Nutrition and Irrigation Studies with Processing Tomato (*Lycopersicon esculentum* Mill.)

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Abstract:

Improved fertilizer and irrigation management has become increasingly important for tomatoes (*Lycopersicon esculentum* Mill.) grown for processing. To reduce potential nutrient loss to the environment due to excessive supply, fertilizer recommendations should reflect plant demand determined in an optimal root environment. An aeroponics experiment examined the effect of low and high nutrient supply during vegetative growth, fruit development and fruit ripening. The use of aeroponics in a glasshouse environment allowed control of fertility directly at the root surface. A further experiment applying aeroponics results was established in the field using drip-fertigation. Both studies were conducted at Massey University, Palmerston North. Across experiments, fruit yield was largely determined by vegetative growth in the 6-8 weeks after transplanting; high fruit yields (> 90 Mg ha^{-1}) were associated with improved vegetative growth, and in particular larger leaf area. Mild N deficiency was the principal cause of poor vegetative growth in low nutrient supply treatments. Higher yield resulted from greater fruit number. Reinstating adequate fertility after vegetative growth stopped and fruit number was determined did not increase fruit yield. For maximum fruit yield, plant uptake of N and K was 9.4 and 13.8 g $plant^{-1}$, respectively (equivalent to approximately 210 and 310 kg ha^{-1} at a medium planting density). Greatest nutrient uptake occurred during fruit development. Where practical, fertilizer application should be concentrated during fruit growth. Heavy late-season K fertigation did not increase the soluble solids concentration (SSC) of fruit.

Although offering considerable flexibility in nutrient fertigation, the use of drip irrigation often results in undesirably low SSC. Late-season irrigation management strategies to increase fruit SSC without excessive yield loss were subsequently investigated in drip-irrigated fields. Two experiments were conducted at the University of California, Davis. Irrigation cutoff prior to fruit ripening reduced fruit set, decreased fruit size, and increased the incidence of fruit rots, making this approach uneconomical. Irrigation cutback to 25-50 % of reference evapotranspiration imposed at the onset of fruit ripening (approximately 6 weeks preharvest) was sufficient to improve fruit SSC and maintain Brix yields (Mg Brix solids ha^{-1}) compared to the current grower practice (late cutoff). Irrigation cutbacks imposed during ripening did not cause excessive canopy dieback, nor were fruit culls or rots increased when the crop was harvested at commercial maturity. Fruit colour and pH were not adversely affected by irrigation cutback. Brix monitoring of the earliest ripening fruit (when 30-60 % of the fruit

surface shows a colour other than green) can help classify fields as to the severity of irrigation cutback required to reach desirable fruit SSC at harvest. Combined, these techniques offer considerable flexibility in managing fields for improved fruit SSC levels.

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OVERVIEW:

Environmental stewardship in agriculture has become increasingly important, particularly as the extent to which poor fertilizer and irrigation management can contribute to environmental pollution is revealed. The trend towards improved stewardship has been further fueled by market demand for "eco-friendly" production practices. Large retailers and processors want to certify products as being produced using environmentally-sound techniques; in as much, growers are being encouraged to adopt production practices that can limit damage to the land.

The agriculture sector in general must therefore continually refine crop management techniques and ensure that appropriate technology is incorporated where possible. A challenge in this process has been balancing what is agronomically acceptable and environmentally desirable; practices that are advantageous to the grower are not always beneficial to the environment, and vice-versa. One technology with the potential to address both agronomic and environmental concerns is drip irrigation and fertigation. By applying nutrients and water directly at the root surface, general management efficiencies can be improved, and the potential for runoff and leaching to the greater environment minimized. In recent years drip technology has increased in use in many agricultural sectors, including the processing tomato industry overseas. Although crop nutrition and water management can be improved with drip technology, traditional fertilizer and irrigation practices must first be calibrated to suit this approach. To address this issue, a series of four experiments were conducted to improve the management of nutrients and water for drip-irrigated processing tomato.

CHAPTER 1: Review of Literature

1.1 Background

The global processing tomato industry has traditionally focused on the production of bulk paste (for use in ketchup, puree, spaghetti sauce, pizza sauces, soups, juices, etc.), although demand for whole peeled, or peeled and diced fruit is increasing. Worldwide, in excess of 30,000,000 Megagram's (Mg) of fruit are produced annually. Of this, over 30 % is grown in California, making it by far the largest supplier of processed tomato product; other notable suppliers include Italy, China, Spain, Turkey and Brazil. By comparison, New Zealand (N.Z.) produces < 0.5 % of the global supply, most of which is consumed domestically. The constant in all markets is that processors demand high quality product at cheap prices; margins on production continue to tighten in most markets. Additionally, other production constraints have emerged. In particular, environmental stewardship continues to be the focus of renewed interest. Two areas of particular agronomic interest in improving short-term and long-term sustainability are nutrient and irrigation management. However, the high economic value of processing tomato often requires high-input production practices to maximize fruit yield and quality.

1.2 Nutrient Management in Processing Tomato Production

To ensure adequate nutrient availability during growth and development, fertilizer applications often exceed critical plant requirements; many growers use generalized fertilizer programs for nitrogen (N), phosphorus (P) and potassium (K), without tailoring them to field-specific conditions (Hartz, 2002a). While excessive fertilization generally does not cause serious agronomic problems, it can be a significant contributor to elevated nutrient concentrations in surface and ground waterways (Hartz, 2002a; Pote *et al.*, 1996; Rahn, 2002). Soil test measures of N and P have been positively correlated with nutrient concentrations in field runoff and leachate from irrigation or rainfall (Blackmer, 1987; Hartz and Johnstone, 2005; McDowell and Sharpley, 2001; Sharpley, 1995, 1997). The negative effect of high levels of soluble nutrients on the eutrophication of water bodies has been well documented (Keeney and

Follett, 1991; Pote *et al.*, 1996; Sims, 1998); nitrate contamination may also present a health risk in drinking water drawn from sub-surface aquifers.

Despite elevated nutrient availability in many soils, growers continue to apply fertilizers to maximize tomato growth during establishment; early growth is almost exclusively vegetative, as the plant canopy and root structure are formed (Picken *et al.*, 1986). However, once fruit set begins and assimilates are diverted to developing fruit, most new vegetative growth stops (Halbrooks and Wilcox, 1980); this is characteristic of the determinate growth pattern in processing tomato. Establishing a strong vegetative framework is therefore essential to maximize the interception of radiation for photosynthetic activity (Greenwood, 2001; Sinclair and Horie, 1989; Tei *et al.*, 2002). The main source of assimilates for fruit growth comes from the leaf (Ho and Hewitt, 1986), so limiting assimilate supply can reduce fruit growth and subsequent yield (Schaffer *et al.*, 1999). Stevens (1976) suggested that there is rarely an excess of assimilate supply in processing tomatoes, because fruit set is compact and leaf areas invariably smaller than with indeterminate fresh-market tomatoes. A compact fruit set is necessary to allow the maximum fruit yield to be ripe for a once-over destructive harvest.

Of the nutrients required for growth, high fruit yield is most commonly limited by N deficiency; this reflects the relative ease with which N can be leached out of the active root zone with heavy rainfall or excessive irrigation and the overall importance of N in vegetative tissue (N is a key constituent of chlorophyll, the photosynthetic unit). Where N limits plant growth, yield is invariably reduced (Adams, 1986; Cavero *et al.*, 1997, 1998; Cerne, 1990; Clark *et al.*, 1999; Colla *et al.*, 1999, 2001; Geisenberg and Stewart, 1986); the degree of decline varies considerably depending on the extent and timing of deficiency. Yield decline has often been associated with low fruit number, apparently reflecting an N limitation on fruit set. Competition for assimilates can cause flowers to abort, as supplies are preferentially directed to fruit that have already set (Ho, 1984; Wardlaw, 1990). Julian (1990) also provided evidence of this effect, suggesting that most fruit set on the first 18 trusses of a plant; later trusses contributed very little to fruit yields. Similar trends were reported by Renquist and Reid (1998). Assimilate supply can also affect mean fruit mass. Fruit size is affected by the number of cells originating from division processes in the first week following anthesis; the remainder of fruit growth consists almost entirely of cell elongation (Gillaspy *et al.*, 1993). Baldet *et al.* (2002) suggested that sugar deprivation limited cell division, reducing overall fruit

size. High fruit set can also decrease mean fruit mass (Colla *et al.*, 1999), although in most instances, yields are not reduced; fruit yield is a function of fruit number and individual mass (Ho and Hewitt, 1986).

