsen and Graham (1985) showed that difference between ψ_l of two citrus rootstocks during a drought experiment were significant at predawn but at midday. McCutchan and Shackel (1992) suggest that variability associated with changing environmental conditions can be reduced by the use of predawn ψ_l measurements. Midday and predawn water potential results were therefore used in this study as a basis for irrigation.

2.3.2. Plant growth

2.3.2.1. Vegetative growth

Water stress affects plants in various physiological and developmental processes. Hsiao (1973) mentioned 30 growth processes affected by water stress. Leaf expansion and organ initiation are the major growth processes affected. Reduced cell expansion is usually the first observable symptom of water stress and the main cause of stunting due to water deficit. Cell division may also be reduced due to water stress.

According to Kozlowski et al. (1991), water stress can affect growth, stomatal behaviour, photosynthesis and photosynthate translocation in tomato plants. Water stress reduces plant size and the number and size of leaves through various physiological disturbances (De Koning and Hurd, 1983; Klapwijk and De Lint, 1974). Similarly water and saline stress reduce relative growth rate of tomato plant (Thakur, 1990; Alarcon et al., 1994). This may lead to reduced dry matter accumulation (Perniola et al., 1994). The reduction in leaf area may be due to smaller cell size (De Koning and Hurd, 1983). However, the number of leaves per plant in eggplant was found to be inversely correlated with water stress (Maximos et al., 1991).

The effect of DI on root growth is different from the above ground parts. In some cases root growth may even increase under water stress (Huck et al., 1983) leading to increased root length (Huck et al., 1986) but not total root dry mass (Hoogenboom et al., 1987). However, in the study by Saunders (1991), root dry mass increased under water stress. Under water stress conditions in the field, the increase in root growth may be related to a rapid elongation of the root axis into

wetter zones and extensive root branching (Scott Russel, 1982). Both will lead to an increase in root length. However, this may not apply to pot grown plants.

Application of water stress can conserve water and at the same time reduce vegetative growth which minimise the cost and time for pruning. Water stress may be a viable management tool in controlling vegetative growth in tomato crop, however level and timing of water stress application needs to be defined.

2.3.2.2. Flower development

Flower formation is a crucial stage in tomato production. Delays in flowering can lead to delayed fruit production (Helyes and Varga, 1994) and differences in the rate of flower formation can lead to differences in fruit production (Atherton and Harris, 1986). In a young reproductive plant, flowers are a weaker sink than the young apical leaves and roots (Ho and Grimbly, 1990). This supports the finding of Helyes and Varga (1994) that flowering is the most sensitive stage to water stress in a growing tomato crop. Thus, for flowers to develop into fruit, plants should not be subjected to water deficit at flowering stage. However, it is difficult to totally avoid water stress during flowering of an indeterminate plant since flowering is continuous.

The effect of water stress on flower development appears to vary with timing, duration and severity of the stress applied and also with environmental factors such as solar radiation levels during the stress period. Favourable effects of water stress on tomatoes have been observed under low levels of irradiation. Klapwijk and De Lint (1974) observed that the incidence of flower abortion under winter conditions was reduced from 50% to 4% when plants were subjected to water stress. De Koning and Hurd (1983) reported an advance of about four days in flower opening

in response to reduced water supply in plants grown at low irradiance levels. In other studies under low irradiance, Atherton and Othman (1983) reported that short periods of water stress produced a small increase in the growth of flower buds. Higher percentages of flower abortion was observed in wet and moist growing medium compared to dry medium (Klapwijk and De Lint, 1974). The beneficial effect of water stress on flower development may be attributed to reduced plant vegetative growth allowing light penetration in the lower trusses which are adversely affected during winter season (De Koning and Hurd, 1983).

Water stress can have adverse effects on flower development when tomato is grown under good light and field conditions. A reduction of water supply before and during inflorescence initiation can reduce flower number (Atherton and Harris, 1986). Water stress accompanied by temperatures above 28C during fruiting resulted in 30-45% flower drop (Rao and Bhatt, 1992). In another study by Rao and Padma (1991), water stress at the flowering stage resulted in a high percentage of flower drop and low fruit set. Flower development was arrested and all flowers dropped when water was withheld for a few days as soil matric water potential fell to -1.0 MPa (Chiaranda et al., 1982). Salinity and low water supply lead to retardation in flower development (Klapwijk, 1974). Bud and flower formation were delayed by salt stress (Dumbroff and Cooper, 1974).

The effect of water stress on flower development seems to depend on other environmental conditions. One aim of this study was to quantify the effect of water stress on flower development under winter glasshouse conditions in New Zealand.

2.3.2.3. Fruit development, size and number

Fruit development starts when pollination and fertilisation have been completed. After anthesis, growth of cherry tomato fruit follows a sigmoid pattern which consists of cell division, cell enlargement, mature green, pink, and red stages (Abdel-Rahman, 1977). Growth is slow, rapid, and slow at cell division, cell enlargement, and the ripening stage respectively (Ho and Hewitt, 1986; Mizrahi et al., 1988). Both cell enlargement and division are very sensitive to water stress but the former is the more sensitive growth parameter (Hsaio, 1973). Wolf and Rudich (1988) observed that water stress shortened the duration of fruit growth, which led to a reduction in final weight due to reduced cell enlargement.

From two weeks after fruit set, tomato fruit growth is essentially by cell enlargement (Rudich et al., 1977). The developed fruit becomes a strong sink competitor for water compared with shoots during the cell enlargement phase thus water deficit has a minimal influence at this stage. However, water stress may affect the size of both mature and immature fruit (Sudjatmiko, 1989).

Total marketable yield and fruit size of fresh tomatoes increase linearly with increasing irrigation rate (Locascio and Smajstrla, 1989; Locascio et al., 1981; Vanadia et al., 1982). Locascio and Smajstrla (1989) also found that increased irrigation during the dry season in Gainesville, Florida increased the yield of extra large, large, and marketable fruit by an average of 76, 44, and 40% respectively.

The effect of water stress on fruit number can be traced back to flowering as previously discussed. Fruit number may be limited by the failure of flowers to produce fruits. Flowers may become arrested and senesce prematurely before flower opening can occur. Fruit set is also a determinant in the number of fruit produced

(Atherton and Harris, 1986). Fully grown flowers may be shed and fail to set fruit under water stress. Even developed fruits can be affected by water stress. Water stress during fruit development increases fruit drop before ripening. In plants continuously stressed after seedling establishment, a fruit drop of 20-50% may incur (Rao and Bhatt, 1992).

However, Mitchell et al. (1991a) reported that fruit number was not significantly affected by either water deficit or saline irrigation treatments. They also concluded that fruit set was insensitive to water stress conditions. Acevedo and Massardo (1984) also reported that water stress reduced yield through reduction in fruit size and weight but had no effect on the number of flowers per cluster. The contradictory reports on the effect of water stress on flower development and fruit set maybe due to the degree and time of stress application and variety of tomato used in the study. Rao and Bhatt (1992) applied a continuous stress after seedling establishment while Mitchell et al. (1991a) watered the plants at the early stage. Cultivars may differ in drought tolerance. It was shown by Rao and Bhatt (1992) that fruit drop under water stress ranged from 20-50% depending on the cultivar. Due to the conflicting reports on the effect of water stress on tomato fruit setting, this was included in my study. In the second experiment, an attempt was made to determine the effect of water stress on fruit yield, size and number per individual fruit truss.

2.4. Water stress and tomato fruit quality

Consumers are becoming increasingly quality conscious about the horticultural produce. As a result, market distributors and retailers are demanding quality product

from producers. To be able to compete in the market, growers must produce high quality product. Consumers' choice is often based on the appearance of the fruit. Internal fruit composition is also important. Repeated purchase of fresh tomatoes depends on edible quality which is determined by fruit internal composition such as soluble sugars and acid concentrations. The quality attributes being considered in this thesis are colour, TSS, soluble sugars, titratable acidity, sugar to acid ratio, mineral concentration, and shelf life.

Mild water stress is reported to be beneficial in increasing product quality but is generally accompanied by a fruit yield reduction. It is desirable to maintain high production and favourable fruit quality at a minimal production cost. Mild water deficit may be used. Among the environmental factors, soil water availability can be controlled and manipulated to increase fruit dry matter concentration and thereby improve fruit quality.

Most of the information regarding the effect of water stress on fruit quality are on processing tomatoes, few studies had been done on fresh market tomato. This section reviews some of the aspects of tomato fruit quality and how they are affected by water stress.

2.4.1. Colour

Colour is one of the most important quality factors associated with evaluation of all food products and is the first aspect noticed by consumers (Gould, 1974). The external colour of tomato fruit is the result of both flesh and skin pigmentation (Grierson and Kader, 1986). Most consumers prefer deep, uniform red-coloured fresh

market tomatoes. Similarly, tomatoes for canning and juicing should be red fleshed and evenly ripened without green shoulders (Salunkhe and Desai, 1984).

The two major groups of pigments found in tomato fruit are chlorophyll and carotenoid (lycopene and β-carotene). Chlorophyll is highest at green colour stage (Salunkhe and Desai, 1984) and beta-carotene content is maximum at pink stage (Dalal et al., 1965). There is a high correlation between development of lycopene and the maturity of tomato fruit (Young et al., 1993; Giuliano et al., 1993). During fruit ripening, the colour changes from green to red as chlorophyll is degraded and carotenoid accumulates (Giuliano et al., 1993; Fraser et al., 1994). Lycopene is the main pigment in ripe tomato and β-carotene being the second most prevalent pigment (Davies and Hobson, 1981). Lycopene is more concentrated in the pericarp tissue whereas β-carotene is more concentrated in locular tissues (Thompson et al., 1965). The presence of high carotenes and carotenol at the locular and outer pericarp respectively give the best tomato colour (Gould, 1974). Maturation and ripening result from a series of coordinated changes in the biochemistry of fruit which affect their colour (Grierson and Kader, 1986).

Brecht et al. (1994) reported that water stress improved fruit colour in two experiments using drip irrigation and polyethylene mulch. Similarly, Rudich et al. (1977) found that deficit-irrigated tomato fruit had higher colour intensity than well-irrigated fruit. Lapushner et al. (1986) reported that colour index ratings were higher in stressed fruit than in normal fruit. Salinity stress similar to water stress may also influence colour. Many authors cite colour improvement in tomato caused by saline irrigation (Mizrahi et al., 1988; Sharaf, 1986; Gough and Hobson, 1990). In contrast, D'Souza et al. (1991) evaluated the effect of water stress on six tomato cultivars in

relation to fruit colour. Three cultivars were unaffected by water stress, two cultivars had a redder colour in non-irrigated than irrigated while one cultivar had an opposite result. Sudjatmiko (1989) found no effect of moisture stress on tomato fruit colour development. Having no conclusive effect of water stress on fruit colour, this was included in the study.

Ethylene produced during ripening increases carotenoid concentration of the tomato fruit (Paz et al., 1982), the peak lycopene formation coinciding with the peak ethylene production (Ishida et al., 1993). Ethylene production increases with increased water stress (Basiouny et al., 1994). Thus it is possible that colour improvement of stressed fruit is due to higher ethylene production. Water stress can also cause a destruction of chlorophyll (Gross and Lenz, 1979) which may aid colour development. Effect of water stress on tomato fruit colour is not conclusive. There is a need therefore to quantify the effect of water stress on tomato skin colour.

2.4.2. Total soluble solids and soluble sugars

The final concentration of TSS depends on the rate of accumulation during the rapid growth period (Ho and Hewitt, 1986), which is affected by season (winter or summer), nutrition and environmental factors (Davies and Hobson, 1981). The TSS content is inversely related to the fruit yield (Stevens and Rudich, 1978). A ripe cultivated tomato has around 4.5% TSS of the total fresh weight as determined by refractometry (Hobson and Grierson, 1993). The refractive index of tomato fruit sap is closely correlated with the total solids content, and these characteristics reflect the sugar status of the fruit (Davies and Hobson, 1981).

Sugars constitute between 65 to 70% of the fruit TSS (Hobson and Grierson, 1993) and account for 50% of the total dry matter of the whole fruit of commercially grown varieties (Davies and Hobson, 1981). Sugars, acids and their interactions determine the sweetness, sourness and overall flavour in tomatoes (Hobson and Grierson, 1993). High sugars and relatively high acids are required for the best flavour. The free sugars are almost entirely reducing sugars consisting of glucose and fructose of approximately equal amount. The sugar content may be higher in the pericarp wall than in the locules (Ho and Hewitt, 1986), but Hobson and Grierson (1993) reported that sugars are mostly found in locule walls and reach a peak when fruit is fully ripe. The total sugar concentration increases progressively from the mature green to the red stage of ripeness (Davies and Hobson, 1981).

Many authors have found that water stress increases TSS of tomato fruit (Rudich et al., 1977; Ho and Grimbly, 1990; Mitchell et al., 1991). According to Ho and Grimbly (1990), water stress reduces the quantity of phloem sap entering the fruit but it also increases the phloem sap concentration. So although less water accumulates in the fruit, the dry matter still accumulates to the same level as normal fruit. The result is a high percentage of dry matter in the fruit or a higher sugar concentration in the fruit juice.

Mitchell et al. (1991a) reported that fruit osmotic potential is significantly reduced by water deficit and it is due to reduction in fruit water import rather than increased solutes accumulation. This higher concentration of fruit solutes results in considerable improvement in fruit quality characteristics such as soluble solid content. Increases are due mainly to the decrease in fruit water content and a slight increase in soluble sugar accumulation (Ho and Grimbly, 1990; Mitchell et al.,

1991a). According to Rudich and Luckinsky (1986), leaf water potential below -0.6 MPa increases TSS. They further suggested that the ability to maintain a high turgor in the fruit by the accumulation of assimilates is an important factor for continued growth and improved fruit quality under water stress.

Mitchell et al. (1991a) observed that starch concentration was increased early in fruit development by water deficit and salinity. Water deficit enhances the conversion of starch to sugars (Kramer, 1983).

Generally water stress as a management tool reduces fruit yield thus producers are hesitant to adopt water stress as a management tool. In this study an attempt was made to determine the level and timing of water stress application to minimise yield reduction while maintaining high level of TSS.

2.4.3. Fruit acid concentration

Acids are one of the major taste components of tomato fruit with the main acids being malic and citric acids (Mahakun et al., 1979). The acid content of the locules is higher than that in the pericarp wall and placental tissue (Ho and Hewitt, 1986). In the immature green fruit, the predominant acid is malic but with increasing maturity, citric acid concentrations rise reaching the peak as the fruit just begin to ripen. At the same time, malic acid concentration declines. In ripe fruit, citric acid accounts for between 45 and 66% of the total acidity of English cultivars, and between 40 and 90 % for American cultivars (Davies and Hobson, 1981). Titratable acidity is closely correlated with citric, but not malic acid (Davies and Hobson, 1981). It is positively correlated to K content of the fruit (Adams and Ho, 1989). Irrigation from fruit development up to 20 % of the ripening stage, lowers the acidity

of the fruit (Rudich et al., 1977). Irrigation cut-off before harvest (at either 50 or 75 days prior to harvest) on processing tomato has increased titratable acidity levels and citrate concentration in one of the two experiments (Mitchell et al., 1991a). Increased fruit ion concentrations resulted from reduced fruit water content. Mitchell et al. (1991b) reported that an increase in the fruit cation:anion ratio results in significantly higher titratable acidity levels and organic acid accumulation at maturity under water stress. Contrary to other results, D'Souza (1991) reported a higher acid concentration in irrigated than non-irrigated fruit in four out of six cultivars. Sudjatmiko (1989) reported no effect of water stress on the acid concentration of tomato fruit. The effect of water stress on fruit acid concentration is therefore not clear, and so it was investigated in this research.

2.4.4. Fruit mineral concentration

Minerals predominantly N, K, Mg, and Ca constitute about 8% of the total dry matter in ripe tomato fruit (Davies and Hobson, 1981). Normal ripe tomato fruit have 0.08, 3.12, and 0.14% (of dry weight) of Ca, K, and Mg respectively (Ward, 1973). Mineral concentration contributes to the flavour of tomato (Adams, 1990).

Mineral composition has been studied primarily to investigate fruit physiological disorders. Blossom-end rot (BER) is thought to be due to Ca deficiency of the fruit (Ho and Adams, 1989). Adams and El-Gizawy (1986) and Ward (1973) found that healthy fruit contains more than 0.07% (dry wt) Ca whereas those with BER contain less than 0.05%. However, Barker and Ready (1994) found no relationship between concentrations of Ca, K, and Mg in fruit with that of BER incidence. Adams and Ho (1993) found that lowest percentage of Ca was found in

the distal placenta and locular tissues where BER first develops. Calcium content is higher at the stem end than blossom end of the fruit (Ward, 1973). Due to restricted mobility of Ca and differences in the proportion of soluble and insoluble forms within the plant, total Ca concentration may be an unreliable predictor of physiological or nutritional status (Marschner, 1974). In apple, Himelrick and Walker (1982) suggested that (Mg + K)/Ca or K/Ca ratio is a more accurate predictor of physiological disorders such as bitter pit than Ca concentration alone.

Calcium is imported into the fruit via the xylem (Ho et al., 1987). The rate of transpiration is the main driving force for Ca transport to the leaves while root pressure at night is the main driving force for Ca transport to the fruit (Ho, 1989). High humidity reduces Ca import by the leaves but increases that by the fruit because accumulation of Ca by the fruit is inversely related to the transport of Ca to the leaves (Adams and Ho, 1993). Low Ca concentration of fruit could be due to low uptake of Ca by roots, reduced movement of Ca within the plant, and high resistance to the import of Ca via the xylem (Ho, 1988).

Water stress and salinity restrict the uptake of most ions except Mg, and increase the ratio of (K+ Mg)/Ca and K/Ca (Goor, 1974; Adams and Ho, 1993). Hegde and Srinvas (1990) reported a decrease in P, K, Ca, and Mg concentrations with reduced irrigation frequency. BER occurs due to dryness or an inadequate supply of Ca in the root zone which leads to poor Ca uptake by the root and/or inadequate distribution of Ca to the fruit at a period of high Ca demand (Adams and Ho, 1993).

Blossom-end rot is always associated with Ca deficiency and insufficient water supply to plant. However, the relationship between Ca and BER is not yet clear, thus further study is needed.

2.4.5. Shelf life

Shelf life is defined as the length of time a uniform batch of fruit of a particular colour stage could reasonably expected to remain acceptable to consumers (Gough and Hobson, 1990). Shelf life in tomato fruit is determined by the rate of respiration, ethylene production, polygalacturonase (PG) activity, and change in colour and firmness of the fruit (Gough and Hobson, 1990; Lu et al., 1994). The above factors are interrelated. For example ethylene synthesis triggers ripening which causes colour and textural changes in the fruit.

Water stress and saline irrigation reduce net water import to the fruit and therefore decrease fruit water- and osmotic potentials (Mitchell et al., 1991a). This may, in turn, influence fruit storage life. Mizrahi (1982) reported that high salinity may affect the shelf life of tomatoes. However, results are not consistent. There is an indication that higher than normal salinity adversely affects the shelf life of tomato (Gough and Hobson, 1990). This confirms the previous finding of Mizrahi (1982) that tomato plants grown under saline conditions shortens the fruit shelf life considerably.

Mizrahi et al. (1988) suggested that salinity may affect shelf life by two opposing mechanisms. Firstly, water loss in fruit from saline-treated plants is lower than in the control due to a lower water potential in the fruit. Similarly Geisenberg and Stewart (1986) speculated that fresh market tomatoes grown under water stress

condition will have less fruit water content, thus shelf life will be improved. Secondly, fruit from saline-treated plants exhibited increased PG activity, which enhances softening and causes shorter shelf life. There is little research done on the effect of water stress on the shelf life of tomato. And so this has been investigated in this thesis.

2.5. Role of carbon dioxide and ethylene in tomato fruit ripening

Carbon dioxide and ethylene are two important gases involved in ripening of climacteric fruit. Many characteristic ripening changes begin to occur at about the same time as the increase in respiration and ethylene production (Grierson and Kader, 1986). Ethylene is known to initiate and hasten fruit ripening while respiration may not be necessary in fruit ripening (Saltveit, 1993; Gray et al., 1993). Fruit ripening is of commercial interest. Depending on the purpose, people are interested in hastening or delaying fruit ripening. Generally it is easier to induce ripening than to retard it. Knowledge of ripening physiology and role of ethylene and carbon dioxide is vital in the manipulation of fruit ripening and thus shelf life.

2.5.1. Respiration and fruit ripening

Fruit have been classified on the basis of their pattern of respiration as climacteric or non-climacteric (Saltveit, 1993). Tomato fruit ripening is considered climacteric. At the onset of ripening, respiration increases, rises to a maximum, called the climacteric peak, and subsequently declines slowly (Grierson and Kader, 1986). These authors observed that, during ripening, CO_2 production increases by factor of two to about 20 µl CO_2 g^{-1} fruit hr^{-1}. Saltveit (1993) also observed 2-fold

increase in carbon dioxide concentration in detached fruit and a linear increase in attached fruit. A climacteric rise has been regarded as the turning point in the fruit's ontogeny when the stages of development and maturation are completed and the tissue begins to senesce (Dostal, 1970).

The respiratory climacteric in tomato begins at prebreaker stage and continues to the breaker stage (Chalmers and Rowan, 1971). It is one of the first signs of ripening, but increased respiration is not necessarily essential for ripening (Grierson and Kader, 1986). The linear increase in carbon dioxide concentration during ripening of attached fruit is just a continuation of the linear increases seen in detached and attached fruit before ripening (Saltveit, 1993). Saltveit (1993) considered respiratory climacteric as an artifact. Little information could be found on the effect of water stress on tomato fruit CO_2 evolution. Kramer (1983) speculated that water stress increase respiration due to sugar accumulation. The role of water stress on fruit CO_2 production was therefore investigated.

2.5.2. Ethylene and fruit ripening

Ethylene plays an important role in the initiation and continuation of ripening in all climacteric fruits including tomato. The rise in ethylene production is one of the earliest indicators of the onset of tomato fruit ripening (Murray et al., 1993). During ripening, ethylene concentrations surge to 10-fold and 20-fold basal levels in detached and attached fruit respectively (Saltveit, 1993). The rate of ethylene synthesis continues to increase during early ripening, reaching a peak at the mid-ripening stage (Grierson and Kader, 1986). Ethylene synthesis at the onset of ripening is involved in regulating expression of some of the ripening genes involved

in changes in colour, flavour, texture, and aroma (Gray et al., 1993). Little research into the effect of water stress on the fruit ethylene production was found in the literature. Basiouny et al. (1994) reported an ethylene increase due to water stress. Tomato stem produced higher ethylene under water stress than under irrigation (Huberman et al., 1993). In perennial crops, apple was reported to evolve higher ethylene when produced under water stress (Ebel et al., 1993). I therefore found it necessary to study the effect of water stress on ethylene production.

2.5.3. Interaction of carbon dioxide and ethylene during ripening

There are conflicting reports about whether the increase in respiration in tomato fruit precedes the rise in ethylene synthesis or vice versa. Some authors have indicated that the respiratory rise in tomato fruit is in response to increased ethylene synthesis which starts a chain of events leading to ripening (Hobson and Grierson, 1993). However, Saltveit (1993) found that in detached tomato fruit respiration peak preceded the ethylene production peak. He concluded that respiration in tomato may not be associated with the climacteric ripening. The interaction of the two gases is not clear and therefore this study will report on it.

Chapter Three: Materials and methods

Two experiments were conducted at the Plant Growth Unit during 1994 and 1995. Both experiments had two treatments (control and deficit irrigation) and had similar materials and methods. Due to the adverse effect of DI on the crop growth and yield in the first experiment, the second experiment was given a different DI timing and a milder level. Most of the parameters measured in the first experiment were also measured in the second experiment (glasshouse environmental conditions, plant development and yield, and quality attributes such as soluble sugars, colour and fruit minerals). Fruit gas exchange was measured in the first experiment while fruit acid concentration, TSS, sugar:acid ratio and shelf life were measured in the second experiment. Only modifications in materials and methods are discussed for the second experiment.

First experiment

3.1. Growing conditions

Tomato seeds, 'Virosa' F1 hybrid which is a fresh market cultivar, were seeded in # 190 plug tray on 9 May 1994. The plants were transplanted into a glasshouse at the five leaf stage, 54 days after sowing (DAS). Eleven litre planter bags holding 100% bark containing ($kg.m^{-3}$): dolomite (3.0); agricultural lime (3.0); superphosphate (1.0); and iron sulphate (0.5) were used. The glasshouse was naturally-lit. Maximum and minimum temperatures were recorded using two thermometers (Brannan, England). Evapotranspiration was measured by a piche evaporimeter using a 5.5-cm filter paper. Solar radiation was monitored using two

Microvolt integrator (type MV 2) linear solarimeters (Delta-T Devices Ltd., Cambridge, UK). Relevant data are presented in Table 3.1.

Table 3.1. Glasshouse environmental condition (averages over season) and water utilisation

		1994	1995
Temperature (C)			
	Maximum	27.8	30.4
	Minimum	17.8	15.91
Evapotranspiration per day (mm)			
	Piche	2.9	2.1
	Petridish	-	0.7
Solar radiation ($w \cdot m^{-2}$)		125	107
Water applied (litre per plant)			
	Control	-	171
	DI	-	54
Water used (litre per plant)			
	Control	-	102
	DI	-	44
Drainage (litre per plant)			
	Control	-	69
	DI	-	10

3.2. Cultural Practices

3.2.1. Training

Plants were trained with support strings. String was tied at the base of the plant then connected to the wire which was approximately 2 m above the ground. The plants were twined into the strings as they grew taller. Lateral shoots were

removed weekly by hand, maintaining a single stem to minimise shoot competition. Plants were stopped upon reaching the wire.

3.2.2. Pollination

During anthesis of each truss, pollination was assisted by the daily use of a truss vibrator.

3.2.3. Fertigation

Fertigation was practised with each watering throughout the experiment using Cooper's (1979) complete nutrient solution. The control plants were irrigated four times a day from stand establishment (2 July 1994) up to the last harvest (3 November 1994). DI plants were given similar irrigation but based on leaf water potential (See section 3.3).

3.2.4. Monitoring of physiological disorders, pest and diseases

Pest and disease levels were continuously monitored and commercial control measures taken. Incidence of blossom-end rot was also recorded.

3.2.5. Harvest

Fruit was harvested when the blossom-end turned orange (breaker stage).

3.3. Experimental treatment and design

There were two treatments: the control which was watered four times a day, maintaining a midday average leaf water potential (ψ_l) of approximately -0.5 MPa,

and the DI treatment which was watered when leaf water potential was -1.0 to -1.2 MPa. DI treatment started at 64 DAS and continued up to the last harvest date at 178 DAS (3 November 1994). The first truss had started to appear when the DI treatment started. A randomised complete-block design with four blocks was used. Each block consisted of two plots. Each plot had two rows of 10 plants each with a spacing of 45 cm between the rows and 40 cm within the row. A row of guard plants was grown around the experimental area.

3.4. Soil moisture content

The soil volumetric moisture content was recorded using time domain reflectometry (TDR) equipment (Tektronic Model 1502B, Beaverton, Oregon). The TDR produces an electrical pulse and measures the resistance to its propagation through the medium. The greater the resistance the lower the moisture content in the medium between and around the probes. The stainless steel TDR probes (3.2 mm in diameter and 300 mm in length) were inserted vertically into 32 of the planter bags, 16 pair of probes per treatment. There were 12 measurement times throughout the season.

3.5. Crop development monitoring

3.5.1. Leaf water potential

Four leaves per treatment (fourth or fifth youngest leaves) were used for ψ_l measurement. However, when the plant growth was stopped upon reaching the wire, the upper most leaves were used for measurement. The ψ_l was monitored two days

after each watering of DI treatment using a Scholander pressure chamber. Measurement time was either at 0900, 1200 HR, or at 1500 HR.

3.5.2. Measurement of flowering and fruit development

At anthesis, 16 plants per treatment (four plants per plot) were randomly tagged to monitor fruit development. The number of trusses and reflexed flowers on these plants was recorded every three days.

3.5.3. Whole plant fresh and dry mass

At final harvest, whole plant fresh mass (root included) was determined using a Mettler PJ6000 balance. Samples were then oven dried at 60C for four days and re-weighed to determine whole plant dry mass.

3.6. Fruit yield

All harvested fruit from 40 plants per treatment (ten plants per plot) were counted (BER fruit included) and weighed using a Mettler PJ6000 balance. Average fruit mass was approximated by dividing the total fruit fresh mass by the total number of fruits.

3.7. Postharvest quality attributes

3.7.1. Fruit gas exchange

Fruit gas exchange was measured twice at 30 days interval and were designated as first and second measurement, respectively. Thirty two fruit per treatment (16 fruit each from the first and second measurement) were selected based

on uniformity of size and colour (breaker stage) for measurement of respiration rate and ethylene production rate. Ethylene and respiration was measured for 10 consecutive days starting from their respective harvest dates (148 and 178 DAS for the first and second measurements, respectively). Whole fruit were individually placed one each in an air-tight jars and sealed for 30 min. One-ml syringes were used to sample the atmosphere of the sealed jars through the septum and were injected into a gas chromatograph (Pye Unicam PU 4500 Chromatograph, Cambridge, UK) fitted with a flame ionization detector for ethylene determination. Similar injections were made into the CO_2/O_2 analyser (Analytical Development Co., Hoddespon, UK) to evaluate fruit respiration. Fruit for gas exchange measurement was also used for colour, mineral and soluble sugar concentration measurements.

3.7.2. Fruit colour

The two colour measurements were also designated as first and second measurements. Colour measurements were made at the equatorial region and blossom-end for 10 consecutive days from harvest using a chromameter (CR-200; Minolta, Osaka, Japan). Fruit colour was measured as hue angle which ranges from 0° to 360°. with the green to red range encompassing approximately 160° to 20° (McGuire, 1992; Voss, 1992).

3.7.3. Mineral concentration

After the final colour measurement, each fruit was cut, transversely, into two sections. One fruit half was used for water content determination and once dried was

ground and used for mineral determination of Ca, K, and Mg. The other half was used for sugar (glucose, fructose, and sucrose) analysis.

Approximately 0.1g of each dried fruit sample was weighed out and refluxed at 150C in 4ml of nitric acid for 6 hours. The acid was then boiled off at 250C. Fruit mineral concentration was determined using an atomic absorption spectrophotometer (AAS) (GBC 904AA, GBC Scientific Equipment Pty Ltd, Victoria, Australia).

3.7.4. Soluble sugar

The concentration of sucrose, glucose and fructose was determined using high performance liquid chromatography (HPLC). Five-gram samples, taken from the pericarp, were preserved in 20 ml of ethanol and stored in the freezer for 33 days to allow the cell components to precipitate. A 1-ml aliquot was then taken and completely dried using a vacuum concentrator (Savant Ltd Inc., Farmingdale, New York). The residue, after dilution in water, was injected into a HPLC system (Waters Millipore Corp., Milford, Mass.) using a Biorad Aminex HPX87C column with Biorad de-ashing guard columns (BioRad Laboratories, Hercules, California, USA).

Second experiment

3.8. Modifications in the second experiment

3.8.1. Seeding and growing conditions

The seed was sown on 4 May and transplanted on 14 June 1995. Ten petridishes of approximately 90 mm in diameter were used for evapotranspiration

measurement. They were filled with water and weighed daily for water loss. Data are presented in Table 3.1.

3.8.2. Fertigation

The plants were watered once a day from 14 June 1995 to 24 July 1995 when the second truss had developed (80 DAS). From 100 DAS (fifth truss development) up to the last harvest (14 November 1995), watering was increased to five times a day. At monthly intervals, the volume of water discharged per dripper was measured from 20 drippers to estimate the amount of water applied to each plant. A collecting pan was also placed under the growing medium to estimate drainage. Water utilization data are presented in Table 3.1.

3.8.3. Deficit irrigation management

Plants in the DI treatment were watered either when ψ_l was -1.0 MPa to -1.2 MPa or when TDR readings were below 10 $m^3 \cdot m^{-3}$. The DI treatment started at 62 DAS when the first truss started to develop. The DI treatment was stopped at 84 DAS (third truss development) to avoid water stress at the height of flowering which is sensitive to water stress (Helyes and Varga, 1994). At 101 DAS, when the fifth fruit truss had developed and fruit from the first and second trusses were about 24 and 13 g respectively, DI treatment was resumed with twice a week irrigation up to the last harvest on 14 November 1995. The amount of water applied and used per DI plant is presented in Table 3.1.

3.8.4. TDR measurement

Soil volumetric water content (Θ) was recorded daily in second experiment. Because Θ in the control pots was steady during first experiment only four probes were used for control plants during the second experiment while 20 probes were used for DI pots.

3.8.5. Fruit and leaf mineral concentration

At 127 DAS, 12 mature green fruit per treatment were selected, based on uniform maturity and size, for analysis of Ca, Mg, and K. Fruit was cut across into two sections and the blossom-end section was used for mineral analysis.

Leaf yellowing occurred in control plants at 158 DAS which was the height of fruiting. Magnesium deficiency was suspected and therefore 32 leaf samples were taken for mineral analysis. Twenty four leaf samples were taken from control plants, eight leaves from each plant showing normal, moderate and severe symptoms. Although no leaf yellowing was observed in the DI plants, eight normal leaves were taken for analysis. The samples were oven-dried at 60C for four days and then ground for Mg analysis.

3.8.6. Whole plant fresh and dry mass

The fresh and dry mass of the leaves, roots, and stem of individual plants were determined separately in the second experiment. The leaf area was also determined at the end of the experiment by removing all the leaves and passing them through a Licor leaf-area meter (Model 3100-Licor).

3.8.7. Fruit yield

Harvesting and recording was done for individual fruit trusses in the second experiment.