For maximum fruit yield and quality, California growers commonly apply between 140-280 kg N ha^{-1} (Hartz and Miyao, 1997); despite such norms, individual grower-operations can vary considerably in nutrient management practices based on a number of perceived production and environmental constraints (soil type, cropping history, humid/arid conditions, etc.). Some research has suggested considerably lower fertilizer applications are satisfactory to maximize fruit yield and quality; Krusekopf *et al.* (2002) found that although grower N application varied among 10 commercial sites from 140-273 kg N ha^{-1}, no more than 100 kg N ha^{-1} was necessary in any field to maximize tomato yield or quality. In these trials, excess N fertilization by the grower not removed in the harvested fruit was presumably prone to environmental loss during the winter, as suggested by Rahn (2002). Others have concluded higher rates are justified (Cerne, 1990; Dadomo *et al.*, 1994a; Dumas, 1990; Halbrooks and Wilcox, 1980; Hills *et al.*, 1983); in some instances supply > 250 kg N ha^{-1} was required for maximum fruit yield. Presumably many experimentally-determined differences relate to the growing environment, original N status of the soil, production practices and cultivar selection.

Both P and K can also limit tomato growth (Besford and Maw, 1975; Biddinger *et al.*, 1998; Fontes and Wilcox, 1984; Hartz *et al.*, 1998, 2001, 2005; Lingle and Lorenz, 1969). However, in many agricultural soils P and K availability is considered to be satisfactory for high fruit yields (Hartz and Miyao, 1997; Strand, 1998) due to high native fertility, or decades of intensive production where fertilizer application rates have exceeded crop removal. Hartz and Miyao (1997) suggested that a soil test value (bicarbonate-extractable) of 12-15 mg kg^{-1} P is generally interpreted as sufficient; in fields with soil test values less than 12 mg kg^{-1} P fertilization may increase fruit yield, while above 15 mg kg^{-1} applications are not likely to be beneficial. However, the current grower practice in California is to apply on average 30-60 kg P ha^{-1} (Hartz and Miyao, 1997), largely irrespective of soil test values. In part, this reflects the grower perception that standard chemical extraction procedures may not accurately measure plant-available forms of P as suggested by Sims *et al.* (2000). Also, many growers apply P fertilizer preplant to guarantee adequate availability during the sensitive period of establishment; poor availability at this time can cause plants to be stunted, reducing

growth potential and therefore yield. This problem is often aggravated by spring plantings, when low soil temperature can limit the conversion of P to plant-available forms (Brady, 1990); Johnstone *et al.* (2005a) found that for each 10 °C decrease in soil temperature bioavailable P was reduced by approximately 40 %.

Research using traditional preplant and side-dressing fertilization techniques has found that soils with an exchangeable K value < 0.35 cmol kg^{-1} may respond to K fertilization (Hartz *et al.*, 2001), although this threshold may be higher when K is fertigated by buried drip lines (Hartz *et al.*, 2005). Improved efficiency under drip may reflect the limited movement of K in many soils (fertigation places K directly in the active root zone), less fixation due to more uniform moisture content (Cassman *et al.*, 1990) and greater availability from frequently increasing soil solution K concentration (Hartz *et al.*, 2005). California growers seldom apply more than 110 kg K ha^{-1} (Hartz and Miyao, 1997), although K uptake associated with high fruit yield can exceed 300 kg K ha^{-1} (Widders and Lorenz, 1979); comparatively low K applications reflect the ability of many soils to supply large amounts of K (due to the previous cropping history or high natural fertility).

A positive relationship between fruit soluble solids concentration (SSC) and K fertilization has been reported in several studies (Dumas, 1990; Lachover, 1972). However, these results have not been widely corroborated. In a survey of 140 commercial processing tomato fields in California, Hartz *et al.* (1999) concluded that the impact of soil or plant K status on fruit SSC was minor. Additionally, in field trials investigating various application amounts (0-800 kg K ha^{-1}), the timing of application (flowering, fruit set and early fruit ripening) and methods of applications (fertigation, foliar sprays, preplant and sidedressed), Hartz *et al.* (2001, 2005) found no relationship between fruit SSC and soil K status or K fertilization. Greater K nutrition has ameliorated some fruit colour disorders (Hartz *et al.*, 1999, 2001, 2005; Picha and Hall, 1981; Trudel and Ozbun, 1970, 1971), although even at very high application rates has not eliminated them. In many instances, K fertilization to maximize fruit colour required rates far higher than that required for maximum fruit yield; Hartz *et al.* (2005) concluded that to justify such applications a grower would need to recover the cost of the fertilizer in higher yield and/or in a price premium for improved fruit quality.

Many growers continue to adopt a liberal approach to fertilizer management, applying too much rather than too little. Although some growers use monitoring tools (including soil testing and leaf analysis) to help guide fertilizer decisions, many do not;

since fertilizer cost is a small component of overall crop production costs, some growers pay insufficient attention to crop fertility issues. To reduce potential environmental risk, current practices can be refined. Issues of sustainability have increasingly become the focus of agricultural research and extension (Hartz, 2002a). However, most research on processing tomato nutrition has been conducted in the field where control of fertility is less precise. McDonald *et al.* (1996) suggested it is desirable to manipulate nutrient supply directly at the root surface, eliminating any buffering capacity of a soil volume. Soil type can affect the availability of applied nutrients in such experiments. Subsequently, applied fertilizer treatments may not accurately represent nutrient availability to the plant. Current fertilizer norms may therefore be inaccurate.

An alternative to field determination is aeroponics, which offers the potential to study plant nutrition in an optimal root environment, where neither water nor oxygen are limited or influenced by intrinsic soil properties (Barak *et al.*, 1996; Waisel, 1996). Eymar *et al.* (2001) concluded that solution culture can improve the accuracy of nutritional studies by reducing external factors; outcomes may therefore represent the optimum conditions in which the crop is grown, becoming a useful standard for comparison. Additionally, conventional fertilization techniques rely on preplant applications and one or more side-dressings made mid-season. A more effective means to match plant uptake with supply is to apply nutrients with irrigation water; fertigation by subsurface drip irrigation allows small amounts of nutrients to be supplied directly to the active root zone at will (Hartz and Hochmuth, 1996). At identical seasonal applications of N and K, continuous drip fertigation improved fruit yield compared to traditional preplant and side-dress methods (Güler *et al.*, 2002). Closely matching supply with plant uptake is also integral to improving fertilizer management (Dumas, 1990; Hartz, 2005; Stark *et al.*, 1983); such practices can decrease the potential for nutrient loss to the environment by reducing availability during periods of low plant demand.

1.3 Irrigation Management in Processing Tomato Production

Successful irrigation management is very important in maximizing plant productivity; where water is limiting, yield and quality of agricultural crops can be greatly affected (Fereres *et al.*, 2003). In most environments, processing tomatoes are irrigated by furrow methods. Irrigation amounts of 50-100 mm are typically applied

every 7-14 days during plant growth and fruit development (Hartz and Miyao, 1997), with significant soil drying occurring between irrigations (Hanson *et al.*, 2000a). Conventional irrigation practices can be subject to poor distribution uniformity (a measure of how uniformly water is applied across the field); Hanson (1995) reported that furrow irrigation frequently achieved a uniformity of < 75 %. Poor uniformity may result from insufficient land levelling, long furrow lengths and slow infiltration rates. In addition to being wasteful and increasing the risk of nutrient loss to the environment (due to leaching and/or surface runoff), under- and over-watering can also reduce tomato yield; Hartz (2002b) suggested that more yield potential is commonly lost due to improper water management than to any other factor under grower control.

By comparison, drip irrigation offers the potential for improved water management by eliminating many engineering and cultural constraints that complicate conventional irrigation methods (Hartz, 1996). Hartz (2005) noted that well-designed drip systems can reach a distribution uniformity of > 90 %. Drip irrigation can also reduce or eliminate surface runoff, deep percolation and soil evaporation; water usage can be lowered by as much 50 % of that required with conventional irrigation methods (Phene, 1999), although in most fields water conservation is typically less, within the range of 10-30 % (depending on the growers' previous irrigation practices).

Drip irrigation minimizes plant water stress during growth and development by supplying frequent, small-volume irrigations (Hanson *et al.*, 2003; Hartz, 1996; Phene, 1999); irrigation amounts of 10-15 mm are commonly applied every 2-3 days with drip. In well-managed fields, conversion to drip irrigation has typically increased processing tomato fruit yield by 10-25 % or more compared to furrow irrigation (Hartz, 2001). Subsequently, the use of drip irrigation in processing tomato production has increased rapidly; in 2005, more than 16,000 ha of land was estimated to be drip-irrigated in California (T.K. Hartz, personal communication), representing approximately 15 % of the total land farmed in this market. Despite this trend, drip irrigation is not currently used on a large scale by N.Z. growers. Although drip systems can be costly to establish, increased productivity and savings in water, energy and labour have generally recouped such expenses within 2-3 years of installation (Linden, 2003); buried drip tapes last for 5-7 years, with the pump equipment and filtration systems 10-15 years. As competition for water among agricultural, industrial and urban uses increases, options that reduce growers' water dependency appear likely to continue to gain popularity.