3.8.8. Fruit water potential

From the time fruit of the first truss was mature green and eighth truss had developed (122 DAS), midday and predawn fruit water potential (ψ_f) was monitored weekly using a Wescor Dew Point Hygrometer (Model HR-33T, Logan, Utah, USA). Four fruit per treatment, taken from the first truss were used. Using a cork borer, flesh samples were taken from the cortex in the equatorial region (excluding the skin). The sample was placed in individual Wescor C-52 sample chambers and allowed to equilibrate for 150 min. Water potential was then determined using a Wescor HR-33 Microvoltmeter. Once ψ_f was determined the sample was removed from the chamber, wrapped in clear plastic and then in aluminium foil and dipped into liquid air. Once thawed, the sample was returned to the chamber and allowed to equilibrate for a further 60 min. Osmotic potential (ψ_s) was then determined. Turgor potential (ψ_p) was calculated as the difference between ψ_f and ψ_s.

3.8.9. Total soluble solids

Sixteen fruit per treatment of the same size and colour stage were stored at 20C and measurement of the TSS was done when fruit were table ripe (completely red). There were three measurements and samples were taken from the 3rd, 5th and 8th trusses respectively for the first, second and third measurements. The fruits were washed, dried and cut transversely. One-half was blended to extract the juice while

the other half was oven dried at 60C for four days for dry mass measurement. The TSS was measured with the use of a hand held refractometer (Atago N-20, Tokyo, Japan).

3.8.10. Titratable acidity

From the same juice extracted for TSS determination, the titratable acidity (TA) was measured using a Mettler DL21 titrator (Mettler Instrumente Ag., Greifensee, Switzerland). One ml of fruit juice was mixed with 40 ml of distilled water. The solution was titrated with 0.1M NaOH to an end point of pH 8.1. Values are expressed as percent citric acid.

3.8.11. Soluble sugar

At the final harvest, 32 fruits (16 fruit per treatment), mostly harvested from the 8th truss and few from the 7th truss were freeze dried. These samples were later used to analyse soluble sugar concentrations (sucrose, fructose, and glucose). The sugar concentrations were subsequently used to evaluate the sugar to acid ratio.

3.8.12. Shelf life

For measurement of shelf life, sixteen fruit per treatment of the same size and colour stage (breaker stage) harvested from the 5th truss and stored at 20C. Weight loss and colour change were recorded using Mettler AE200 balance and chromameter (CR-200; Minolta, Osaka, Japan), respectively, for 10 consecutive days from harvest. The same fruit was then monitored at two-day intervals up to the time the fruit was

unacceptable for market. The fruit was unacceptable when there was a sign of damage or wrinkle.

3.9. Data analysis

All data in the first experiment were analysed by analysis of variance and t-test with the Minitab statistical package (version 8.2; Minitab Inc, State College, PA, USA). Data for the second experiment were analysed using statistical analysis system (SAS) software (SAS Institute, Cary, N.C., USA). Data were analysed as a randomised complete block design (RCBD) with four blocks and two treatments. Mean comparisons were carried out using least significant difference (LSD) at 5% and 1% level.

Chapter Four: Results and discussion

4.1. Results

First experiment

4.1.1. Volumetric water content

Growing medium water content under DI was lower than for the control throughout the experimental period (Fig. 4.1). The Θ difference was smallest at the start of measurement but increased with time. The Θ of DI ranged from 0.07 to 0.18 $m^3 \cdot m^{-3}$ while in the control medium, it ranged from 0.22 to 0.28 $m^3 \cdot m^{-3}$. There was less fluctuation of Θ in the control compared with DI whose Θ values fluctuated throughout the experimental period (Fig. 4.1).

4.1.2. Leaf water potential

The leaf water potential (ψ_l) of DI was generally lower than the controls throughout the growing season (Fig. 4.2). The ψ_l of the controls were steadily maintained at an average of -0.5MPa, while the ψ_l for DI fluctuated throughout the stress period probably due to irregular water supply and diurnal changes. After every watering, ψ_l was similar for both treatments. However, during the later growth stages (160 to 178 DAS) the ψ_l of the DI plant was always lower than in the control (Fig. 4.2).

4.1.3. Whole plant fresh and dry mass

Leaves and stems of the DI plants were generally smaller than the control plants. Whole plant fresh and dry masses were higher in the control plants ($P \leq$

0.01) than in DI plants (Table 4.1). The DI fresh and dry masses were 53% and 65% respectively of the control plants.

4.1.4. Plant truss and flower development

Truss number for both treatments was the same early in the experiment, but the control plants developed more fruit trusses than DI plants from 95 DAS (Fig. 4.3A), The plants were stopped when they reached the wire (approximately at 2 m height). The control and DI plants developed an average of 8.4 and 7.9 fruit trusses respectively. Similarly, throughout the flowering season more flowers with reflexed petals were present on the control plants (Fig. 4.3B). The control plants also attained their flowering peak earlier (98 DAS) than DI plants (115 DAS). From 125 DAS, flowering in both treatments declined.

4.1.5. Fruit yield

The yield of DI was 39% that of control (Table 4.1) due to reductions in both fruit number and size. Fruit number, which includes fruit with BER, was reduced more (52% of control) than fruit size (75% of control). The control fruit were larger and heavier than DI fruit, and had higher water contents ($P \leq 0.05$) than DI fruit (Table 4.1).

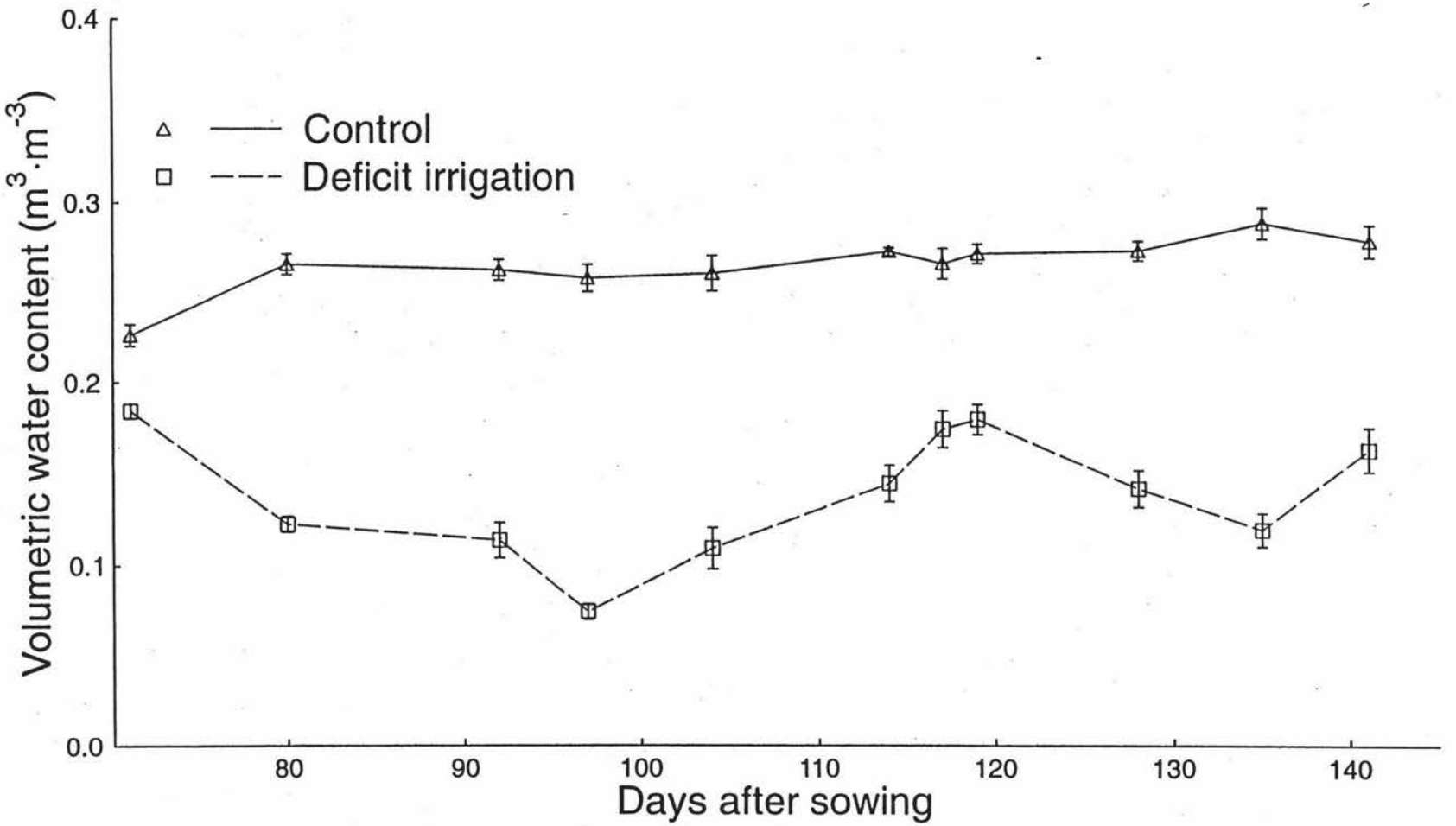

Fig. 4.1. Volumetric water content of the pots for control and deficit irrigation in 'Virosa' tomato (first experiment). The bar on each mean are twice the standard error of the mean based on 16 pots per treatment.

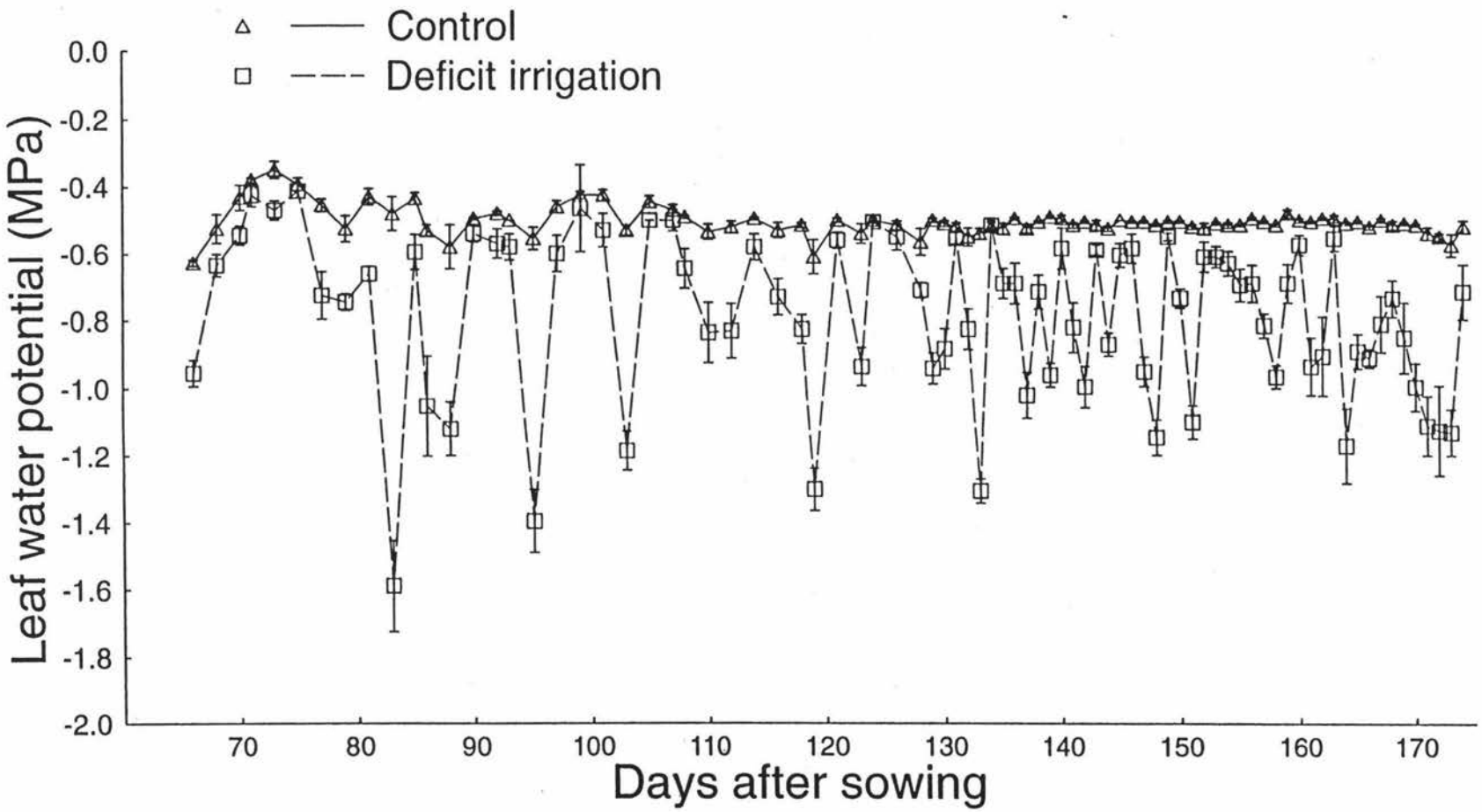

Fig. 4.2. Effect of DI on the midday leaf water potential in 'Virosa' tomato (First experiment). The bar on each mean represents twice the standard error of the mean based on four replicate plants per treatment.

Table 4.1. Effect of deficit irrigation (DI) (first experiment) on whole plant weight, fruit water content, yield, number, and size in 'Virosa' tomatoes

Treatment	Whole-plant weight ($g \cdot plant^{-1}$)		Fruit water content (%)	Fruit yield ($kg \cdot plant^{-1}$)	Fruit No· $plant^{-1}$	Fruit size (g)
	Fresh	Dry				
Control (C)	1098.3[z]	114.89[z]	94.11[y]	2.32[x]	40.70[x]	57.06[x]
DI	583.8	75.18	91.13	0.90	21.23	42.76
Significance	**	**	*	**	**	**
DI as % of C	53	65	97	39	52	75

*,**Significant at $P \leq 0{\cdot}05$ or $P \leq 0{\cdot}01$, respectively.

[z]Means of 8 replicate plants per treatment

[y]Means of 32 replicate fruit per treatment, 16 from the first and 16 from the second measurement

[x]Means of 40 replicate plants per treatment

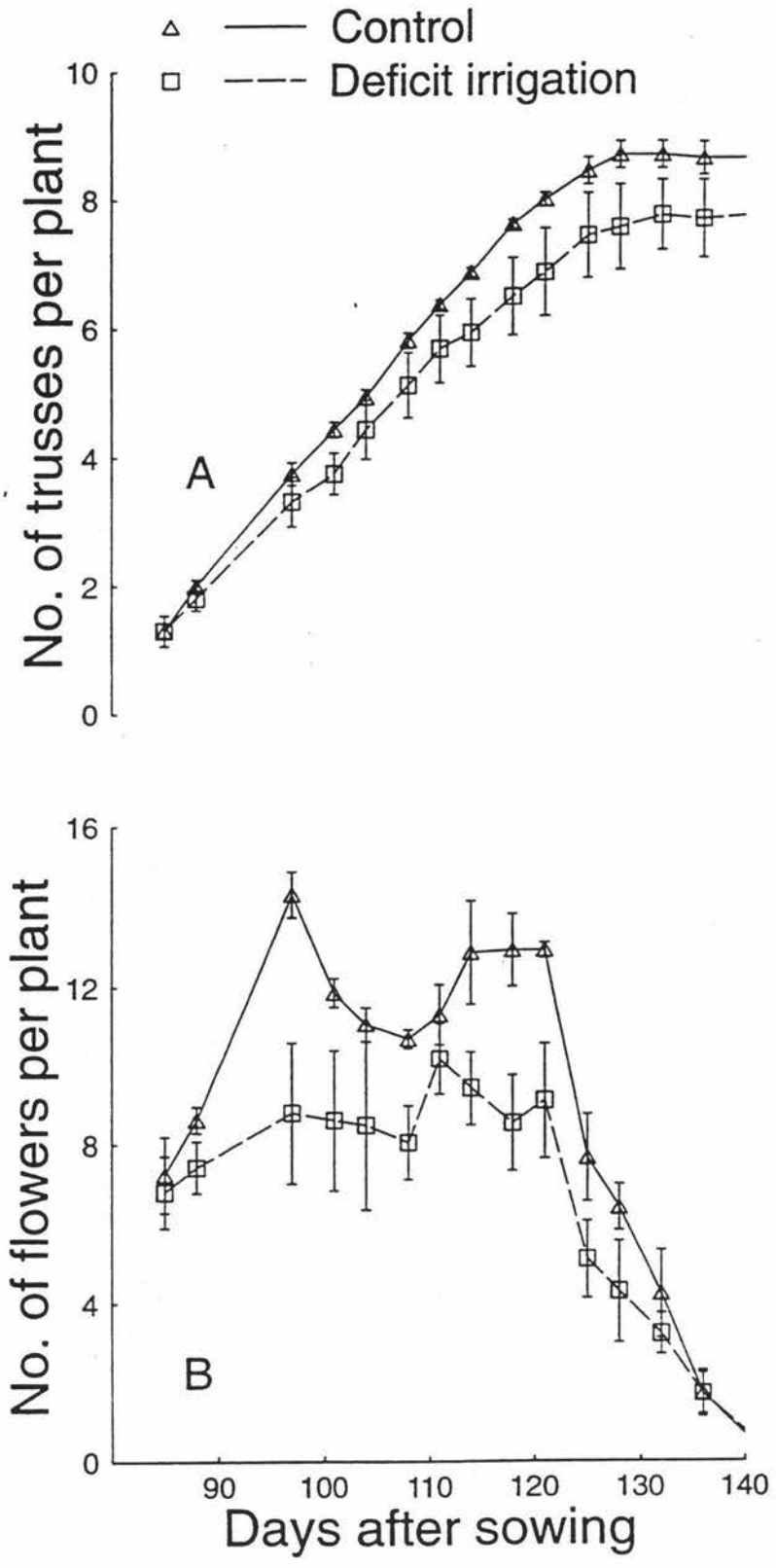

Fig. 4.3. (A) Mean number of trusses per plant and (B) mean number of flowers with reflexed petals per plant in 'Virosa' tomato. The bar on each mean represents twice the standard error of the mean based on 16 replicate plants per treatment.