However, some processors remain hesitant of drip irrigation because fruit SSC has generally been lower than that achieved with furrow irrigation; drip-irrigated fields have commonly been 0.2-0.5 °Brix lower than furrow averages (Hartz, 2001). Acceptable fruit SSC levels are typically > 5.0 °Brix. Because factory processing involves evaporating of unnecessary water, fruit with low SSC reduce both paste yield per unit of fresh fruit and overall processing efficiency. Even small improvements in fruit SSC are important to processors because the savings can be substantial (Renquist and Reid, 2001). Linden (2004) reported that each 0.1 °Brix decrease in SSC costs California processors approximately US$1.30 per Mg of raw product in additional processing and handling; at an average commercial yield of 90 Mg ha^{-1}, a decline in fruit SSC of between 0.2-0.5 °Brix would increase processing costs by approximately US$230-580 ha^{-1}. Growers who consistently deliver fruit with low SSC may risk contracts in competitive markets where supply is high. Some processors have implemented price premiums for fruit with higher SSC, providing an incentive to manage for improved fruit quality. Management techniques that consistently increase fruit SSC in drip-irrigated fields with minimal yield loss are therefore required.

Irrigation management affects both tomato yield and SSC (Cahn *et al.*, 2001, 2003; Calado *et al.*, 1990; Dumas *et al.*, 1994; Lowengart-Aycicegi *et al.*, 1999; May *et al.*, 1990; May and Gonzales, 1999; Murray, 1999; Renquist and Reid, 2001). All reported that imposing soil moisture stress during fruit sizing and ripening reduced yield while increasing SSC. Poor fruit SSC in drip-irrigated fields has primarily resulted from insufficient water stress as fruit ripen. Water stress increases plant water potential (Mitchell *et al.*, 1991a; Renquist and Reid, 2001; Rudich *et al.*, 1981), which reduces the movement of solutes into developing fruit; this decreases fruit expansion and results in higher sugar concentrations (Ehret and Ho, 1986). Phene *et al.* (1986) found that in processing tomato, plant water use during fruit ripening is only 80-90 % of reference evapotranspiration (ET_o) due to natural leaf senescence and declining water loss; ET_o refers to water loss from a standardized crop, commonly closely-clipped, actively-growing grass. This range reflected plants with strong vigour; actual water use may be even lower in fields with poor vigour or incomplete canopy cover. Irrigation management for improved fruit SSC therefore needs to account for this decline in water use, and also include an additional degree of water deficit to ensure plants are sufficiently stressed late in the season.

A common management approach to increasing fruit SSC in drip-irrigated fields has been full irrigation cutoff implemented during fruit ripening. With the determinate cultivars currently used, fruit ripening typically encompasses the final 6 weeks preharvest. During this period, fruit ripen at an average rate of 2-3 % of fruit reaching the pink stage of maturity each day. Although irrigation cutoff 6 weeks or more preharvest increases fruit SSC, it can also dramatically reduce fruit set (Atherton and Othman, 1983; Colla *et al.*, 1999; May *et al.*, 1990; Wudiri and Henderson, 1985; Zegbe-Domínguez *et al.*, 2003), decrease fruit size (May and Gonzales, 1994; Mitchell *et al.*, 1991b), and substantially increase the incidence of fruit rots (May and Gonzales, 1999; Murray, 1999). The more severe the irrigation deficit, the greater the loss; May and Gonzales (1999) suggested that fruit yield from a very early cutoff 80 days preharvest was 30 Mg ha^{-1} less than the grower standard; despite improved fruit SSC with greater water stress, Brix yields (marketable yield x SSC) were significantly lower. Irrigation cutoffs are also typically irreversible; by the time symptoms of vine-collapse and dieback are observed (indicators of excessive plant water stress), it is usually too late to remedy without substantial yield loss. Furthermore, lateral movement of water can be restricted in fine-textured soils when they are allowed to dry above 50 % moisture depletion, making it difficult to re-wet the soil in the event that irrigation is required (Cahn *et al.*, 2001). Collectively, these findings make early cutoff approaches uneconomical.

Irrigation cutoffs implemented within the final 6 weeks preharvest have given highly variable results, in some fields having no impact on SSC, while in others causing an unacceptable degree of yield loss. This variability appears largely related to field-specific factors (including soil texture, rooting depth and wetting pattern away from the drip tape), making it impossible to develop a generic cutoff date recommendation for drip-irrigated fields. Management tools that help tailor late-season irrigation strategies to account for field-specific factors are required.

The rapid sensitivity of soil water status to irrigation application, particularly in the primary root zone, has resulted in soil-based monitoring techniques being favoured to track plant water availability. Capacitance probes, resistance blocks and tensiometers have all been investigated (Cahn *et al.*, 2004; Hanson *et al.*, 2000a, b; Hanson and Peters, 2000). Resistance blocks and tensiometers have been largely favoured to prevent over- or under-watering, because they are comparatively cheap and can be automated. However, such measures are not consistently predictive of fruit quality; for

example, Cahn *et al.* (2004) found that fruit SSC could vary as little as 0.4 °Brix over a soil tension range as large as 225 kPa. This presumably relates to the fact that soil-based measures do not take into consideration other dynamics, such as plant vigour, disease or cultivar selection.

Other more direct indicators of plant water status including leaf water potential, infrared leaf thermometry and stomatal conductance exist (Cahn *et al.*, 2000; Calado *et al.*, 1990; Reid and Renquist, 1997; Renquist and Reid, 2001; Rudich *et al.*, 1981; Zegbe-Domínguez *et al.*, 2003), although such techniques are often time consuming, require a high level of user expertise and can be prone to large sampling variability. Fulton *et al.* (2001) and McCutchan and Shackel (1992) have reported that covering plant leaves with a reflective water-impervious bag allowed equilibrium to be reached between the leaf and stem by effectively stopping transpiration. This method improved the accuracy of leaf water potential measurements in tree crops by reducing transient sources of variation, although no work has been published with row crops such as processing tomato.

In the absence of reliable indicators, many growers have adopted a conservative approach of full irrigation until cutoff approximately 3 weeks preharvest, choosing to maximise fruit yield. This approach has been based on that advocated for conventional irrigation methods. Due to distinctly different soil moisture patterns between furrow and drip-irrigation techniques, such a late-season cutoff has not consistently increased fruit SSC. An alternative approach to complete irrigation cutoff is cutback irrigation. Imposing a controlled water deficit early in the fruit ripening phase has shown the potential to increase SSC with only a minimal sacrifice in fruit yield (Cahn *et al.*, 2001; Renquist and Reid, 2001). Deficit cutback irrigation regimes supply less than 80-90 % of ET_o during fruit ripening. Cahn *et al.* (2001) suggested that at 70 % of ET_o, fruit SSC of an early cutback (initiated when 5-10 % of fruit were ripe) was greater than the standard grower practice (full cutoff 3 weeks preharvest), with no overall loss in Brix yield.

Maintaining Brix yield appears to be a useful benchmark for late-season irrigation management; where Brix yield is significantly reduced, price premiums for fruit with higher SSC are unlikely to balance the disproportionate loss of yield that has resulted. Continuing to apply a small amount of irrigation but less than plant demand may also allow a greater cumulative water stress to be imposed without the risk of excessive plant canopy dieback. Dieback may increase the incidence of fruit culls,

which can occur when fruit are directly exposed to solar radiation and tissue over-heats (Adegoroye and Jolliffe, 1983). For drip irrigation to continue to gain market acceptance for processing tomato production reliable strategies are required to manage late-season irrigation for high fruit SSC and minimal yield loss.

1.4 Statement of Objectives

This study focuses on the potential to improve the management of nutrients and water for processing tomato crops, with particular emphasis on utilizing the practical benefits offered by the use of drip irrigation technology. A series of experimental studies were devised to:

1.) Evaluate nutrient demand of processing tomato in an ideal root environment without typical field constraints; uptake determined in this environment was then to be used as the basis for establishing optimal fertilizer norms and supply patterns in the field using drip technology.

2.) Evaluate late-season irrigation management of processing tomato in drip-irrigated fields to increase fruit SSC with minimal yield loss.

CHAPTER 2: 1998-1999 Aeroponic Nutrition Trial

A glasshouse nutrition experiment was conducted at the Plant Growth Unit (long. 175° 37'E; lat. 40° 23'S), Massey University, Palmerston North, during the summer of 1998-1999. The aim was to evaluate the effect of low and high fertility during three distinct development phases (vegetative, fruit development and fruit ripening) on plant growth and subsequent fruit yield and quality of processing tomato. Aeroponic technology was selected to enable sharp comparison of fertility regimes in each growth period; supply of nutrients directly at the root surface also effectively eliminates any buffering capacity of a soil volume, which is a limitation of traditional fertilizer trials in the field. After determining plant demand under aeroponic conditions, these results were then to be evaluated in the field using drip fertigation as a method for improving the efficiency of fertilizer applications by closely matching predicted plant nutrient demand with supply.

2.1 Materials and Methods

2.1.1 Experimental Site

A 9 m x 18 m glasshouse was used for this experiment, with an east-west orientation. A minimum air temperature of 15 °C was maintained; side and roof venting was activated at 25 °C. During the day, relative humidity was between 60-80 %. There was no enrichment with carbon dioxide. Average outdoor solar radiation during the summer production months was approximately 20 MJ m^{-2} day^{-1} (Leathwick *et al.*, 2002).