4.1.6. Postharvest quality attributes

4.1.6.1. Mineral concentration and blossom-end rot incidence

Concentrations of Ca, Mg, and K were the same on a dry weight basis for both irrigation treatments (Table 4.2). On a fresh weight basis these concentrations were higher in DI fruit than in control fruit (Table 4.2).

Blossom-end rot occurred solely in DI fruit from 108 to 145 DAS and affected only 0.9% of the total number of fruit harvested from this treatment.

4.1.6.2. Fruit sugar concentration

Concentrations of sucrose, fructose, and glucose were higher ($P \leq 0.01$) in DI fruit than in control fruit (Table 4.2). Among the sugars analysed, fructose was most abundant followed by glucose and sucrose.

4.1.6.3. Gas exchange

Deficit-irrigated fruit for both measurements produced higher quantities of CO_2 and ethylene compared to control fruit (Fig. 4.4). The difference was greater in the second measurement, when plants had been exposed to longer duration of DI. In the first measurement, the peak for respiration and ethylene production occurred four days after harvest (Fig. 4.4 A and C). But in the second measurement the respiration peak preceded the ethylene production peak (Fig. 4.4 B and D).

Table 4.2. Effect of DI (first experiment) on the concentration of mineral elements (dry and fresh weight basis) and soluble sugars in 'Virosa' tomato fruit

	Mineral elements ($mg \cdot kg^{-1}$ dry weight)			**Mineral elements ($mg \cdot kg^{-1}$ fresh weight)**			**Soluble sugars ($mg \cdot kg^{-1}$ fresh weight)**		
Treatment	**Ca**	**K**	**Mg**	**Ca**	**K**	**Mg**	**Sucrose**	**Fructose**	**Glucose**
Control	1180[z]	3720[z]	1900[z]	67[z]	107[z]	211[z]	176[y]	11518[y]	10746[y]
DI	1020	3690	2060	90	175	312	782	14696	14333
Significance	NS	NS	NS	*	**	**	**	**	**

[NS,*,**]Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively

[z]Mean of 20 fruit per treatment

[y]Mean of 32 replicate fruit per treatment (16 from the first and 16 from second measurement)

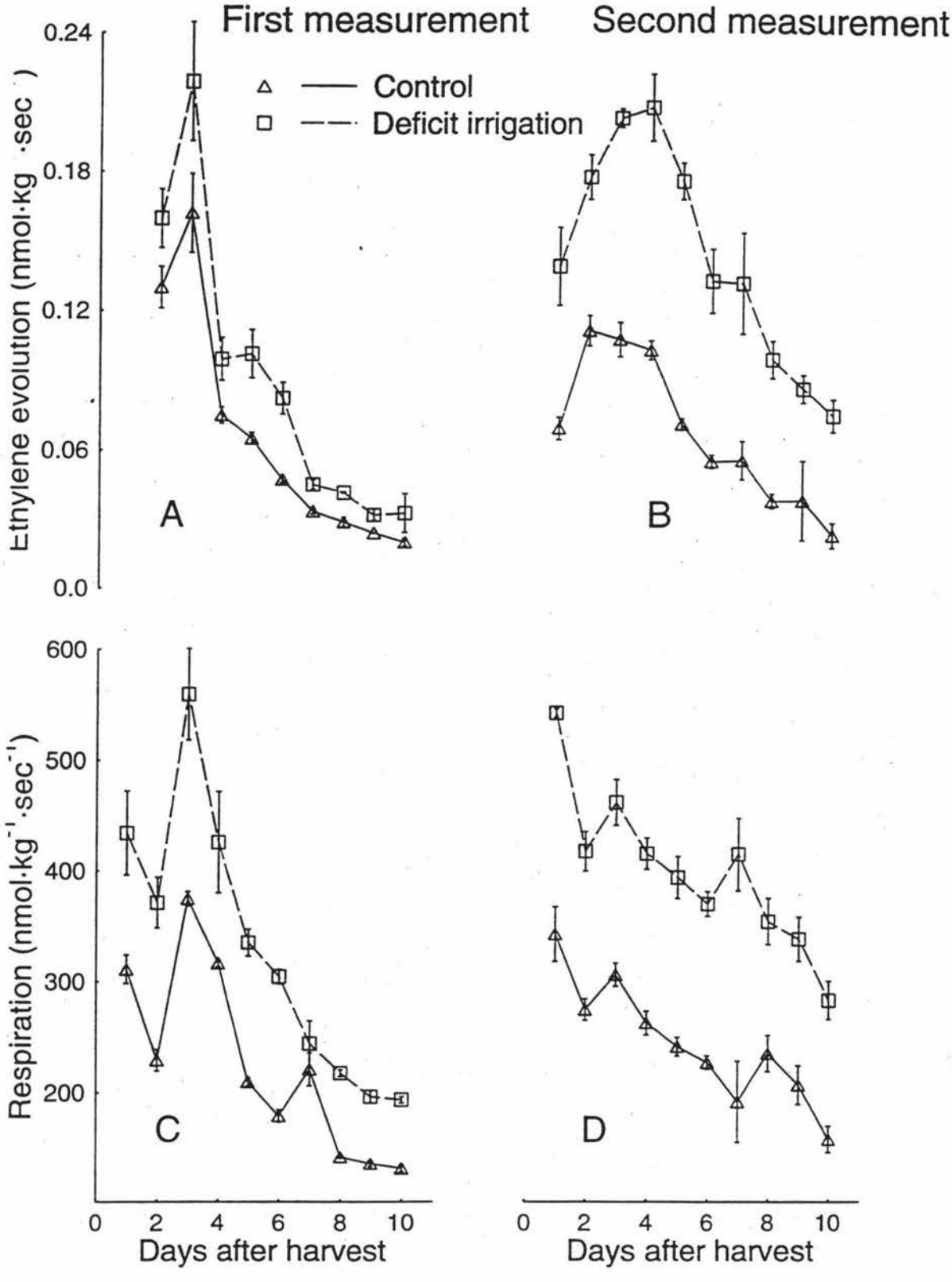

Fig. 4.4. Effect of deficit irrigation (first experiment) on postharvest ethylene evolution (A & B) and respiration (C & D) in 'Virosa' tomato fruit. The bar on each mean represents twice the standard error of the mean based on 16 replicate fruit per treatment.

4.1.6.4. Fruit colour

Fruit colour development, as reflected in changes of hue angle, followed a similar trend for both measurements in both treatments (Fig. 4.5). Colour change was rapid in the first four to five days after harvest and very slow thereafter. The DI fruit had lower hue angle values than control fruit throughout in the first measurement (Fig. 4.5) while in the second measurement, DI fruit had a lower hue angle value from 3 to 8 days after harvest (Fig. 4.5). This means that DI fruit were generally redder than control fruit.

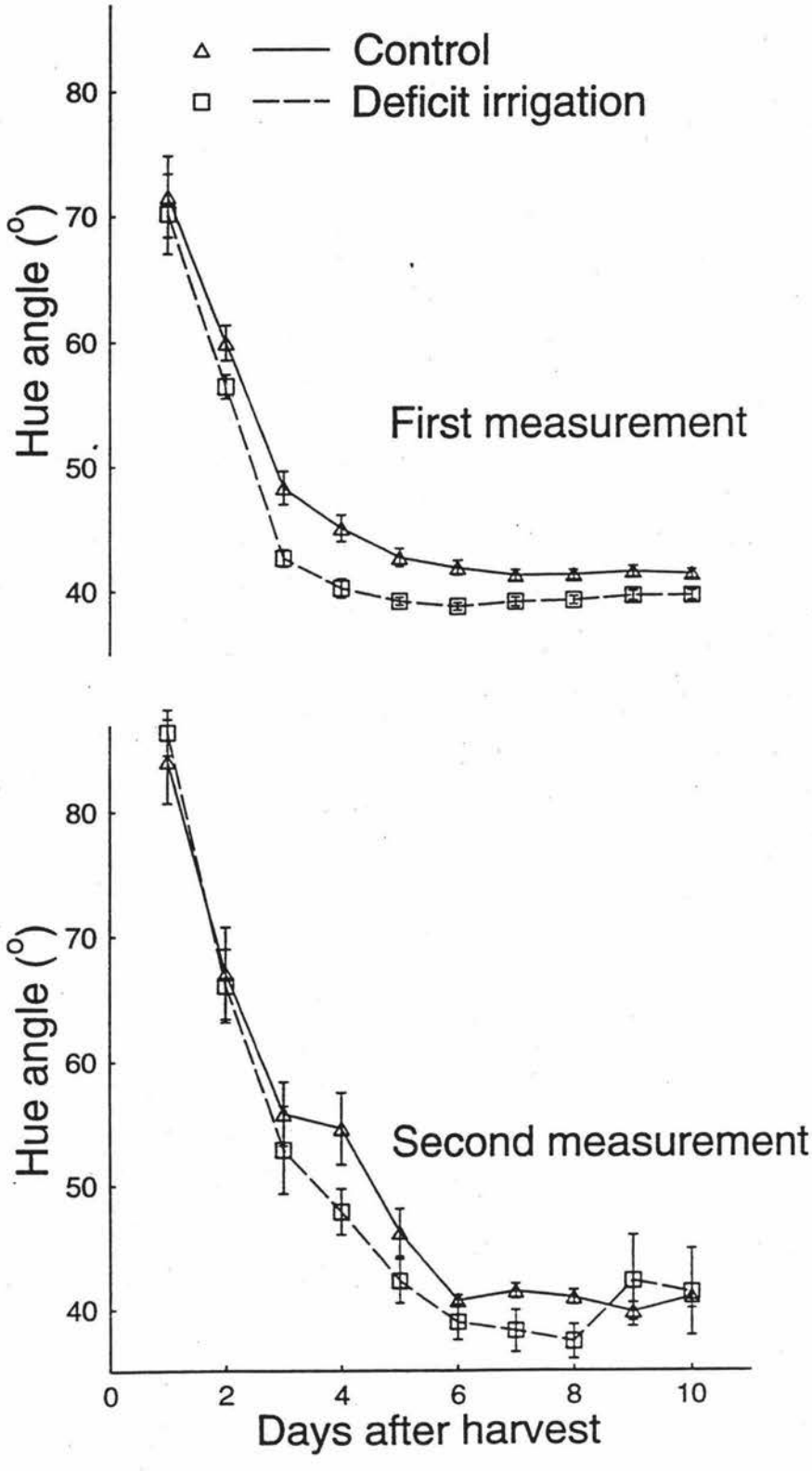

Fig. 4.5. Effect of deficit irrigation (first experiment) on fruit colour in terms of hue angle in 'Virosa' tomato fruit. The bar on each mean represents twice the standard error of the mean based on 16 replicate fruit per treatment.

Second experiment

4.1.7. Volumetric water content (Θ)

Volumetric water content of the growing medium was lower in DI than in control plants (Fig. 4.6). The Θ of the DI plants was lower than the control at the start of the experiment. It started to increase when DI treatment was stopped (84 to 100 DAS) but dropped abruptly when DI treatment was resumed at 101 DAS. Thereafter, a Θ difference between the two treatments developed. The Θ of the control medium ranged from 0.14 to 0.33 $m^3 \cdot m^{-3}$ while that of the DI ranged from 0.06 to 0.27 $m^3 \cdot m^{-3}$.

4.1.8. Leaf water potential

The midday leaf water potential (ψ_l) throughout the cropping season is presented in Figure 4.7. Generally the plants subjected to DI had lower ψ_l than that of the control plants. The ψ_l difference between the treatments was minimal at the beginning but it increased with time. At 84 to 101 DAS the water potential was the same for both treatments because DI treatment was stopped to avoid water stress at the height of flowering. At the resumption of DI and up to the last harvest (102 to 194 DAS), the DI plants were watered twice a week and each watering made their ψ_l similar to that of the control plants. There is also a trend with age with older plants having lower ψ_l.

From 125 to 153 DAS predawn ψ_l was measured at weekly intervals. The predawn ψ_l in DI plants was significantly lower than in control plants at four of the five measurement times (Table 4.3). On the other hand, midday ψ_l measurements (on same day as predawn measurement) showed that for DI plants ψ_l was

significantly lower than control in two of the five measurements (Table 4.3). Midday ψ_l was generally lower than the predawn ψ_l (Table 4.3).

4.1.9. Fruit water potential

The predawn and midday fruit water-, osmotic-, and turgor potentials were measured at weekly intervals from 122 to 150 DAS. The predawn fruit water potential was generally lower in the DI than in the control fruit but the difference was not significant (Table 4.4). The slight decrease in the DI fruit water potential paralleled a trend towards a decreased fruit osmotic potential. This reduction was not significant (Table 4.4). No significant difference in turgor potential existed between the two treatments.

The midday fruit water-, osmotic-, and turgor potentials (Table 4.5) were measured for four times only. The results were similar with the predawn measurement (Table 4.4).

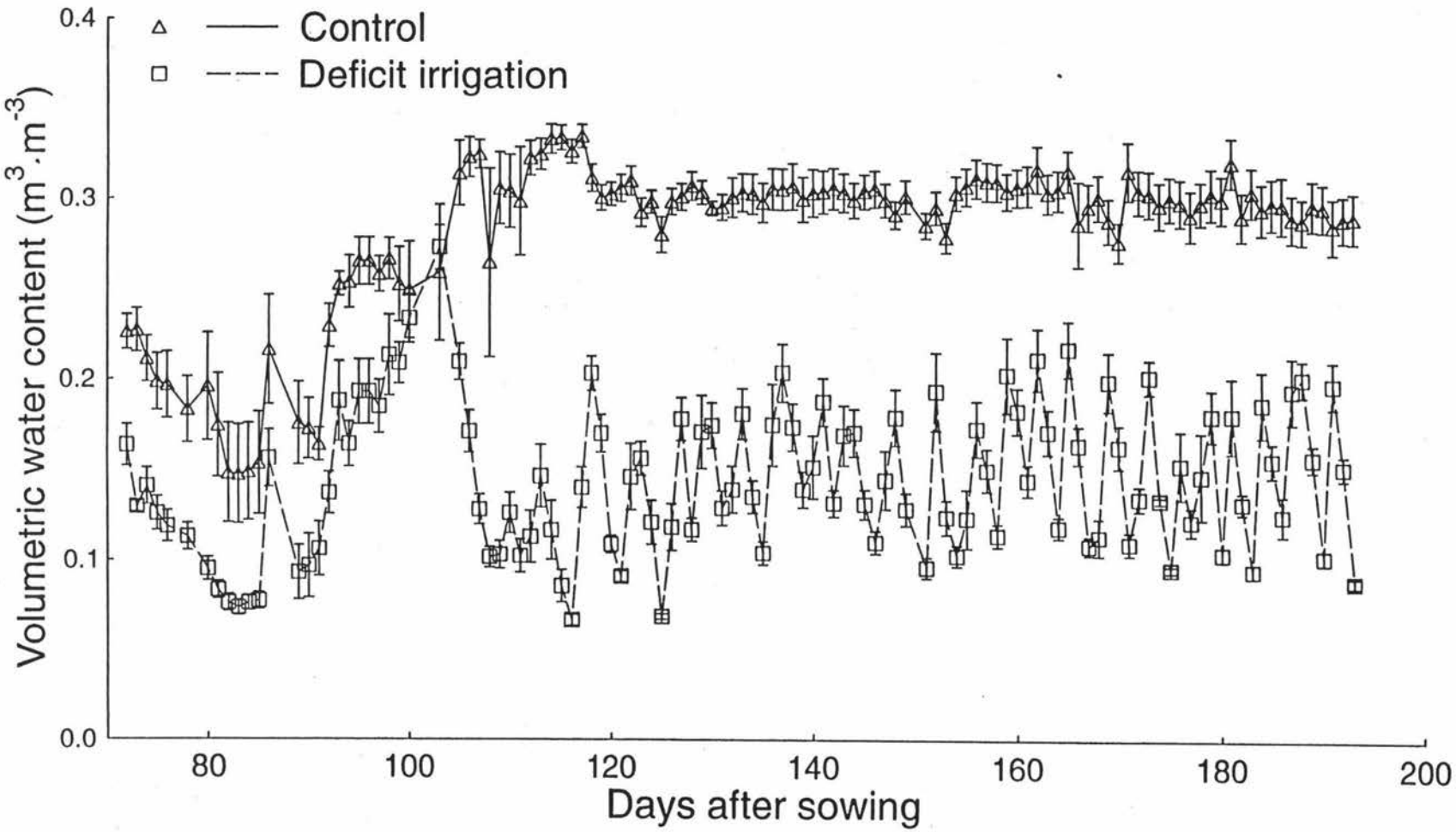

Fig. 4.6. Volumetric water content of the pots for control (C) and deficit irrigated (DI) 'Virosa' tomato (second experiment). The bar on each mean are twice the standard error of the mean based on 20 DI pots and four C pots.