2.1.2 Production Details

The hybrid cultivar 'Cannery Row' was used in this study as a prominent N.Z. industry standard. Seed was supplied by Heinz Wattie's Ltd. (Hawkes Bay, N.Z.). Germinated seedlings were potted into vermiculite in plastic cells (75 ml volume capacity) 10 days after sowing. There was one healthy seedling per cell. Vermiculite was used because it provides ideal aeration and drainage in hydroponic/aeroponic culture, and is typically sterile and free from diseases. At field capacity, the physical

characteristics of the vermiculite were 30 % solid, 29 % water-filled pore space and 41 % air-filled pore space; total porosity was 70 %. Potted seedlings were raised in a greenhouse until transplanting into the aeroponic system approximately 5 weeks after sowing. During this period, all plants were hand-watered daily and fed as required with a complete fertilizer solution (Pan *et al.*, 1999); of the major nutrients, this solution supplied approximately 100, 30, and 100 mg L^{-1} of N, P and K, respectively. Important production and phenological dates are summarized in Table 2.1.

Table 2.1. Production and phenological dates, 1998-1999.

		Phenological stage		
Sown	*Transplanted*	*First flowering*	*First fruit set*	*First ripe fruit*
November 17	December 21	January 20	February 1	March 19

Aeroponic tanks (3.70 m x 1.25 m x 0.65 m) were made from reinforced polystyrene lined with black polyethylene. The planting density was initially 40 cm between double rows and 30 cm within rows. There were 24 harvestable plants per tank, with an additional two guard plants at each end; guard plants were moved after each harvest to create equal competition amongst the remaining plants. The final plant population was a single row with 30 cm in-row spacing; this was equivalent to 22,222 plants ha^{-1}, a medium-density field planting (Fig. 2.1a, b). At flowering, two boxes of pollinator bees were placed in the glasshouse; because elevated air temperatures appeared to reduce bee activity, a hand-held electric vibrator was also used to ensure adequate pollination and fruit set. Flowers were vibrated three times per week, starting 35 days after transplanting (DAT). Control for white fly (*Trialeurodes vaporariorum*) was with a wasp parasitoid (*Encarsia formosa*). Sticky yellow insect traps were also placed above plants. No substantial disease pressure was observed.

Fig. 2.1a. Early-season vegetative growth at 21 DAT.

Fig. 2.1b. Mid-season flowering and fruit development at 42 DAT.

2.1.3 Experimental Design

Experimental design was randomized complete block with two replications; the number of replications was constrained by glasshouse size and aeroponic system design. There were 16 aeroponic tanks in total (eight per replicate). Two fertility regimes with either a low conductivity (L = 0.7 dS m^{-1}) or high conductivity (H = 2.0 dS m^{-1}) were delivered factorially to plants during three growth periods, vegetative development (P_{d1}), fruit development (P_{d2}) and fruit ripening (P_{d3}). Solution conductivities > 2.5 dS m^{-1} can limit tomato growth (Maas, 1986) and were therefore avoided. Because processing tomato has a determinate growth habit, each of the three growth periods was more distinct than in semi-determinate or indeterminate cultivars (like those grown for fresh market). Effectively, during vegetative growth there were only two treatments (L or H). At fruit development these two regimes were split to provide four treatments (LL, LH, HL or HH), and during fruit ripening they were split again to provide eight separate treatments (LLL, LLH, LHL, LHH, HLL, HLH, HHL or HHH). A summary of the factorial treatment structure is provided in Table 2.2. Both the low and high fertility regimes were based on a complete balanced nutrient solution recommended for N.Z. greenhouse tomato production (Tregidga *et al.*, 1986). A complete description of both regimes is provided in Appendix I. All plants received high conductivity (2.0 dS m^{-1}) during the initial 15 DAT (the aim of the experiment was not to cause extreme deficiency, as this was not representative of 'normal' production practices).

Table 2.2. Factorial treatment design under aeroponics between 16-92 DAT.

Vegetative development	Fruit development	Fruit ripening
16-43 DAT	44-64 DAT	65-92 DAT
Low (L)[z]	Low (LL)	Low (LLL)
		High (LLH)
	High (LH)	Low (LHL)
		High (LHH)
High (H)	Low (HL)	Low (HLL)
		High (HLH)
	High (HH)	Low (HHL)
		High (HHH)
4 tanks each	2 tanks each	1 tank each

[z] Low fertility (L) was equivalent to 0.7 dS m^{-1}; high fertility (H) was equivalent to 2.0 dS m^{-1}

Inside each aeroponic tank emitters misted treatment solutions directly onto plant roots for 10 seconds every 2 minutes (Fig. 2.2). Runoff from each treatment drained directly back into separate 500 L sump reservoirs (in essence, a re-circulating system). Top-up solutions were 100 times the concentration of the standard solution and were used to adjust reservoir conductivity back to either 0.7 or 2.0 dS m^{-1} (the low and high treatments, respectively). Solution pH was kept at 6.5 using potassium hydroxide and phosphoric acid. Conductivity and pH were monitored and amended daily. Reservoir solutions were dumped every 10-14 days, reducing the likelihood of nutrient imbalances (over time, removal of certain nutrients at rates greater than others may cause solution ratios to change).

Fig. 2.2. Root growth inside the aeroponic tank at 72 DAT.

2.1.4 Data Collection

2.1.4.1 Leaf Analysis

Representative whole-leaf samples were taken weekly (alongside destructive growth measurements) to document the N, P and K status of the crop. On each sampling occasion, 10-20 leaves were removed per replicate of each treatment. Youngest mature leaves (YML; fourth leaf from the plant apex) were selected for

standardization purposes (Hartz *et al.*, 1998). Leaves were oven dried at 65 °C for 48 hours and then ground to pass through a 0.5 mm screen. Total N and P concentrations (expressed as % of dry mass) were determined colourimetrically following Kjeldahl acid digestion (Twine and Williams, 1971). Total K concentration (expressed as % of dry mass) was determined by flame-emission spectroscopy following nitric acid digestion (Technicon, 1973).

2.1.4.2 Destructive Whole-Plant Sampling

There were 12 destructive plant harvests between 8 and 92 DAT; a summary of harvest dates relative to treatment regimes is provided in Table 2.3. At each harvest two plants were removed from each aeroponic tank. During the phase of establishment when only high fertility was supplied (0-15 DAT), 16 plants per replicate were therefore sampled (all 8 tanks in the replicate x 2 plants). However, in each subsequent period the number of plants sampled decreased due to the factorial design. During vegetative development, sampling of each treatment was equal to 8 plants per replicate (4 tanks x 2 plants). During fruit development, sampling of each treatment was equal to 4 plants per replicate (2 tanks x 2 plants). During fruit ripening, sampling of each treatment was equal to 2 plants per replicate (1 tank x 2 plants).

On each sampling occasion, the fresh biomass of individual whole-plants was recorded. Plants were then separated into leaf, stem, fruit and root tissues, and each component weighed. A representative leaf sample was further separated into leaf lamina and petiole material and the mass of each recorded. Leaf laminae were used to measure leaf area by leaf area meter (Model 3100, LI-COR Biosciences, Lincoln, NE). A representative stem sample was also collected and weighed. Samples were oven dried at 65 °C for 48 hours before being weighed dry and ground to pass a 0.5 mm screen. The entire root biomass was dried, weighed and ground. The handling of fruit tissue is described separately as yield and quality (Section 2.1.4.3). Ground leaf and stem samples were analyzed for Total N, P and K concentration as previously described. Nutrient concentrations could not be successfully determined for root tissue due to what appeared to be silicon contamination in the ground samples (from dried vermiculite that was inadvertently incorporated with roots).

Table 2.3. Destructive plant sampling between 8-92 DAT relative to fertility treatments.

Harvest ocassion	Sampling date	DAT
	All plants received H during first 15 days [z]	
1	December 29	8
2	January 5	15
	Treatments L and H initiated at 16 days	
3	January 12	22
4	January 19	29
5	January 26	36
6	February 2	43
	Change over from L and H to LL, LH, HL and HH at 44 days	
7	February 9	50
8	February 16	57
9	February 23	64
	Change over from LL, LH, HL, HH to LLL, LLH, LHL, LHH, HLL, HLH, HHL, HHH at 65 days	
10	March 2	71
11	March 11	80
12	March 23	92

[z] Low fertility (L) was equivalent to 0.7 dS m^{-1}; high fertility (H) was equivalent to 2.0 dS m^{-1}

2.1.4.3 Fruit Yield and Quality Measurements

Of the twelve whole-plant harvests made, only eight resulted in a measurable fruit biomass. Beginning 36 DAT, all fruit were hand-harvested and weighed to determine the total yield of each treatment. Fruit were sorted according to four categories, including marketable (sound, intact red and coloured fruit), green (no colour), blossom-end rot fruit (BER) and pathological rots. The number and mass of fruit in each category was recorded, and mean individual fruit mass calculated. At each harvest, approximately 20-25 intact fruit per replicate of each treatment (representing the maturity at that time) were selected for nutrient analysis; fruit that had lost integrity due to either BER or pathological rot were not included in these analyses. Fruit were cut longitudinally, weighed fresh and then oven dried at 65 °C before being weighed dry. Samples were subsequently ground to pass through a 0.5 mm screen and analyzed for Total N, P and K concentration as previously described. Additionally, the concentration of Total Ca and Mg (expressed as % of dry mass) were determined by atomic absorption spectroscopy following nitric acid digestion (Technicon, 1973).

At the final harvest (92 DAT), 20-25 intact marketable fruit per replicate of each treatment were randomly collected to assess quality. Fruit were mechanically juiced,

and a filtered sample (using cheese-cloth) was collected for determination of SSC and titratable acidity. Fruit SSC (°Brix) was measured using a temperature-compensated refractometer (N1, Atago Ltd., Tokyo, Japan). Titratable acidity was measured using an automatic pH titrator (DL 21, Mettler-Toledo Inc., Columbus, OH). To determine titratable acidity, 1 mL of juice was diluted to 50 mL in distilled water. With continuous stirring, the sample was titrated against 0.1 N sodium hydroxide to pH 8.1 (Mencarelli and Saltveit, 1988). Results were expressed as the equivalent mass of citric acid as a percent of total dry mass; citric acid is the predominant organic acid in ripe tomatoes (Davies and Hobson, 1981). Lycopene content was determined on the unfiltered pulp sample. From the blended sample, 100 µg of tomato pulp was added to 7.0 mL of 4:3 (v/v) ethanol:hexane mixture (Barrett and Anthon, 2001). Samples were vortexed intermittently for one hour out of bright light, after which time 1.0 mL of distilled water was added to each sample and briefly mixed. Samples were left to stand for 10 minutes allowing the solvent phases to separate. The hexane layer was removed and the absorbance read by spectrophotometer (Model U-2000, Hitachi Ltd., Tokyo, Japan) at 503 nm. At 92 DAT, harvest index (H.I.) was determined as the proportion of fruit yield to total plant biomass (both dry).

2.1.4.4 Growth Analysis

The primary data used in growth analysis calculations were leaf area and dry plant biomass (leaf and total). Total plant biomass referred only to the above-ground constituents (leaf, stem and fruit); root biomass was excluded to allow comparisons with previous studies (in the field, accurately exhuming roots has proven difficult). Growth analysis variables were calculated for each defined period of plant development; because fertility regime targeted three distinct phases of growth, this approach offered the greatest practical insight into overall treatment effects. The following formulas were used:

2.1.4.4a RELATIVE GROWTH RATE (RGR)

$$\mathbf{RGR = Log_e\ T_{dw2} - Log_e\ T_{dw1} / t_2 - t_1}$$

Where:

RGR = relative growth rate ($g\ g^{-1}\ day^{-1}$)

T_{dw} = total plant dry biomass (g)

t = time (days)

$_{1, 2}$ = subscripts denote previous and current harvests, respectively

2.1.4.4b NET ASSIMILATION RATE (NAR)

$$\mathbf{NAR = (T_{dw2} - T_{dw1}) \times (\log_e LA_2 - \log_e LA_1) / (LA_2 - LA_1) \times (t_2 - t_1)}$$

Where:

NAR = net assimilation rate (g cm^{-2} day^{-1})

T_{dw} = total plant dry biomass (g)

LA = leaf area (cm^2)

t = time (days)

$_{1, 2}$ = subscripts denote previous and current harvests, respectively

2.1.4.4c LEAF AREA RATIO (LAR)

$$\mathbf{LAR = LA / T_{dw}}$$

Where:

LAR = leaf area ratio (cm^2 g^{-1})

LA = leaf area (cm^2)

T_{dw} = total plant dry biomass (g)

2.1.4.4d LEAF WEIGHT RATIO (LWR)

$$\mathbf{LWR = L_{dw} / T_{dw}}$$

Where:

LWR = leaf weight ratio

L_{dw} = leaf dry biomass (g)

T_{dw} = total plant dry biomass (g)

2.1.4.4e SPECIFIC LEAF AREA (SLA)

$$\mathbf{SLA = LA / L_{dw}}$$

Where:

SLA = specific leaf area (cm^2 g^{-1} L_{dw})

LA = leaf area (cm^2)

L_{dw} = leaf dry biomass (g)

2.1.4.5 Nutrient Uptake

Nutrient uptake into leaf, stem and fruit tissue was calculated for N, P and K; total uptake of each nutrient was the sum of these constituents. Because fertility regimes targeted vegetative development, fruit development and fruit ripening, cumulative uptake of N, P and K was calculated at the end of each period of growth. The following formulas were used:

2.1.4.5a LEAF UPTAKE

Leaf uptake = L_{dw} x % N, P or K in leaf

Where:

L_{dw} = leaf dry biomass (g plant^{-1})

% N, P or K = concentration of nutrient in the leaf sample

2.1.4.5b STEM UPTAKE

Stem uptake = S_{dw} x % N, P or K in stem

Where:

S_{dw} = stem dry biomass (g plant^{-1})

% N, P or K = concentration of nutrient in the stem sample

2.1.4.5c FRUIT UPTAKE

Fruit uptake = F_{dw} x % N, P or K in fruit

Where:

F_{dw} = fruit dry biomass (g plant^{-1})

% N, P or K = concentration of nutrient in the fruit sample

2.1.5 Statistical Analysis

Experimental data were subjected to ANOVA tests using the SAS General Linear Model (GLM) procedure (SAS Institute Inc., Cary, N.C.). Means separation was made on significant ANOVA tests using the Least Significant Difference (LSD) method ($p < 0.05$). Where relevant, statistical analyses were made on log-transformed (to render variability more homogenous with time) or arc-sine-transformed (to ensure

normality assumptions were met) data sets. Because ANOVA outcomes were consistently poor (clearly limited by replication constraints) a series of orthogonal contrasts were made as a means to compare specific treatments (Table 2.4); such contrasts allowed combinations of interest to be considered within the overall analysis (therefore not losing degrees of freedom). This technique generally clarified plant responses to fertility, which were often numerically distinct between fertility regimes. Most contrasts focused on early-season fertility, primarily due to the determinate growth habit in processing tomatoes. Periods of vegetative and fruit development typically account for most active plant growth (during ripening it is predominantly metabolic changes that occur in fruit). Therefore, many plant responses appeared likely to be influenced by fertility during the initial two periods of growth. Additional contrasts were made where the expected response to fertility warranted (i.e. those relating to fruit quality, which may be influenced by late-season fertility).

SAS non-linear (NLIN) regression procedures were used to test the significance of logistic modelling in describing seasonal trends in biomass accumulation. Correlation analysis was used to report positive and negative linear relationships between variables of interest.

Table 2.4. Standard orthogonal contrasts made during each period of plant growth.

Growth period	Contrast description	Abbreviation
Vegetative development [z]		
Fruit development	LL *vs.* HH	border treatments
	(LL + LH) *vs.* (HL + HH)	L*x vs.* H*x*
Fruit ripening	(LLL + LLH) *vs.* (LHL + LHH)	LL*x vs.* LH*x*
	(HLL + HLH) *vs.* (HHL + HHH)	HL*x vs.* HH*x*
	LLL *vs.* HHH	border treatments
	(LLL + LLH + LHL + LHH) *vs.* (HLL + HLH + HHL + HHH)	L*xx vs.* H*xx*

[z] No contrasts were made during the initial period because there were only two treatments

2.2 *Results*

2.2.1 Fertility Index

Field studies typically involve a known fertilizer application (e.g. kg ha^{-1}); however, there was no practical method in which to quantify the mass of nutrients that were applied seasonally using the aeroponic system. Calculated nutrient uptake was only indicative of that absorbed by plants for growth; this was not equivalent to the mass of nutrients 'applied'. It would also have been misleading to represent the quantity of fertilizers placed in the starter and top-up solutions as the quantity of nutrients applied. This difficulty was not unique to aeroponic study; most, if not all, solution-culture experiments are affected in a similar manner. Nevertheless, the aeroponic approach remained a convenient and effective way to study growth responses to nutrient supply while controlling other potentially limiting factors. The design of the experiment was in fact such that either sub-optimal or optimal fertility (low and high treatments, respectively) were applied, where the quantity of each mineral was less important than availability.