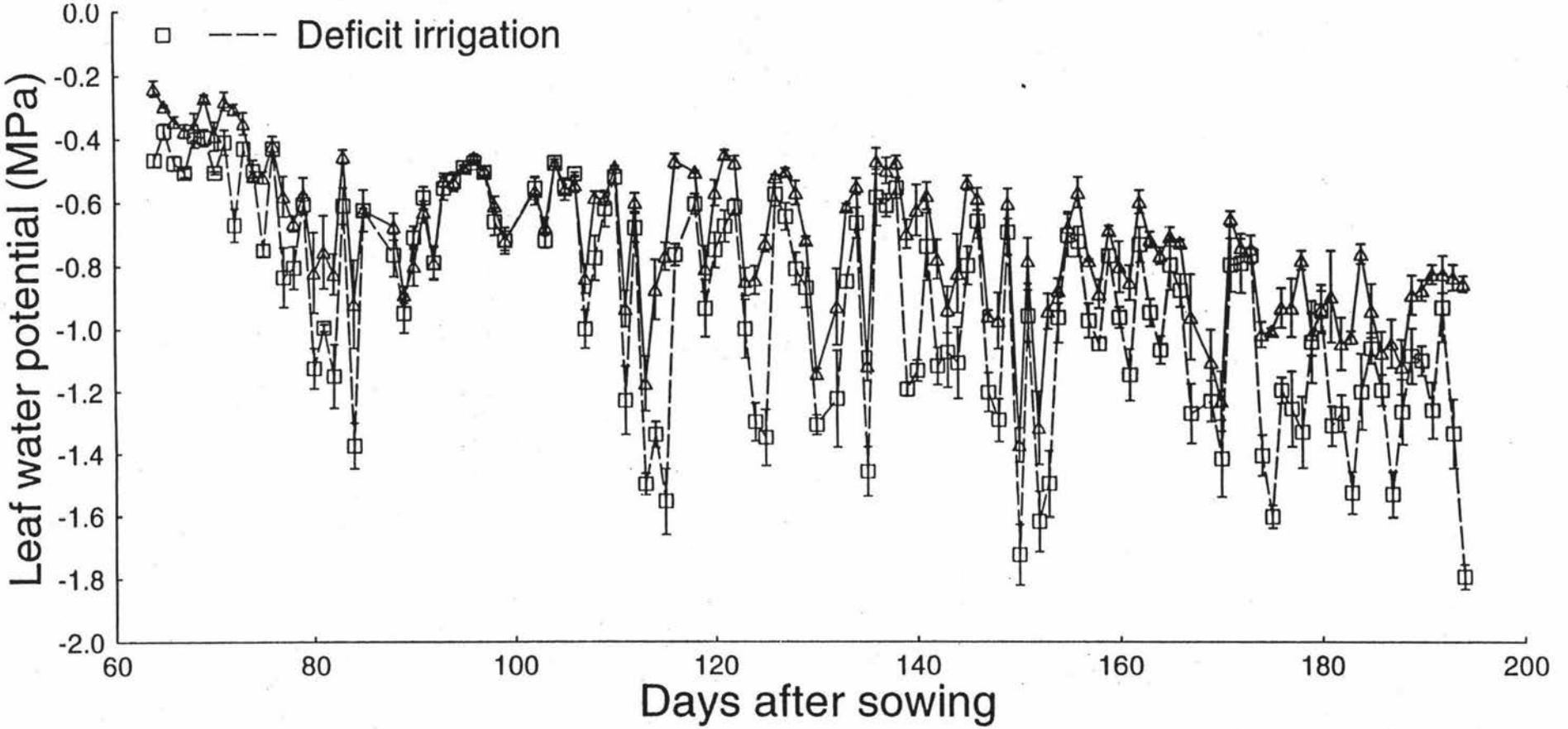

Fig. 4.7. Effect of DI on the midday leaf water potential in 'Virosa' tomato (second experiment). The bar on each mean represents twice the standard error of the mean based on four replicate plants per treatment.

Table 4.3. The effect of deficit irrigation (DI) on the predawn and midday leaf water potential in 'Virosa' tomato. DI started from 62 DAS.

Treatment	Days after sowing				
	122	**128**	**136**	**143**	**150**
A)Predawn ψ_l (MPa)					
Control	-0.47[z]	-0.39[z]	-0.45[z]	-0.45[z]	-0.52[z]
DI	-0.71	-0.51	-0.57	-0.52	-0.85
Significance	**	*	ns	*	*
B)Midday ψ_l (MPa)					
Control	-0.52	-0.93	-0.62	-0.96	-0.88
DI	-0.57	-1.23	-1.13	-1.2	-0.96
Significance	ns	*	**	ns	ns

[ns, *, **] Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$ respectively.

[z] Mean of 4 replicate per treatment

Table 4.4. Effect of deficit irrigation (DI) on predawn fruit water-, osmotic-, and turgor potentials in 'Virosa' tomato. DI started from 62 DAS.

	Days after sowing				
Treatment	**122**	**128**	**136**	**143**	**150**
A) Fruit water potential (MPa)					
Control	-1.54[z]	-2.27[z]	-1.90[z]	-1.96[z]	-1.92[z]
DI	-2.06	-2.16	-2.59	-2.54	-2.34
Significance	ns	ns	ns	ns	ns
B) Osmotic potential (MPa)					
Control	-1.81	-2.55	-2.08	-2.14	-2.67
DI	-2.22	-2.38	-3.31	-2.88	-2.98
	ns	ns	ns	ns	ns
C) Turgor potential (MPa)					
Control	0.27	0.28	0.18	0.18	0.75
DI	0.16	0.22	0.72	0.34	0.64
	ns	ns	ns	ns	ns

[ns], Nonsignificant

[z]Means of 4 replicate fruit per treatment

Table 4.5. Effect of deficit irrigation (DI) on midday fruit water-, osmotic-, and turgor potentials in 'Virosa' tomato. DI started from 62 DAS.

Treatment	Days after sowing			
	128	**136**	**147**	**150**
A) Fruit water potential (MPa)				
Control	-1.74[z]	-1.93[z]	-1.94[z]	-2.02[z]
DI	-2.04	-2.55	-2.57	-2.61
Significance	ns	ns	ns	ns
B) Osmotic potential (MPa)				
Control	-1.93	-2.16	-2.15	-2.21
DI	-2.31	-2.72	-2.83	-2.79
	ns	ns	ns	ns
C) Turgor potential (MPa)				
Control	0.18	0.23	0.21	0.19
DI	0.27	0.17	0.26	0.18
	ns	ns	ns	ns

[ns], Nonsignificant

[z]Means of 4 replicate fruit per treatment

4.1.10. Plant mass, leaf area, lateral shoot growth and leaf magnesium

Leaf area, fresh mass, and dry mass of the stem and of the root were the same for both treatments (Table 4.6). Leaf fresh mass of control plants was higher ($P \leq 0.05$) than DI plants. Total fresh mass of the control plants was higher ($P \leq 0.05$) than DI plants but the dry mass was similar. It seems water stress did not affect vegetative growth but control plants produced heavier ($P \leq 0.01$) lateral shoots than DI plants. This was manifested in the weekly lateral shoot removal wherein DI fresh mass was 49% of the control (Table 4.6).

At the height of fruiting (160 DAS), approximately 15% of the control plants showed yellowing of the leaves. Magnesium deficiency was suspected. Magnesium concentration was highest in DI leaves and lowest in affected control leaves (Table 4.7). The normal control leaves had significantly higher concentrations of Mg than the moderately and severely affected leaves which had similar concentration.

Table 4.6. Effect of DI (second experiment) on plant mass (fresh and dry), leaf area and lateral shoot growth in 'Virosa' tomato

Treatment	Leaf ($g \cdot plant^{-1}$)		Stem ($g \cdot plant^{-1}$)		Root ($g \cdot plant^{-1}$)		Leaf area ($m^2 \cdot plant^{-1}$)	Lateral shoot fresh wt ($g \cdot plant^{-1}$)
	Fresh	Dry	Fresh	Dry	Fresh	Dry		
Control	649.34[z]	76.12[z]	453.70[z]	58.66[z]	46.96[z]	8.33[z]	1.49[z]	29.22[x]
DI	444.83	61.70	342.62	50.20	43.40	7.80	1.03	14.39
Significance	*	ns	ns	ns	ns	ns	ns	**

[ns,*,**]Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively

[z]Means of 8 replicate plants per treatment

[x]Means of 72 replicate plants per treatment in 12 pruning.

Table 4.7. Effect of DI on the leaf magnesium concentration in 'Virosa' tomato. Mean with same letter are not significantly different ($P \leq 0.01$).

Treatment		**Mg (mg g^{-1} dry wt)**
Control	a) Normal	4.90[x] b
	b)Moderately affected	1.76 c
	c)Severely affected	1.01 c
DI (Normal)		7.76 a

[x]Mean of 8 leaves per treatment

4.1.11. Plant truss and flower development

Truss and flower formation started at 70 DAS in both treatments (Fig. 4.8). Throughout the flowering stage, both treatments had developed the same number of fruit trusses (Fig. 4.8A). At 126 DAS, both treatments developed eight trusses each and the plants were stopped. Both treatments had the same number of flowers at the start of flower formation and had a rapid increase in reflexed flowers which reached a maximum at 105 DAS (Fig. 4.8 B). From the peak, it started to decline with the decrease being greater in the DI than control plants. From 110 to 130 DAS the control plants had more flowers than the DI plants. Both had the same number of flowers from 130 to 150 DAS and decline was at a similar rate (Fig. 4.8 B).

4.1.12. Fruit yield

Fruit number, yield and size were recorded by plant truss (Table 4.8). Fruit number in both treatments was the same in all trusses except in the seventh truss where control plants had more fruit than DI plants (Table 4.8 A). Control fresh fruit mass was heavier than DI fruit in three trusses (Table 4.8 B). The yield reduction in the DI (31 % of control) was due to the reduced fruit number (by 10 % in DI) and fruit size (by 33 % in DI). The fruit size (total fruit mass/total fruit number) in four fruit trusses were smaller in DI than control fruit (Table 4.8 C)

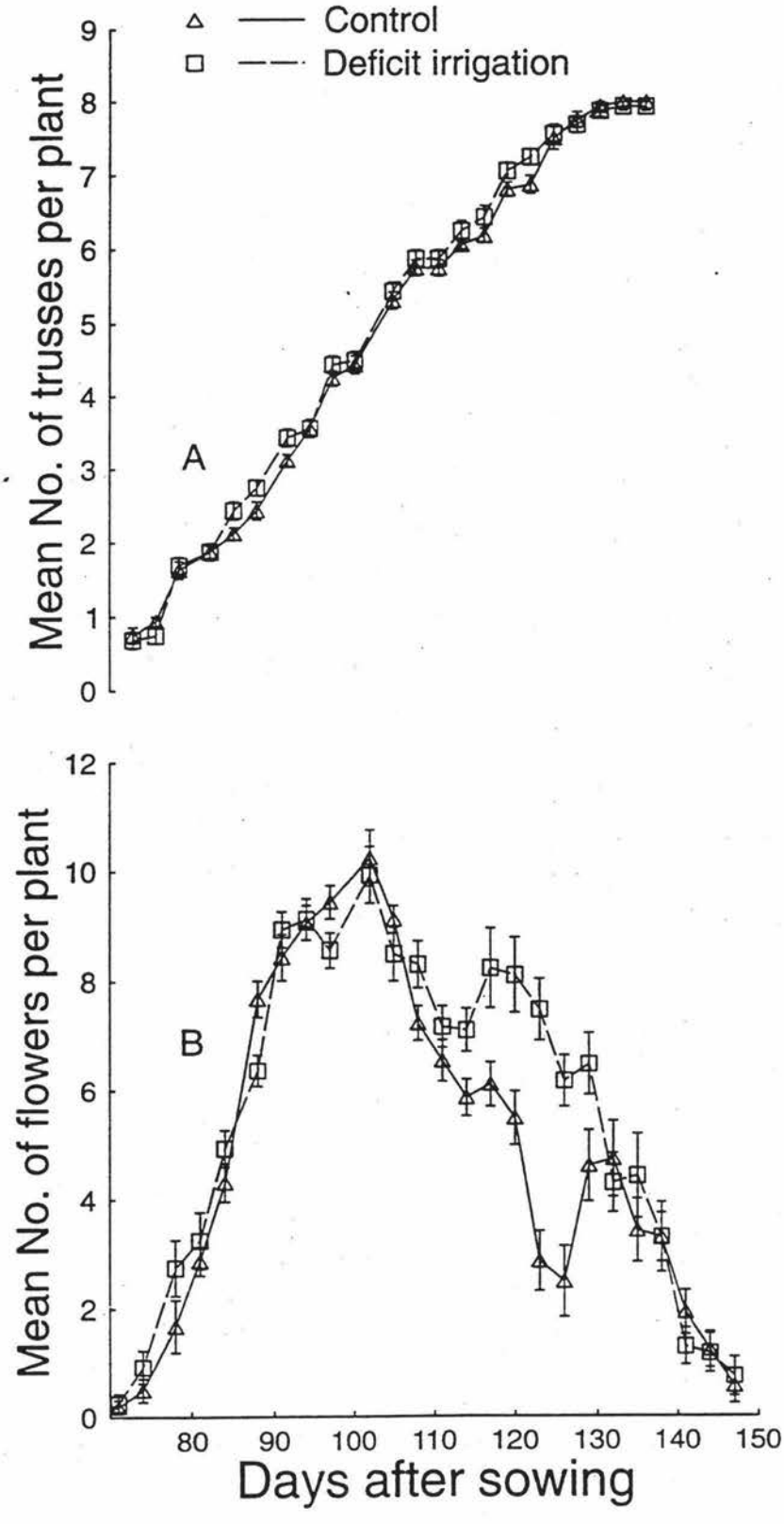

Fig. 4.8. (A) Mean number of trusses and (B) mean number of flowers per plant in 'Virosa' tomato. The bar on each mean represents twice the standard error of the mean based on 16 replicate plants per treatment.

Table 4.8. Effect of DI (second experiment) on fruit number, yield and size per truss in 'Virosa' tomatoes

Treatment	Truss Numbers								Total/ average per plant
	1	2	3	4	5	6	7	8	
	A) Number of fruit per truss								
Control	6.48[z]	8.55[z]	9.55[z]	9.05[z]	8.28[z]	8.08[z]	7.70[z]	6.28[z]	62.95
DI	5.95	8.08	8.97	8.63	8.10	7.23	3.60	5.13	56.68
Significance	ns	ns	ns	ns	ns	ns	*	ns	*
	B) Total fruit mass per truss (g)								
Control	341.62	406.78	453.75	413.94	438.86	434.33	460.81	345.45	3.30kg[z]
DI	278.69	320.20	351.48	349.65	326.54	352.29	139.17	168.50	2.29kg
Significance	ns	ns	ns	ns	*	ns	**	**	**
	C) Average fruit size per truss (g)								
Control	52.07	47.25	50.16	47.79	53.96	53.67	60.18	55.21	52.31
DI	46.73	39.76	36.73	38.76	40.32	49.81	36.43	33.28	40.35
Significance	ns	ns	**	*	*	ns	ns	**	**

[ns,*,**]Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively

[z]Means of 40 replicate plants per treatment

4.1.13. Postharvest quality attributes

4.1.13.1. Fruit total dry mass, soluble solids and mineral concentration

Fruit dry mass, TSS and mineral concentration are presented in Table 4.9. The fruit dry mass was higher in DI fruit than control fruit in all three trusses sampled. Similarly, TSS was higher in the DI plants than in control plants. Fruit mineral concentration (Ca, Mg, and K) was the same for both treatments on a dry weight basis.

4.1.13.2. Fruit sugar concentration, titratable acidity and sugar:acid ratio

The results showed that there was no significant difference between the control and DI fruit in concentration of glucose, fructose and sucrose (Table 4.10). The titratable acidity (citric acid) was slightly higher in the control fruit than in DI fruit for all the fruit trusses measured (Table 4.10). The sugar to acid ratio was higher in the control than DI fruit (Table 4.10). The sugar to acid ratio may not be accurate since different samples were used for sugar and acid measurement, although fruit samples were mostly harvested in the same truss.