As an alternative to the mass of nutrients applied, a weighted fertility index (F_{IN}) was created allowing crop nutrition to be correlated to variables of interest. The index was calculated for each of the eight treatment combinations by calculating mean solution conductivity across the three defined growth periods (Eq. 2.1); these values therefore fell between 0.7 and 2.0 dS m^{-1}, the range of the two border treatments receiving either continuous low or high fertility (LLL and HHH, respectively; Table 2.5).

$$F_{IN} = \frac{(N_1 \text{ x EC during } P_{d1}) + (N_2 \text{ x EC during } P_{d2}) + (N_3 \text{ x EC during } P_{d3})}{(N_1 + N_2 + N_3)} \qquad \textit{(Eq. 2.1)}$$

Where:

N_1, N_2 and N_3 = the number of days during P_{d1}, P_{d2} and P_{d3}, respectively

EC (dS m^{-1}) = low (0.7) or high (2.0) conductivity during P_{d1}, P_{d2} and P_{d3}

Although the index did not directly weight the relative importance in the timing of these regimes, a poor correlation between F_{IN} and the response variable may suggest that timing of fertility was more important than the mean regime concentration across all periods. An adjusted fertility index ($F_{INAdj.}$) was also created for treatment

combinations across only the final two growth periods (Eq. 2.2); this index was specifically designed for correlation with fruit quality variables, which are typically determined after fruit have set. As with the original index, these values continued to fall between 0.7 and 2.0 dS m^{-1}, the range of the LLL and HHH treatments, respectively (Table 2.5).

$$F_{INAdj.} = \frac{(N_2 \text{ x EC during } P_{d2}) + (N_3 \text{ x EC during } P_{d3})}{(N_2 + N_3)} \qquad \textit{(Eq. 2.2)}$$

Where:

N_2 and N_3 = the number of days during P_{d2} and P_{d3}, respectively

EC (dS m^{-1}) = low (0.7) or high (2.0) conductivity during P_{d2} and P_{d3}

Table 2.5. Fertility regime, fertility index (F_{IN}) and adjusted fertility index ($F_{INAdj.}$) between 16-92 DAT.

Treatment schedule [z]	Fertility regime (dS m^{-1})			F_{IN}	$F_{INAdj.}$
	P_{d1} (16-43 DAT)	P_{d2} (44-64 DAT)	P_{d3} (65-92 DAT)	(dS m^{-1})	(dS m^{-1})
LLL	0.7	0.7	0.7	0.7	0.7
LLH	0.7	0.7	2.0	1.2	1.4
LHL	0.7	2.0	0.7	1.1	1.3
LHH	0.7	2.0	2.0	1.5	2.0
HLL	2.0	0.7	0.7	1.2	0.7
HLH	2.0	0.7	2.0	1.6	1.4
HHL	2.0	2.0	0.7	1.5	1.3
HHH	2.0	2.0	2.0	2.0	2.0

[z] Low fertility (L) was equivalent to 0.7 dS m^{-1}; high fertility (H) was eqivalent to 2.0 dS m^{-1}

2.2.2 Destructive Whole-Plant Sampling

Twelve destructive growth measurements were made between 8 and 92 DAT. An error in biomass measurements made 71 DAT was found; all data collected from this date were subsequently omitted.

2.2.2.1 Total Plant Dry Biomass

Most field studies have been unable to accurately exhume the below-ground portion of the tomato plant; using aeroponics root biomass was easily retrieved. However, to allow comparisons with previous experiments root biomass was considered

independently to above-ground constituents. Total plant dry biomass (T_{dw}) therefore only comprised leaf, stem and fruit tissue. Fertility regime during P_{d1} appeared to largely determine seasonal T_{dw} accumulation (vegetative framework was established during this period, as was flower number and therefore subsequent fruit number). Accordingly, to display seasonal accumulation of plant biomass, treatments were grouped according to the low or high fertility regime received during this initial period (designated L*xx* and H*xx*, respectively; Fig. 2.3); L*xx* included the LLL, LLH, LHL and LHH treatments, whereas H*xx* included the HLL, HLH, HHL and HHH treatments. To further illustrate the close relationship between biomass productivity and initial fertility regime, the continuous low and high border treatments (LLL and HHH, respectively) were also retained for comparison against the L*xx* and H*xx* groupings.

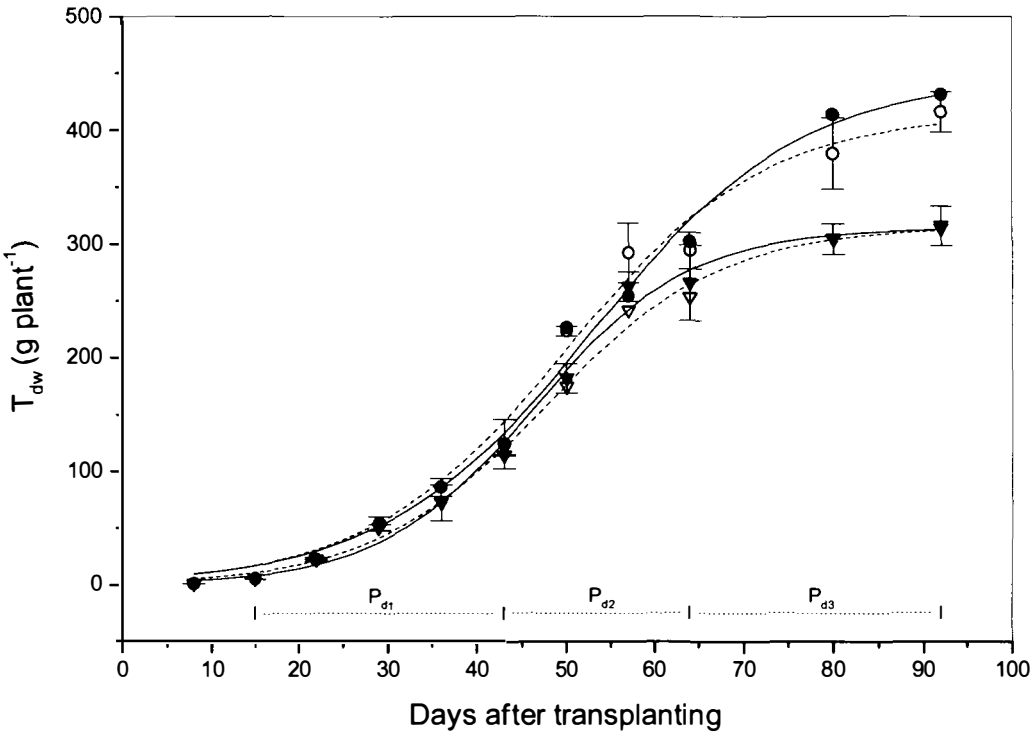


Fig. 2.3. Effect of fertility regime on seasonal total plant dry biomass (T_{dw}) accumulation. Treatment means are given ± standard error (for L*xx* and H*xx* only). Treatments were T_{dw} for L*xx* (---▽---), H*xx* (---○---), LLL (—▼—) and HHH (—●—). T_{dw} included leaf, stem and fruit dry biomass. Significant logistic growth models were fitted to each treatment ($p < 0.05$).

Total dry weight accumulated steadily during P_{d1} in both treatments, largely attributed to vegetative (leaf and stem) growth. There was an increasing numerical trend towards greater T_{dw} in plants receiving high fertility during this initial period, although at 43 DAT this effect was not significant (Table 2.6). During P_{d2}, T_{dw} accumulated rapidly in all treatments, largely attributed to fruit growth. The difference

between the L*x* (LL and LH) and H*x* (HL and HH) treatments increased during this phase of growth, although the overall effect of fertility regime was not significant at 64 DAT. Contrasts on specific treatment means were also not significant at this time, despite a continued trend towards greater T_{dw} with higher fertility.

Table 2.6. Effect of fertility regime on total above-ground dry biomass (T_{dw}) accumulation at the end of each defined growth period.

	Total above-ground dry biomass (g)		
Fertility regime	43 DAT (end of P_{d1})	64 DAT (end of P_{d2})	92 DAT (end of P_{d3})
LLL	114	253	314
LLH			361
LHL		278	288
LHH			302
HLL	124	286	433
HLH			414
HHL		302	385
HHH			431
SE	9	18	18
p-value	*ns*	*ns*	*ns*
Contrasts			
LL *vs.* HH		*ns*	
L*x* *vs.* H*x*		*ns*	
LL*x* *vs.* LH*x*			*ns*
HL*x* *vs.* HH*x*			*ns*
LLL *vs.* HHH			*
L*xx* *vs.* H*xx*			***

^{ns}, *, *** non-significant at $p < 0.10$, or significant at $p < 0.10$ or 0.01, respectively

The rate of T_{dw} accumulation slowed during P_{d3}, a pattern consistent with fruit ripening. This slowing was more distinct in plants that had initially received low fertility. At 92 DAT there was no difference in T_{dw} between the LLL and grouped L*xx* treatments. By comparison, T_{dw} gain was greater in treatments that had received high fertility during P_{d1}; however, there was also little difference between the HHH and grouped H*xx* treatments at 92 DAT. Despite large numerical differences in plant biomass between fertility regimes, the overall effect of treatment on T_{dw} was not significant at 92 DAT. Statistical separation was clearly limited by the number of replicates possible using the glasshouse setup. Contrasts clarified the T_{dw} response to fertility at 92 DAT; both HHH and H*xx* fertility regimes resulted in significantly greater biomass accumulation when compared separately to LLL and L*xx* fertility (respectively). Total plant dry biomass at 92 DAT was weakly correlated with F_{IN} ($p <$

0.08, r = 0.46). This relationship appeared overstated, because LLL fertility achieved similar T_{dw} to LHH fertility, as was also the case for HLL and HHH fertility; these treatment comparisons represented the most dissimilar regimes after the initial period (i.e. those most likely to be different if F_{IN} across all periods was important). These observations instead implied the importance of adequate early-season fertility in determining plant biomass outcomes.

2.2.2.1a LEAF BIOMASS

Leaf dry biomass (L_{dw}) included both leaf lamina and petiole material. Seasonal L_{dw} accumulation was sigmoid, distinguished by a large plateau after fruit began to develop; because L_{dw} was largely determined in response to fertility during P_{d1}, only the grouped L*xx* and H*xx* treatments were retained figuratively (Fig. 2.4). Similar patterns were also observed for the continuous low and high border treatments.

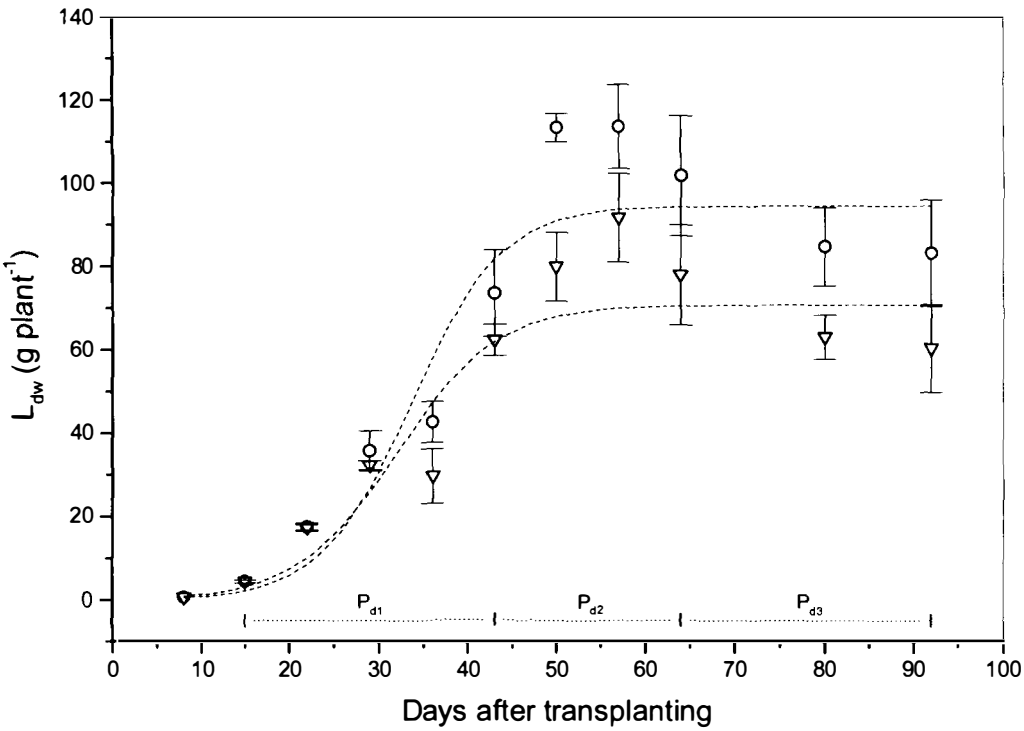


Fig. 2.4. Effect of fertility regime on seasonal leaf dry biomass (L_{dw}) accumulation. Treatment means are given ± standard error. Treatments were L_{dw} for L*xx* (---▽---) and H*xx* (---○---). L_{dw} included both leaf lamina and petiole dry biomass. Significant logistic growth models were fitted to both treatments ($p < 0.05$).

Leaf dry weight accumulated rapidly in both treatments during P_{d1}. Leaf biomass was uncharacteristically low at 36 DAT, but appeared unrelated to fertility

regime; no noticeable decline in T_{dw} was observed on this date. There was an increasing numerical trend towards greater L_{dw} in plants receiving high fertility during P_{d1}, although this effect was not significant at 43 DAT (Table 2.7). Plants initially receiving low fertility had accumulated most leaf biomass by 43 DAT. By comparison, plants initially receiving high fertility continued to accumulate new leaf biomass into the early part of P_{d2}; however, there was no difference in L_{dw} between the HL and HH treatments, suggesting this dynamic was largely controlled by high fertility during the initial period. Despite numerical differences between the L*x* and H*x* treatments, the effect of fertility on L_{dw} accumulation remained not significant at 64 DAT. The coefficient of variation (cv, a measure of sampling variability) was large on this occasion (cv = 43 %). The lack of statistical separation at 64 DAT appeared a transient effect related to this variability; on the two previous harvest occasions during P_{d2} (50 and 57 DAT), H*x* fertility resulted in significantly greater leaf biomass than L*x* fertility ($p < 0.06$ and 0.07, respectively).

Table 2.7. Effect of fertility regime on leaf dry biomass (L_{dw}) accumulation at the end of each defined growth period.

	Leaf dry biomass (g)		
Fertility regime	**43 DAT** (end of P_{d1})	**64 DAT** (end of P_{d2})	**92 DAT** (end of P_{d3})
LLL	62	73	73
LLH			80
LHL		83	39
LHH			49
HLL	74	101	106
HLH			72
HHL		102	60
HHH			95
SE	6	10	9
p-value	*ns*	*ns*	*ns*
Contrasts			
LL *vs.* HH		*ns*	
L*x vs.* H*x*		*ns*	
LL*x vs.* LH*x*			*ns*
HL*x vs.* HH*x*			*ns*
LLL *vs.* HHH			*ns*
L*xx vs.* H*xx*			*ns*

ns non-significant at $p < 0.10$

During P_{d3} there was effectively no new accumulation of L_{dw} in any treatment; this was consistent with the determinate growth habit in processing tomatoes, where

new vegetative growth stops once fruit sinks have developed. Although L_{dw} in the L*xx* and H*xx* treatments declined late in the season, this observation appeared to simply reflect plant-to-plant differences (sample size decreased as the experiment progressed) rather than a specific growth response to fertility; leaf die-back in the glasshouse environment was minimal. Furthermore, leaf biomass for the LLL and HHH border treatments remained largely unchanged during this period (as representative of the fertility 'extremes'). Despite distinct numerical differences between the L*xx* and H*xx* regimes at 92 DAT, the overall effect of fertility on L_{dw} was not significant. Contrasts at this time were also not significant. Presumably this reflected the high sampling variability observed at 92 DAT (cv = 54 %). Leaf biomass dynamics so late in the season were of little practical relevance to yield outcomes, because fruit number and size were already determined. There was no correlation between L_{dw} at 92 DAT and F_{IN}, confirming that the timing of low or high fertility was more important than the mean regime concentration across all periods.

2.2.2.1b STEM BIOMASS

Stem dry biomass (S_{dw}) included all above-ground tissue that was not otherwise leaf or fruit. Seasonal S_{dw} accumulation was sigmoid, also characterized by an increasing plateau as fruit developed (particularly under L*xx* fertility). Although S_{dw} accumulation did not truncate distinctly at the end of P_{dl}, the stem framework still appeared to be largely a function of fertility during this initial phase of plant growth; for continuity, the grouped L*xx* and H*xx* treatments were retained figuratively (Fig. 2.5). Similar patterns were also observed for the continuous low and high border treatments.

Stem biomass accumulated steadily in both treatments during P_{dl}. At 36 DAT, S_{dw} was comparatively high, although was matched by a small decline in L_{dw} as previously noted. The effect of fertility regime on S_{dw} was not significant at 43 DAT (Table 2.8). After 57 DAT there was very little new stem biomass developed in plants that had initially received low fertility (at 80 DAT, stem biomass was abnormally high). By comparison, plants initially receiving high fertility continued to accumulate S_{dw} late into the season. Despite distinct numerical differences between the L*x* and H*x* regimes, the overall effect of fertility was not significant at 64 DAT. However, contrasts on specific treatment means were significant at this time; both HH and H*x* fertility resulted in greater S_{dw} accumulation than LL and L*x* fertility, respectively.