Table 4.9. Effect of DI (second experiment) on fruit dry mass, TSS and mineral concentration ($mg \cdot g^{-1}$ dry wt) in 'Virosa' tomato fruit

Treatment	Dry Mass (%)			Total Soluble Solids (%)			Concentration		
	Truss Number			Truss Number			Ca	Mg	K
	1	5	8	1	5	8			
Control	5.15[z]	5.49[z]	5.32[z]	3.59[z]	3.75[z]	3.68[z]	0.62[z]	2.80[z]	157.5[z]
DI	6.20	6.88	7.23	3.99	4.45	4.58	0.58	2.39	151.5
Significance	*	*	*	*	*	**	ns	ns	ns

[ns,*,**]Nonsignificant or significant at $P \leq 0.05$ or $P \leq 0.01$, respectively

[z]Means of 16 replicate fruit per treatment

Table 4.10. Effect of DI (second experiment) on fruit sugar and acid (citric) concentration and sugar:acid ratio in 'Virosa' tomato

	Sugar ($mg \cdot kg^{-1}$ fresh weight)			Sugar:acid ratio	Titratable acidity (%)		
	Truss 8				Truss number		
Treatment	**Glucose**	**Fructose**	**Sucrose**		**1**	**5**	**8**
Control	9400[z]	11901[z]	200[z]	50:1[z]	0.72[z]	0.62[z]	0.59[z]
DI	9200	10900	300	35:1	0.56	0.47	0.44
Significance	ns	ns	ns	*	ns	ns	ns

[ns,*] nonsignificant or significant at $P \leq 0.05$

[z]Mean of 16 fruit replicate per treatment

4.1.13.3. Shelf life

Shelf life was measured in terms of weight loss, colour change, and storage life. The cumulative weight loss throughout the measurement was the same for both treatments (Fig. 4.9 A). Colour change was rapid in the first six days after harvest and slowed down thereafter. At two to nine days after harvest (Fig. 4.9 B), the hue angle value for the control fruit was slightly lower than the DI fruit but not significantly. At 20C room temperature, DI and control fruit could be stored after harvest for respectively 24 and 23 days without significant differences between treatments.

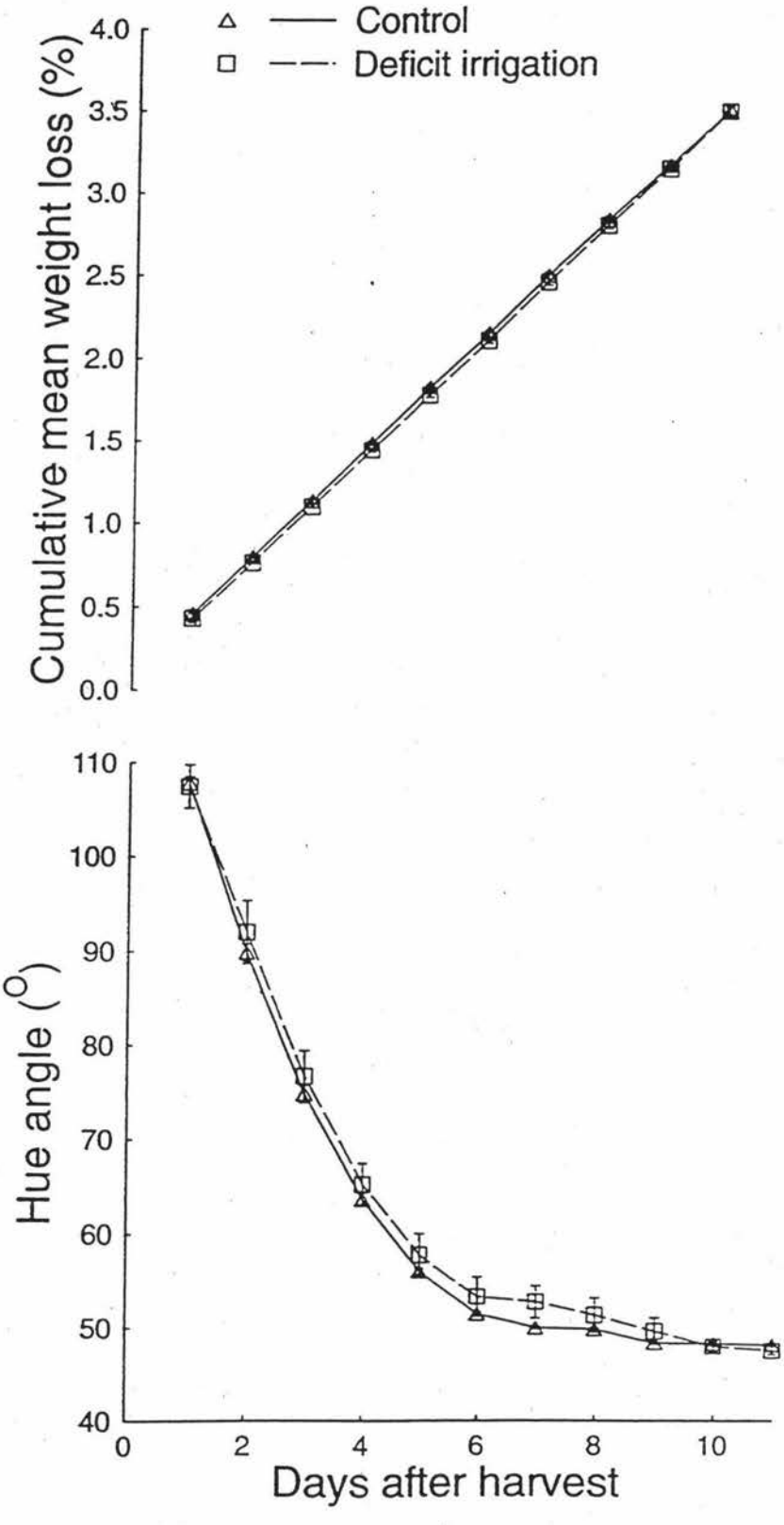

Fig. 4.9. Effect of DI (second experiment) on (A) cumulative weight loss and (B) fruit colour in terms of hue angle in 'Virosa' tomato fruit. The bar on each mean represents twice the standard error of the mean based on 16 replicate plants per treatment.

4.2. Discussion

First experiment

4.2.1. Water relations of the tomato plant

The potting medium of the control plants had a steady Θ throughout the experimental period (Fig. 4.1). This is expected as the growing medium of the control plants was watered daily to replace water lost through evapotranspiration. The DI pots were watered on the basis of the plant water potential. Water content was not measured at regular intervals so that the increase in Θ in the DI pots cannot be seen after each irrigation. The water content difference between the treatments was smallest at the start of measurement (Fig. 4.1) and increased with time. For two weeks following transplanting both treatments received the same amount of water. The water content difference developed when the DI treatment was imposed (64 DAS) and continued throughout the experiment.

The ψ_l of control plants was steadily higher than DI plants throughout the cropping season (Fig. 4.2). The ψ_l of DI plants fluctuated. It increased following every watering and then slowly or abruptly dropped depending on the climatic condition of the glasshouse following irrigation. According to Rudich et al. (1981) the plant water potential decreases as the plant ages, due to decreasing root activity and increasing resistance to water flow in the leaves and stems. After watering at the later stages of the experiment (160 to 178 DAS), the leaf water potential of the DI plants no longer increased to the level of the control plants due to plant age.

Water and salt stresses are known to lower the water potential of the plant (Torrecillas et al., 1995; Alarcon et al., 1994). The decrease in the ψ_l values during water stress is due to an increased in resistance to water flow in the xylem (Rudich

et al., 1981). The ψ_l generally falls in response to a decrease in the water status of the growing medium surrounding the roots although the evaporative demand of the atmosphere may also have an effect (Hsaio, 1990). In my experiment the water content of the growing medium and ψ_l were constantly lower in the DI than control plants throughout the experimental period (Fig. 4.1 & 2). This indicates that water availability in the growing medium was reflected by the water potential of the plant.

4.2.2. Effect of deficit irrigation on tomato growth and development

Whole plant fresh and dry mass were higher in the control plants than in DI plants (Table 4.1). DI affected fresh mass more than dry mass, with respective of 65% and 53% compared to control. Similar results were reported by Rao and Padma (1991).

Truss number for both treatments was similar early in the experiment, but the control plants developed more fruit trusses than DI plants beginning 95 DAS (Fig. 4.3 A). Similarly, more flowers with reflexed petals were present in the control plants (Fig. 4.3 B). There were more flowers in the control plants than DI plants. Water stress combined with high temperature and irradiation caused DI flowers to drop or collapse early while flowers in the control plant could still be counted in the next monitoring. The results reflect the importance of adequate watering at the flowering stage. According to Helyes and Varga (1994), tomatoes are most sensitive to water stress at flowering and fruit set. In young reproductive plants, flowers are the weakest sink compared with the young apical leaves and roots (Ho and Grimbly,

1990). Flowering and fruit set are continuous on indeterminate cultivars as new trusses develop. Therefore, stress during flowering and fruit set could not be avoided.

The yield of DI plants was 39% that of control plants (Table 4.1) due to reductions in both fruit number and size. Fruit number, which included the BER fruit, was reduced more (52% of the control) than fruit size (75% of the control). The fruit number and size reduction in the DI plant could be the cumulative effect of deficit irrigation on the vegetative phase, flowering and fruit set. The DI plants were smaller, had fewer fruit trusses and flowers than the control plants which led to fewer and smaller DI fruit than the controls. The effect of water stress on fruit number could be traced back from flowering as previously discussed (Section 2.3.2.2). Fully grown flowers may shed and fail to set fruit under water deficit as observed in this experiment.

The smaller plant size of the DI treatment may have had an influence on fruit size. The fruit size reduction in the DI plant may be attributed to reduced assimilates at the time of fruit development and maturation (Hsiao,1993). This was coupled with reduced water entering the fruit, since fruit water content is lower in the DI than control fruit (Table 4.1). Restricted watering can reduce tomato fruit size by reducing the quantity of the phloem sap entering the fruit (Ho and Grimbly, 1990). Ho and Grimbly (1990) also found that when the supply of sugars to the fruit is not limiting, the enlargement of a tomato fruit is regulated mainly by temperature and water supply. A similar result was found by Alarcon et al. (1994) who found that yield were reduced significantly as a result of fewer and smaller fruits. Adams and Ho (1989) indicated that fruit size reduction was due to reduced water content rather

than in dry matter accumulation. According to Mizrahi et al. (1988), growth and development of the tomato fruit follow a sigmoid pattern in which the growth rate slows down towards fruit ripening. In this experiment water stress was applied throughout the fruit growth thus there was a great reduction in fruit size.

The level of DI based on ψ_l of -1.0 to -1.2 MPa, required that DI plants be watered on only 29 days compared to 120 days for control plants throughout the course of the experiment. For both treatments, plants were watered four times per day, during their respective watering day, and ψ_l in DI plants increased to levels of control plants the day following re-watering. Reduction in fruit yield observed with the DI treatment in this study would be unacceptable in production systems where water is not a limiting factor in production.

4.2.3. Effect of deficit irrigation on fruit quality

Blossom-end rot occurred solely in DI fruit from 108 to 145 DAS and affected only 0.9% of the total number of fruit harvested from this treatment. Calcium is transported through the transpiration stream (Tibbitts, 1979) and is implicated in the BER incidence in the tomato fruit (Barker and Ready, 1994). There was no relationship between total Ca concentration in fruit and BER incidence. The incidence of BER might be due to the uneven distribution of Ca within DI fruit. However, this was not investigated. Adams and Ho (1993) found the lowest percentage of Ca in the distal placenta and locular tissues where BER first develops. According to Marschner (1974), the restricted mobility of Ca and differences in the proportion of soluble and insoluble forms within the plant makes total Ca concentration an unreliable predictor of physiological or nutritional status.

Concentrations of Ca, Mg, and K were the same on a dry weight basis for both irrigation treatments (Table 4.2). On a fresh weight basis these concentrations were higher ($P \leq 0.05$ for Ca and $P \leq 0.01$ for Mg and for K) in DI fruit than in control fruit. Barker and Ready (1994) also found no relationship between fruit concentrations of Ca, Mg, and K and BER incidence in tomato.

Concentrations of sucrose, fructose, and glucose were higher in DI fruit than in control fruit (Table 4.2). Mitchell et al. (1991a) observed that starch concentration early in fruit development was increased by water deficit and salinity. Water deficit causes the conversion of starch to sugars and, during water stress, carbohydrates metabolism is disturbed often leading to accumulation of sugars (Kramer, 1983). Increases in reducing sugars could also be in response to reduction in the fruit water content (Adams and Ho, 1989).

According to Ho and Grimbly (1990), water stress reduces the quantity of phloem sap entering the fruit but it also increases the phloem sap concentration. Although less water accumulates in the fruit, the dry matter still accumulates to the same level as normal fruit. The result is a high percentage of dry matter in the fruit or a higher sugar concentration in the fruit juice.

Deficit-irrigated fruit from both measurements produced higher quantities of CO_2 and ethylene compared to control fruit (Fig. 4.4). The difference was greater for the second measurement, when plants had been exposed to a longer DI. Water stress is thought to increase respiration due to sugar accumulation (Kramer, 1983). This could have occurred in this experiment since the DI fruit had a higher concentration of soluble sugars than the control fruit (Table 4.2). An increase in

ethylene production from water-stressed tomato fruit was also observed by Basiouny et al. (1994), but the mechanisms were not stated.

The fruit gas exchange data (Fig. 4.4) reflect the conflicting reports in the literature regarding the position of postharvest respiration and ethylene production peaks. Some authors have indicated that the respiratory rise in tomato fruit is in response to increased ethylene synthesis, which starts a chain of events leading to ripening (Hobson and Grierson, 1993). However, Saltveit (1993) found that in detached tomato fruit the respiration peak preceded the ethylene production peak. My results also indicate this and it can be concluded that respiration in tomato may not be associated with the climacteric ripening. The data in this experiment support this view (Fig. 4.4, B & D). The coincidence in ethylene production and respiration peaks in Fig. 4.4 (A & C) does not necessarily indicate a cause-effect relationship.

Fruit colour development, as reflected in changes of hue angle, followed a similar trend in both measurements for both treatments (Fig. 4.5). Colour change was rapid in the first four to five days after harvest and nearly stopped thereafter. Deficit-irrigated fruit had lower hue angle values than control fruit for the first measurement (Fig. 4.5 A), which means they were redder than control fruit. Brecht et al. (1994) reported that water stress improved fruit colour in two experiments using drip irrigation and polyethylene mulch. Similarly, Rudich et al. (1977) found that deficit-irrigated tomato fruit had higher red colour intensity than well-irrigated fruit. During fruit ripening, the colour changes from green to red as chlorophyll is degraded and lycopene accumulates (Hobson and Grierson, 1993). Ethylene increases carotenoid concentration of the tomato fruit (Paz et al., 1982), the peak lycopene formation coinciding with the peak ethylene production (Ishida et al., 1993).

It is possible therefore that the redder colour of the DI fruit (Fig. 4.5) was a result of the higher ethylene production of these fruit (Fig. 4.4, A & B). Even if a cause-effect relationship does not exist between ethylene production and carotenoid synthesis, ethylene promotes ripening which brings about lycopene accumulation.

This study showed that deficit-irrigated tomatoes could produce a crop when container-grown and at a 0.7 MPa reduction in ψ_l compared to well-watered plants. In areas where water is either limited or expensive, the lower cost of fertigation may compensate for the yield reduction. Improvement in some fruit quality attributes could also be realised under reduced watering. Obtaining a higher yield than reported here for deficit-irrigated greenhouse-grown tomato plants may be possible by applying a milder water stress than used in this study. This was done for the second experiment.

Second Experiment

4.2.4. The effect of deficit irrigation on the water relations of tomato

Since the water content of the potting medium is one of the determinants of plant water status (Rudich and Luchinsky, 1986) it follows that control plants had higher ψ_l than DI plants (Fig. 4.7). When the growing medium was given the same amount of water (84-100 DAS), the ψ_l was the same for both treatments, although the water content was still lower in the DI pots compared to the control pots (Fig. 4.6). This could mean that the water content in the DI pots was sufficient for the plant, the DI root system is more efficient in water absorption, and/or the control had

a higher transpiration rate than the DI plant. The trend of decreasing ψ_l with time (Fig. 4.7) is attributed to plant age as discussed in the first experiment (Section 4.2.1).

Predawn ψ_l could be better indicator than midday ψ_l for expressing water status. The midday water potential is affected more by factors other than soil water availability (Rudich and Luchinsky, 1986), as environmental factors continuously change.

The fruit water potential and osmotic potential were not different between treatments. Unlike ψ_l which was significantly lower in DI leaves. This may mean that fruits are less sensitive to water stress than the leaves. This may be because the fruit sample was taken from the first truss which had been previously exposed to water stress. According to Cutler and Rains (1977), exposure to water stress at early development moderates the impact of a later stress. The developing fruit become strong sinks for water as they grow (Ho and Grimbly, 1990). Thus water stress may have less effect on fruit than shoots. Araki (1993) found that when soil water potential is -0.002 MPa, the water potential is highest in the stem and lowest in the fruit but when it declines to -0.062 MPa, the water potential was highest in the fruit and lowest in the leaves.

4.2.5. The effect of deficit irrigation on tomato growth and development

The leaf area and the fresh and dry mass of the stems and roots were not reduced in DI plants when compared to the control. Leaf fresh mass was lower ($P \leq 0.05$) in DI than control plants but leaf dry mass was not different (Table 4.6). It seems there was little effect of deficit irrigation on the vegetative growth based on

the above parameters. This may have been because the plants had been stopped while approximately 2 m high. Thus the DI plants were able to attain a maximum permitted growth with time. The final plant mass could have been different if the plant had been allowed to grow indefinitely. My data show that root growth was not affected by water stress (Table 4.6).

The lateral shoots, removed at weekly intervals, give a better indication of the effect of water stress on the vegetative growth of the plant as all plants were topped at the same height. The lateral shoots pruned from the controls were heavier ($P \leq 0.01$) than DI plants (Table 4.6). Saunders (1991) found that water stress reduced lateral shoot number and percent dry weight by more than 50 % relative to the control. Klapwijk (1974) found that the effect of water stress was more pronounced on growth expressed on a fresh weight basis. This was also the case in my results.

Leaves from healthy plants generally contain 0.4 to 1.8% Mg while below 0.3% Mg is considered deficient (Winsor and Adams, 1987). This is consistent with this experiment (Table 4.7). According to Christou et al. (1994), fruit minerals like Mg were reduced with increasing irrigation. Magnesium deficiency usually occurs under a heavy fruiting load (Winsor and Adams, 1987) which might have been the case in this experiment.

The sensitivity of flower development can be seen in Figure 4.8, where flowering in the DI plants started to decline (starting 101 DAS) when water stress was reimposed. The increased flower number in the control plants after 120 DAS was due to the extended flowering of the lower trusses whose fruits were already developed. Generally water stress reduced fruit number, mass, and size (Table 4.8). The major cause of yield reduction was fewer and smaller fruit as was found by

Alarcon et al. (1994). Water stress and salinity are known to reduce fruit number (Rao and Bhatt, 1992; Alarcon et al., 1994). According to Peet and Willits (1995), fruit number increased by 9.5% when extra water was added. Results from this study revealed that water stress reduced fruit number in truss 7 only ($P \leq 0$ .05). Fruit number reduction maybe traced back to the effect of water stress on the flowering stage. The resumption of water stress coincided with the flowering of the upper trusses.

The effect of DI was more pronounced on fruit mass than on fruit number. The DI fruit mass in three fruit trusses was lower than control fruit. The reduction in fruit mass in truss numbers 5 and 8 was due to smaller fruit size while the reduction in truss number 7 was due to decreased fruit number (Table 4.8).

DI fruit in truss numbers 3, 4, 5, and 8 were smaller than control fruit (Table 4.8 C). At the resumption of water stress treatment (101 DAS) the fruit in the first and second fruit trusses were about 24 g and 13 g respectively. The reduction in fruit size in truss numbers 3, 4, and 5 may have been due to limited assimilates and water supply. There was less reduction in fruit mass in trusses 6 and 7 possibly because the lower trusses (1 and 2) were already harvested thus reducing assimilate competition among fruit sinks. According to Slack and Calvert (1977) removal of fruit truss can increase fruit size of other fruit trusses. Fruit size reduction in truss 8 could be due competition with fruits in trusses 6 and 7. In this experiment, the effect of DI was more pronounced on fruit size which was reduced by 23% in DI fruit than on fruit number which was reduced by 10% in DI treatment.

4.2.6. Effect of deficit irrigation on fruit quality

A ripe tomato fruit contains 95% water and 5% dry matter (Mitchell et al., 1991a). The percent dry weight is a measure of the total solids, consisting of water soluble and insoluble solids (Young et al., 1993). In a ripe tomato, soluble solids account for 75% to 85% of the total solids depending on the cultivar (Young et al., 1993). Processing tomato fruit quality is usually measured in terms of the concentration of TSS and this parameter could be applied to fresh market tomato. The final TSS depend on the rate of solute accumulation during the rapid growth period (Ho and Hewitt, 1986), which is affected by season, nutrition and environment (Davies and Hobson, 1981). Water and nutrient availability appear to be main agronomical factors which determine soluble solid concentration (Dumas et al., 1994). Irrigation is known to increase yield but reduce soluble solid concentration (May et al., 1990; Mitchell et al., 1991). The increase in TSS with reduced irrigation could be due to enhanced conversion of starch to sugars which occurs as a result of water stress (Kramer, 1983). It could also be due to the reduction of fruit water accumulation leading to a high percentage of dry matter (Ho and Grimbly, 1990) with a resulting higher concentration of soluble solids.

Sugars constitute between 65% to 70% of the fruit TSS (Hobson and Grierson, 1993). It is therefore expected that fruit with higher TSS should have higher sugars. However, results from this experiment showed that the soluble sugars (glucose, fructose and sucrose) concentration was the same for both treatments in the second experiment.

There is no consensus on effect of DI on the titratable acidity of tomato fruit. Mitchell et al. (1991a) found that DI increased titratable acidity in one experiment

but this was not confirmed in their second experiment. Rudich et al. (1977) also reported an increase in fruit acidity under deficit irrigation. D'Souza et al. (1991) reported an opposite result. Fruit acid content of four out of six tomato cultivars were slightly higher in irrigated than non-irrigated plants. Sudjatmiko (1989) found no effect of moisture stress on fruit acidity. The present results shows that DI had no effect on the titratable acidity of the fruit.

The sugar to acid ratio was higher in the control than DI fruit (Table 4.10). Individually, sugar and acids are not statistically different in both treatment but control had slightly higher percent of sugars and acid than DI fruit. The small difference in both sugars and acid made a significant difference when sugar to acid ratio was considered. Sugar, acids and their interactions determine the sweetness, sourness and overall flavour of fruit (Hobson and Grierson, 1993). High sugars and high acids are required for the best flavour. Similarly high solids:acid ratio are essential in processing tomatoes (Stevens, 1972). Since the sugar:acid ratio was significantly higher in the control than DI fruit, the control fruit may have a better flavour.

Deficit irrigation has no effect on the shelf life of tomato expressed as weight loss, colour change and storage life. Weight loss for both treatments was the same for all measurement times. Colour change was the same throughout the measurement time for both treatments. Similarly, D'Souza et al. (1991) reported no significant difference in colour change in three tomato cultivars grown in irrigated and non-irrigated conditions. Since there was no significant difference in terms of weight loss and colour change, it is not surprising therefore that the shelf life of the fruit was the same for both treatments.

Chapter Five: General discussion

Tomato (cultivar 'Virosa') was subjected to DI to evaluate growth, yield and fruit quality. Fruit quality improvement by DI is well documented in processing tomatoes (eg. Mitchell et al., 1991a). Changes in fruit quality under DI in fresh market tomatoes may be similar although quality requirement of processing is different from the fresh market type. It is therefore possible to apply similar DI technique to fresh market tomatoes to obtained similar results with that of the processing tomatoes. This section compares the result of the two experiments and highlights the important results of this research.

5.1. Water relation, growth and yield

One important determinant of plant water status is the Θ of the growing medium (Jones, 1990). A lower ψ_l in the DI plants than in the controls is likely attributed to the lower Θ in the DI medium than in the controls. The plant physiological processes such as transpiration and photosynthesis may be disturbed due to the decrease in ψ_l in the DI plant. This in turn may lead to plant growth reduction under DI, although photosynthesis and transpiration were not measured. To compare the effect of severe (first experiment) and milder (second experiment) water stress on plant growth and yield, these data are retabulated and presented in Table 5.1. Both experiment may have the same value of ψ_l for DI but ψ_l in the second experiment was the same for DI and control plants from 84 to 100 DAS (Fig. 4.7).

Table 5.1. Comparison of growth and yield of 'Virosa' tomato in the two experiments

	1994			1995		
	Treatment			Treatment		
	Control	DI	% reduction	Control	DI	% reduction
A) Plant mass ($g \cdot plant^{-1}$)						
Fresh	1098.30	583.80	47	1150.00	830.90	28
Dry	114.89	75.18	35	143.11	119.70	12
B) Fruit yield						
Number ($plant^{-1}$)	40.70	21.23	48	62.95	56.68	10
Size (g)	57.06	42.76	25	52.31	40.35	23
Mass ($kg \cdot plant^{-1}$)	2.32	0.90	61	3.30	2.29	31

Values of total vegetative growth were lower in the first than the second experiment. Fruit number was greater in the second experiment compared to the first. However individual fruit size was smaller in the second experiment (Table 5.1). This may be attributable to the degree and timing of DI application. The DI plants in the first experiment were subjected to DI from 64 DAS up to the last harvest date while the DI plants in the second experiment were given similar treatment but were not water stressed at 84 to 100 DAS which was the height of flowering stage. On the other hand, the bigger fruit size in the first experiment compared to the second maybe due to the difference in total number of fruit per plant. The average fruit number per plant was lesser in the first experiment than the second. The average number for the first and second experiment were 31 and 60 fruit per plant respectively. There was a large difference in fruit number because unripened fruit in the last harvest of the first experiment was not included while it was included in the second experiment. Yield reduction in the first experiment was predominantly due to reduced fruit number. In the second experiment, it was due to the decrease in individual fruit size (Table 5.1). The fruit size reduction in the control plants in the second experiment could be attributed to the occurrence of magnesium deficiency at the height of fruiting. Yield loss due to moderate and severe Mg deficiency ranges from 6 to 29% (Winsor and Adams, 1987).

5.2. Fruit quality

The occurrence of fruit BER in the first experiment could have been due to the level of stress developed in plants. Low water uptake leads to poor Ca absorption by the plant (Ho, 1988). This disorder did not occur in the second

experiment which was given a milder DI. Calcium deficiency is generally implicated in the BER incidence (Barker and Ready, 1994). However, mineral concentration (Ca, Mg, and K) was the same in both treatments and experiments. Adams and Ho (1993) found that distal placenta and locular tissue to be lowest in calcium percentage where BER first develops. Thus in the second experiment, the blossom-end of the fruit was analysed to check the problem of Ca distribution within the fruit. The result still showed the same concentration for both treatments. The problem could therefore be the proportion of soluble and insoluble forms as was reported by Marschner (1974). Although the Ca in the fruit may have been sufficient, it may not have been absorbed at the right time. Adams and Ho (1993) reported the importance of the timing of Ca absorption at a period of high Ca demand which is during the rapid fruit growth.

Fruit dry mass was higher in DI than in control treatment in both experiments. Total soluble solids account for 75% to 85% (Young et al., 1993). It was therefore expected that DI fruit had a higher TSS than control fruit in the second experiment. Similarly, soluble sugars was expected to be higher in the DI than control fruit as was observed in the first experiment. This was expected because sugars constitute 65% to 70% of the fruit TSS (Hobson and Grierson, 1993). An increase in the soluble sugars was not observed in the second experiment and instead slightly higher soluble sugars was attained in the control than the DI fruit. No explanation can be offered, and D'Souza et al. (1991) reported a similar result. There was no effect of DI on TA but sugar to acid ratio was higher in the control than DI fruit in the second experiment. The significant differences may have been due to the slightly higher sugar and acid concentrations in the control than DI fruit. This result was in

agreement with the findings of D'Souza et al. (1991), who reported a higher TSS and acid concentration in irrigated than non-irrigated tomato.

The DI fruit produced higher quantities of carbon dioxide and ethylene than control fruit in the two measurements in the first experiment. However the position of respiration and ethylene production peak was not consistent. In the first measurement, both gas production peaks coincided, while respiration peak preceded that of ethylene peak in the second measurement. Saltveit (1993) reported that respiration in tomato may not be associated with climacteric ripening.

The effect of DI on tomato colour was not clear. Brecht et al. (1994) reported that DI improved tomato colour as was found in the first experiment. D'Souza (1991) found that DI effect on colour depended on the cultivar. Sudjatmiko (1989) found no effect on colour which was in agreement with my second experiment. Similarly, no effect of DI was observed in terms of tomato shelf life.

5.3. Conclusion

Deficit irrigation reduces tomato growth and yield. Yield reduction particularly in the first experiment would be unacceptable in horticultural systems where water is not limited. The degree of reduction depends on the level of stress and the timing of DI application. Yield reduction in this study was mainly due to decrease in fruit number and size. These reductions could be minimised if water stress was avoided at flowering stage and fruit development. However, flowering and fruit set are continuous on indeterminate cultivars as new trusses develop. It is therefore considered as a serious drawback to the application of DI in glasshouse tomatoes. Despite yield reduction, water stress enhanced fruit desirability in terms

of higher concentration of TSS, soluble sugars (only in one experiment) and higher colour intensity and dry mass. However, DI management needs to be further investigated before it can be recommended as a commercial practice in production of fresh market tomatoes.

5.4. Recommendation

It is recommended that the degree and timing of DI be further investigated. The degree of DI could easily be adjusted but timing of DI application is difficult to modify for an indeterminate tomato cultivar due to flowering characteristics. Deficit irrigation may be detrimental to flowering and fruit growth but it is difficult to avoid these stages since flowering and fruiting are continuous in an indeterminate cultivar. A possible way of solving this problem is to lessen the number of fruit trusses that are maintained. It is easier to avoid DI at critical stages with few fruit trusses rather than with many trusses. Another possibility is the removal of in-between trusses. This will minimise water and assimilate competition among the developing fruit. The first truss will have set fruit before the next fruit set begins on the next truss.

Milder DI may also be useful as was done in the second experiment. The amount of water applied in the DI treatment of the second experiment was 32% of the control treatment. Increasing water volume may lessen the adverse effect of DI on plant. However, in administering milder DI, water potential as a basis for irrigation should be augmented with other methods such as volumetric water content of the growing medium.

LITERATURE CITED

Abbott, J.D., M.M. Peet, D.H. Willits, and R.E. Gough. 1985. Water management of greenhouse tomatoes. HortScience. 20(4):688-690.

Abdel-Rahman, M. 1977. Patterns of hormones, respiration and ripening enzymes during development, maturation and ripening of cherry tomato fruit. Physiol. Plant. 39:115-118.

Acevedo, H.E. and V.C. Massardo. 1984. Effect of water deficit at two stages of development of tomato (*Lycopersicon esculentum* Mill.). Phyton. Argentina. 44(2):151-166.

Adams, P. 1990. Effects of watering on the yield, quality and composition of tomatoes grown in bags of peat. J. Hort. Sci. 65:667-674.

Adams, P. and A.M. El-Gizawy. 1986. Effect of salinity and watering level on the calcium content of tomato fruit. Acta. Hort. 190:253-259.

Adams, P. and L.C. Ho. 1989. Effects of constant and fluctuating salinity on the yield, quality and calcium status of tomatoes. J. Hort. Sci. 64(6):725-732.

Adams, P. and L.C. Ho. 1993. Effects of environment on the uptake and distribution of calcium in tomato and on the incidence of blossom-end rot. Plant and Soil. 154(1):127-132.

Alarcon, J.J., M.C. Bolarin, M.J. Sanchez-Blanco, and A.Torrecillas. 1994. Growth, yield and water relations of normal fruited and cherry tomato cultivars irrigated with saline water. J. Hort. Sci. 69(2)283-288.

Araki, Y. 1993. Relationship between plant water status and water movement in tomato. J. Jpn. Soc. Hort. Sci. 62(1):121-128.

Atherton, J.G. and G.P. Harris. 1986. Flowering, pp167-200 In: J.G. Atherton and J. Rudich (eds.). The tomato crop. Chapman and Hall, London.

Atherton, J.G. and S. Othman. 1983. Effects of irradiance and water stress on flower abortion in the glasshouse tomato. Acta Hort. 134:133-137.

Barker, A.V. and K.M. Ready. 1994. Ethylene evolution by tomatoes stressed by ammonium nutrition. J. Amer. Soc. Hort. Sci. 119(4):706-710.

Basiouny, F.M., K. Basiouny, and M. Maloney. 1994. Influence of water stress on the abscisic acid and ethylene production in tomato under different PAR levels. J. Hort. Sci. 69 (3):535-541.

Behboudian, M.H., G.S. Lawes, and K. M. Griffith. 1994. The influence of water deficit on water relations, photosynthesis and growth in Asian pear (*Pyrus serotina* Rehd.). Scientia Hortic. 60:89-99.

Brecht, J.K., S.J. Locascio, and K.A. Bergsma. 1994. Water quantity affects quality of drip-irrigated tomato fruit. HortScience 29(5):154-160.

Brown, D.A. and J.C. Scott. 1984. Dependence of crop growth and yield in root development and activity, pp101-136 In: Barbers, S.A. and D.R. Bouldin (eds.). Roots, nutrients and water influx and plant growth. ASA Publication, Madison, USA.

Chalmers, D.J. 1989. A physiological examination of regulated deficit irrigation. N.Z. J. Agr. Sci. 23:44-48.

Chalmers, D.J. and K.S. Rowan. 1971. The climacteric in ripening tomato fruit. Plant physiol. 48:235-240.

Chiaranda, F.Q., P. Tedeschi, and G. Zerbi. 1982. The effect of a short period of water shortage on flower development and berry growth in tomato. Rivista De Agronomia. 16(1):47-50.

Christou, M., S. Leoni, P. Cornillon, A. Gainza, Y. Dumas, A. Rodriguez, A. Dimirkou, A. Rincon-Del-Rodriguez, and B.J. Bieche. 1994. Influence of water and nitrogen availability on elemental composition of processing tomato in E.U. countries. Acta Hort. 376:279-284.

Cooper, A. 1979. The ABC of NFT: nutrient film technique. Grower Books, London.

Cutler, J.M. and D.W. Rains. 1977. Effects of irrigation history on responses of cotton to subsequent water stress. Crop Sci. 17:329-335.

Dalal, K.B., D.K. Salunkhe, A.A. Boe, and L.E. Olson. 1965. Certain physiological and biochemical changes in the developing tomato fruit (*Lycopersicon esculentum.* Mill). J. Food Sci. 30:504-508.

Davies, J.N. and G.E. Hobson. 1981. The constituents of tomato fruit: the influence of environment, nutrition, and genotype. CRC Critical reviews in food science and nutrition. 15:205-280.

De Koning, A. and R.G. Hurd. 1983. A comparison of winter-sown tomato plants grown with restricted and unlimited water supply. J. Hort. Sci. 58(4):575-581.

Dostal, H.C. 1970. The biochemistry and physiology of ripening. HortScience 5:8-9.

D'Souza, M.C., M.K. Head, and M. Ingle. 1991. Quality of processed field-grown tomatoes as influenced by growth of plants under less than optimum soil moisture conditions. J. Sustainable Agri. 2(1):41-48.

Dumas, Y., C. Leoni, C.A.M. Portas, and B. Bieche. 1994. Influence of water and nitrogen availability on yield and quality of processing tomato in the European union countries. Acta Hort. 376:185-192.

Dumbroff, E.B. and A.W. Cooper. 1974. Effects of salt stress applied in balanced nutrient solutions at several stages during growth of tomato. Bot. Gaz. 135(3):219-224.

Ebel, R.C., E.L. Proebsting, and M.E. Patterson. 1993. Regulated deficit irrigation may alter apple maturity, quality, and storage life. HortScience 28(2):141-143.

Fraser, P.D., M.R. Truesdale, C.R. Bird, W. Schuch, and P.M. Bramley. 1994. Carotenoid biosynthesis during tomato fruit development. Plant Physiol. 105:405-413.

Geisenberg, C. and K.Stewart. 1986. Field crop management, pp511-557. In:J.G. Atherton and J. Rudich (eds.). The tomato crop. Chapman and Hall, London.

Giuliano, G., G. E. Bartley, and P.A. Scolnik. 1993. Regulation of carotenoid biosynthesis during tomato development. Plant Physiol. 5:379-387.

Goor, B.J.-Van. 1974. Influence of restricted water supply on blossom-end rot and ionic composition of tomatoes grown in nutrient solution. Commun. in soil Sci. and Plant Anal. 5(1):13-24.

Gough, C. and G.E. Hobson. 1990. A comparison of the productivity, quality, shelf-life characteristics and consumer reaction to the crop from cherry tomato plants grown at different levels of salinity. J. Hort. Sci. 65(4):431-439.

Gould, W.A. 1974. Tomato production, processing and quality evaluation. AVI. Publishing Co. Westport, Conn.

Gray, J.E., S. Picton, R. Fray, A.J. Hamilton, H. Smith, S. Barton, and D. Grierson. 1993. Altered gene expression, leaf senescence, and fruit ripening by inhibiting ethylene synthesis with EFE-antisense genes, pp82-89. In: J.C. Pech, A. Latche, and C. Balague (eds.). Cellular and molecular aspects of the plant hormone ethylene. Proceedings of the international symposium on cellular and molecular aspects of biosynthesis and action of the plant hormone Ethylene. 1992. Agen, France.

Grierson, D. and A.A. Kader. 1986. Fruit ripening and quality, pp241-280 In: J.G. Atherton and J.Rudich (eds.). The tomato crop. Chapman and Hall, London.

Gross, J. and F. Lenz. 1979. The effect of an induced water stress on pigment changes in broccoli (*Brassica oleracea* Var. Italica). Gartenbauwissenschaft. 44(4):159-161.

Hegde, D.M. and K. Srinivas. 1990. Growth, nutrient accumulation and quality of tomato fruits in relation to irrigation. South Indian Hort. 38(2):90-94.

Helyes, L. and G. Y. Varga. 1994. Irrigation demand of tomato according to the results of three decades. Acta Hort. 376:323-328.

Himelrick, D.G. and C.E. Walker. 1982. Seasonal trends of calcium, magnesium and potassium fractions in apple leaf and fruit tissues. J. Amer. Soc. Hort. Sci. 107(6):1078-1080.

Ho, L.C. 1988. The physiological basis for improving dry matter content and calcium status in tomato fruit. Appl. Ag. Res. 3(5):275-281.

Ho, L.C. 1989. Environmental effects on the diurnal accumulation of ^{45}Ca by young fruit and leaves of tomato plants. Ann. Bot. 63:281-288.

Ho, L.C. and P. Adam. 1989. Calcium deficiency a matter of inadequate transport to rapidly growing organs. Plants Today. 2:202-207.

Ho, L.C., R.I. Grange, and A.J. Picken. 1987. An analysis of accumulation of water and dry matter in tomato fruit. Plant Cell and Environ. 10:157-162.

Ho, L. and P. Grimbly. 1990. The physiological basis for tomato quality. Grower 113(8):33-36.

Ho, L.C. and J.D. Hewitt. 1986. Fruit development, pp201-239. In: J.G. Atherton and J. Rudich (eds.). The tomato crop. Chapman and Hall, London.

Hobson, G. and D. Grierson. 1993. Tomato, pp405-443. In: G. Seymour and G. Tucker (eds.). Biochemistry of fruit ripening. Chapman and Hall, London.

Hoogenboom, G., M.G. Huck, and C.M. Peterson. 1987. Root growth of soy beans as affected by drought stress. Agron. J. 79:607-614.

Hsiao, T.C. 1973. Plant responses to water stress. Ann. Rev. Plant Physiol. 24:519-570.

Hsiao, T.C. 1990. Plant-atmosphere interactions, evapotranspiration, and irrigation scheduling. Acta Hort. 278:55-66.

Hsiao, T.C. 1993. Growth and productivity of crops in relation to water status. Acta Hort. 335:137-148.

Huberman, M., E. Pressman, and M.J. Jaffe. 1993. Pith autolysis in plants. IV. The activity of polygalacturonase and cellulase during drought stress induced pith autolysis. Plant and cell physiol. 34(6):795-801.

Huck, M.G., K. Ishihara, C.M. Peterson, and T. Ushijima. 1983. Soybean adaptation to water stress at selected stages of growth. Plant Physiol. 73:422-427.

Huck, M.G., C.M. Peterson, G. Hoogenboom, and C.D. Busch. 1986. Distribution of dry matter between shoots and roots of irrigated and non irrigated determinate soy beans. Agron. J. 78:801-813.

Ishida, B.K, E.A. Baldwin, R.G. Buttery, S.H. Chui, and L.C. Ling. 1993. Flavour volatiles, sugars and color development in ripening in vitro-cultured tomato fruit and calyx. Physiol. Plant. 89:861-867.

Jones, H.M. 1990. Physiological aspects of the control of water status in horticultural crops. HortScience 25(1):19-26.

Katerji, M., B. Itier, I. Ferreria, and L.S. Pereira. 1987. Water stress indicator for tomato crop, pp 155-161. In: (Anonymous editors) Measurement of soil and plant water status, Intl. conf., Utah State Univ. 6-10 July 1987.

Kilili, A.W. 1996. Fruit quality and composition, growth, water relations and postharvest performance of 'Braeburn' apples (*Malus domistica* Borkh.) under reduced irrigation. Ms thesis. Massey Univ., Palmerston North, New Zealand.

Klapwijk, D. 1974. Effect of drought and increased salt concentration on the growth and development of young tomato plants. Landbouwkundig-Tijdschrift. 86(4):101-104.

Klapwijk, D. and P.J.A.L. De Lint. 1974. Fresh weight and flowering of tomato plants as influenced by container type and watering conditions. Acta. Hort. 39:237-247.

Kozlowski, T.T., P.J. Kramer, and S.J. Pallady. 1991. The physiological ecology of woody plant. Academic press, Inc.

Kramer, P.J. 1983. Water relations of plants. Academic Press, Inc.

Lapushner, D., R. Frankel, and Y. Fuchs. 1986. Tomato cultivar response to water and salt stress. Acta Hort. 190:247-252

Locascio, S.J., J.M. Myers, S.R. Kostewicz. 1981. The quantity and rate of water application for drip irrigated tomatoes. Florida State Hort. Soc. 94:163-166.

Locascio, S.J. and A.G. Smajstrla. 1989. Drip irrigated tomato as affected by water quantity and N and K application timing. Florida State Hort. Soc. 102:307-309.

Lu, C.G., H.L. Xu, R.C. Yang, and W.G. Yu. 1994. Storage linked physiological characters of tomato carrying fruit repining mutant genes and their implications in breeding. Jiangsu J. Agri. Sci. 10(3):5-10.

Mahakun, N., P.W. Leeper, and E.E. Burns. 1979. Acidic constituents of various tomato fruit types. J. Food Sci. 44:1241-1244.

Marschner, H. 1974. Calcium nutrition of higher plants. Neth. J. Agr. Sci. 22:275-282.

Maximos, S., M. Abo-Ravash, Z. Behairy, and R. Bashear. 1991. Studies on the effect of irrigation and some growth retardants on fig transplants. I effect on vegetative growth. Annu. Agr. Sci. Cairo 36(1):171-181.

May, D.M., T. Walcott, D. Peters, and D. Grimes. 1990. Moisture stress as it affects yield, soluble solids and viscosity of tomatoes. Acta Hort. 277:123-128.

McCutchan, H. and K.A. Shackel. 1992. Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L.cv. French). J. Amer. Soc. Hort. Sci. 117:607-611.

McGuire, R.G. 1992. Reporting of objective color measurements. HortScience 27(12):1254-1255.

Mengel, K. and E.A.Kirkby. 1987. Principles of plant nutrition. International Potash Institute, Berr. Switzerland.

Mitchell, J.P., C. Shennan, S.R. Grattan, and D.M. May. 1991a. Tomato fruit, yields and quality under water deficit and salinity. J. Amer. Soc. Hort. Sci. 116(2):215-221.

Mitchell, J.P., C. Channam, and S.R. Grattan. 1991b. Developmental changes in tomato fruit composition in response to water deficit and salinity. Physiol. Plant. 83:177-185.

Mizrahi, Y. 1982. Effect of salinity on tomato fruit ripening. Plant Physiol. 69:966-970.

Mizrahi, Y., E. Taleisnik, and V. Kagan-Zur. 1988. A saline irrigation regime for improving tomato fruit quality without reducing yield. J. Amer. Soc. Hort. Sci. 113(2):202-205.

Murray, A.J., G.E. Hobson, W. Schuch, and C.R. Bird. 1993. Expression of efe antisense RNA in tomato causes retardation of leaf senescence and most fruit ripening characteristic, pp327. In: J.C. Pech, A. Latche, and C. Balague (eds.). Cellular and molecular aspects of the plant hormone ethylene. Proceedings of the international symposium on cellular and molecular aspects of biosynthesis and action of the plant hormone . Ethylene. 1992. Agen, France.

Paz, O., H.W. Janes, B.A. Prevost, and C. Frenkel. 1982. Enhancement of fruit sensory quality by post-harvest applications of acetaldehyde and ethanol. J. Food Sci. 47(1):270-273.

Peet, M.M. and D.H. Willits. 1995. Role of excess water in tomato fruit cracking. HortScience 30(1):65-68.

Perniola, M., A.R. Rivelli, and V.Candido. 1994. Yield response to water and stress indexes on tomato. Acta Hort. 376:215-225.

Picken, A.J.F., K. Stewart, and D. Klapwijk. 1986. Germination and vegetative development, pp111-166. In:J.P. Atherton and J. Rudich (eds.). The tomato crop. Chapman and Hall, London.

Poincelot, R.P. 1990. Agriculture in transition. J. Sustainable Agri. 1:9-40.

Rao, N.K.S. and R.M. Bhatt. 1992. Responses of tomato to moisture stress: Plant water balance and yield. Plant physiol. and Biochem., New Delhi. 19(1):36-41.

Rao, D.V.R. and S.S.V. Padma. 1991. Effect of induced moisture stress at different phenological stages on growth and yield of tomato cultivars. South Indian Hort. 39(2):81-87.

Rudich, J. and U. Luchinsky. 1986. Water economy, pp335-365 In: J.G. Atherton and J. Rudich (eds.). The tomato crop. Chapman and Hall, London.

Rudich, J., D. Kalmar, C. Geizenberg, and S. Harrel. 1977. Low water tensions in defined growth stages of processing tomato plants and their effects on yield and quality. J. Hort. Sci. 52:391-399.

Rudich, J., E. Rendon-Poblete, M.A. Stevens, and A.I. Ambri. 1981. Use of leaf water potential to determine water stress in field grown tomato plants. J. Amer. Soc. Hort. Sci. 106(6):732-736.

Saltveit, M.E. 1993. Internal carbon dioxide and ethylene levels in ripening tomato fruit attached to or detached from the plant. Physiol. Plant. 89:204-210.

Salunkhe, D.K. and B.B. Desai. 1984. Postharvest biotechnology of vegetables. Vol.1. CRC. Press. Boca Raton, Florida.

Saunders, A.B. 1991. The effect of mild water stress on the vegetative growth in tomato (*Lycopersicon esculentum* Mill.) and *Pyrus betulaefolia* Bunge. PhD Thesis. Massey Univ., Palmerston North, New Zealand.

Scott Russel, R. 1982. Plant root system: their functions and interaction with the soil. McGraw-Hill. Maidenhead, Beaks.

Sharaf, A.R., and G.E. Hobson. 1986. Effect of salinity on the yield and quality of normal and non-ripening mutant tomatoes. Acta Hort. 190:175-181.

Slack, G. and A. Calvert. 1977. The effect of truss removal on the yield of early sown tomatoes. J. Hort. Sci. 52:309-315.

Stevens, M.A. 1972. Citrate and malate concentrations in tomato fruits: genetic control and maturational effects. J. Amer. Soc. Hort. Sci. 97(5):655-658.

Stevens, M.A. and J. Rudich. 1978. Genetic potential for overcoming physiological limitation on adaptability, yield and quality in the tomato. HortScience 13:673-678.

Sudjatmiko, S. 1989. Study of factors affecting yield and quality of processing tomatoes. Diploma Diss. Massey Univ., Palmerston North, New Zealand.

Syvertsen, J.P. and J.H. Graham. 1985. Hydraulic conductivity of roots, mineral nutrition and leaf gas exchange of citrus rootstocks. J. Amer. Soc. Hort. Sci. 110:865-869.

Thakur, P.S. 1990. Different physiological responses of tomato (*Lycopersicum esculentum* Mill.) cultivars to drought. Acta Physiol. Planta. 12(2):175-182. (CD Abstr.)

Thompson, A.E., M.L. Tomes, E.V. Wann, J.P. McCollum, and A.K. Stoner. 1965. Characterization of crimson tomato fruit colour. Proc. Amer. Soc. Hort. Sci. 86:610-616.

Tibbitts, T.W. 1979. Humidity and plants. BioScience 29(6):358-363.

Torrecillas, A., C. Guillaume, J.J. Alarcon, and Ma. C.R. Sanchez. 1995. Water relations of two tomato species under water stress and recovery. Plant Sci. 105:169-176.

Tüzel, Y., M.A. Ul, and I.H. Tüzel. 1994. Effects of different irrigation intervals and rates on spring season glasshouse tomato production. II. Fruit quality. Acta Hort. 366:389-396.

Vanadia, S., V. Dellacecca, and L. Mancini. 1982. The influence of irrigation regime on the yield of tomatoes in an unheated glasshouse. Culture Protette. 11(8/9):27-32.

Van Schilfgaarde, J. 1994. Irrigation - a blessing or a curse. Agr. Water Mgmt. 25:203-219.

Voss, D.H. 1992. Relating colorimeter measurement of plant color to the *Royal Horticultural Society Colour Chart*. HortScience 27(12):1256-1260.

Ward, G.M. 1973. Causes of blossom-end rot of tomatoes based on tissue analysis. Can. J. Plant Sci. 53:169-174.

Wills, R.B.H., T.H. Lee, D. Graham, W.B. McGlasson, and E.G. Hall. 1981. Postharvest - An introduction to the physiology and handling of fruit and vegetables. Granada.

Winsor, G. W. and P. Adams. 1987. Tomato, pp52-71. In: J.B.D. Robinson (ed.). Diagnosis of mineral disorders in plants. Vol.3. Glasshouse Crops. HMSO, London.

Wolf, S. and J. Rudich. 1988. The growth rates of fruit on different part of the tomato plant and the effect of water stress on dry weight accumulation. Scientia Hortic. 34:1-11.

Young, T.E., J.A. Juvik, and J.G. Sullivan. 1993. Accumulation of the components of total solids in ripening fruits of tomato. J. Amer. Soc. Hort. Sci. 118(2):286-292.