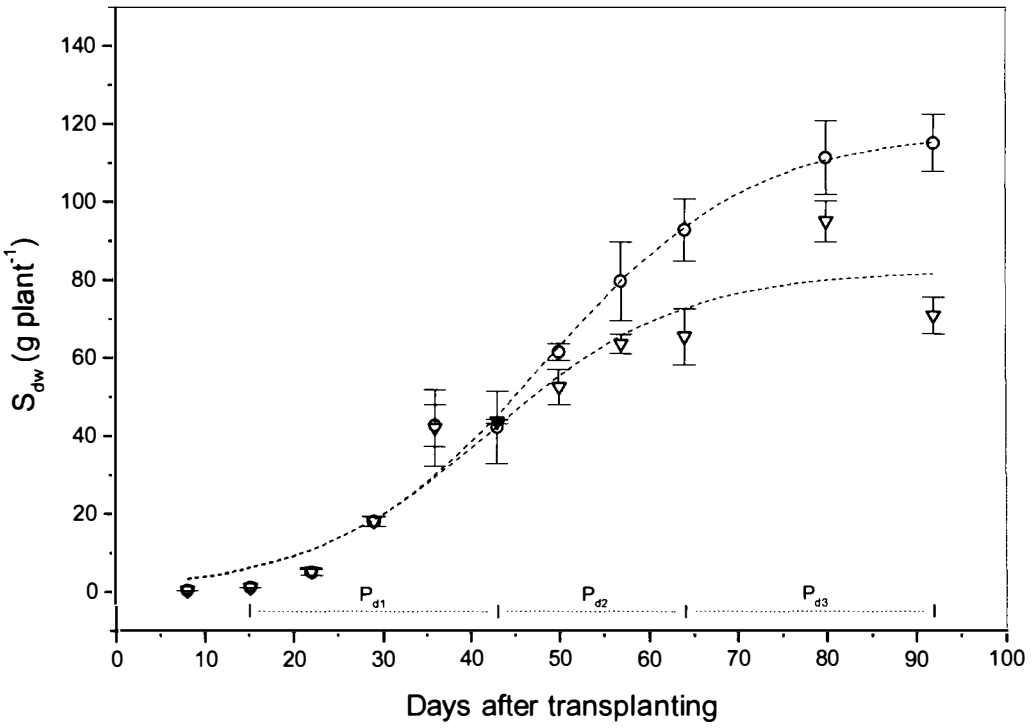


Fig. 2.5. Effect of fertility regime on seasonal stem dry biomass (S_{dw}) accumulation. Treatment means are given ± standard error. Treatments were S_{dw} for L*xx* (---▽---) and H*xx* (---○---). S_{dw} included all above-ground tissue that was not otherwise considered as leaf or fruit. Significant logistic growth models were fitted to both treatments ($p < 0.05$).

Similar statistical trends were also established at 92 DAT; HHH and H*xx* fertility resulted in greater S_{dw} accumulation than LLL and L*xx* fertility, respectively. The detailed means separation at 92 DAT appeared to be of limited practical relevance, because fruit number and size were already determined; additionally, both of these yield components relate more closely to assimilate supply from leaves rather than the stem. Although S_{dw} at 92 DAT was weakly correlated with F_{IN} ($p < 0.06$, r = 0.59), this appeared to be an anomaly in light of the contrasts made (LL*x* vs. LH*x* and HL*x* vs. HH*x* were both not significantly different).

Table 2.8. Effect of fertility regime on stem dry biomass (S_{dw}) accumulation at the end of each defined growth period.

Fertility regime	Stem dry biomass (g) 43 DAT (end of P_{d1})	64 DAT (end of P_{d2})	92 DAT (end of P_{d3})
LLL	44	59	59 d
LLH			84 bc
LHL		71	60 d
LHH			80 c
HLL	42	92	112 a
HLH			135 a
HHL		93	111 ab
HHH			102 abc
SE	4	7	7
p-value	*ns*	*ns*	***
Contrasts			
LL *vs.* HH		**	
L*x vs.* H*x*		**	
LL*x vs.* LH*x*			*ns*
HL*x vs.* HH*x*			*ns*
LLL *vs.* HHH			***
L*xx vs.* H*xx*			***

ns, **, *** non-significant at $p < 0.10$, or significant at $p < 0.05$ or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

2.2.2.1c FRUIT BIOMASS

Fruit dry biomass (F_{dw}) included all fruit that had a diameter greater than 10 mm. Seasonal F_{dw} accumulation was generally sigmoid. Because total fruit number and total yield at 92 DAT appeared largely determined according to plant growth during P_{d1} (fruit yield dynamics are described in Section 2.2.4) the grouped L*xx* and H*xx* treatments were retained figuratively (Fig. 2.6); almost identical patterns were observed for the continuous low and high border treatments.

A measurable fruit mass did not occur until 36 DAT; because only fruit of a certain size threshold were collected, fruit biomass may have been slightly underestimated on earlier dates. There was no effect of fertility regime on F_{dw} during P_{d1}, with equivalent fruit biomass at 43 DAT (Table 2.9). During P_{d2}, F_{dw} accumulated rapidly in all treatments; fruit biomass was numerically greater in plants that had initially received low fertility, which may have reflected slightly earlier flowering. However, this difference in fruit biomass was not significant at 64 DAT. Contrasts on specific treatment means at this time were also not significant.

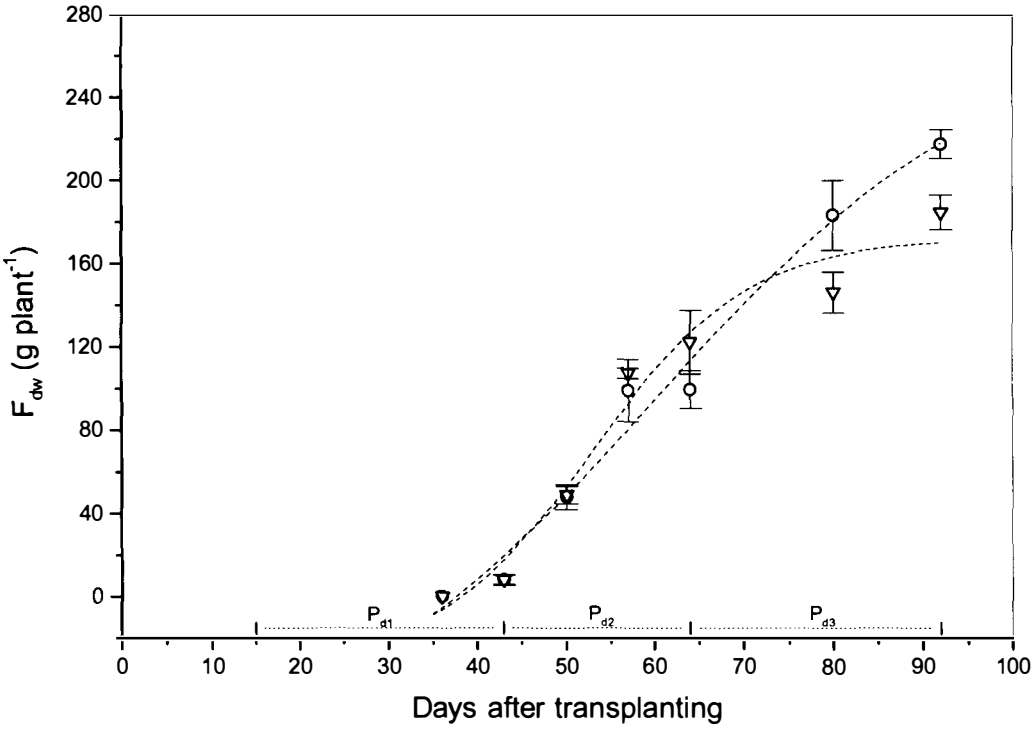


Fig. 2.6. Effect of fertility regime on seasonal fruit dry biomass (F_{dw}) accumulation. Treatment means are given ± standard error. Treatments were F_{dw} for L*xx* (---▽---) and H*xx* (---○---). F_{dw} included all fruit with a diameter greater than 10 mm. Significant logistic growth models were fitted to both treatments ($p < 0.01$).

Accumulation of F_{dw} in plants initially receiving low fertility slowed during P_{d3}; by comparison, plants initially receiving high fertility continued to accumulate F_{dw}. This phase of extra biomass accumulation largely accounted for the difference in F_{dw} between L*xx* and H*xx* treatments. Despite quite large differences, the overall effect of fertility regime on F_{dw} was not significant at 92 DAT. However, contrasts at this time clarified the general effect of fertility on fruit biomass; both HHH and H*xx* fertility regimes resulted in significantly greater F_{dw} accumulation than LLL and L*xx* fertility, respectively. The remaining contrasts were not significant. Fruit dry biomass at 92 DAT was weakly correlated with F_{IN} ($p < 0.09$, r = 0.44). As with previous biomass measures, this relationship appeared overstated because LLL fertility achieved similar F_{dw} to LHH fertility, as was also the case for HLL and HHH fertility. Collectively, these observations reinforced that the timing of low or high fertility was most important in determining yield outcomes rather than the mean regime concentration across all periods. The effect of fertility regime on harvest index (H.I.) was not significant at 92 DAT. Across treatments, the index averaged 0.56; a typical H.I. for processing tomato grown in the field is approximately 0.60 (T.K. Hartz, personal communication).

Table 2.9. Effect of fertility regime on fruit dry biomass (F_{dw}) accumulation at the end of each defined growth period.

Fertility regime	Fruit dry biomass (g)		
	43 DAT (end of P_{d1})	64 DAT (end of P_{d2})	92 DAT (end of P_{d3})
LLL	8	121	182
LLH			196
LHL		124	188
LHH			173
HLL	8	93	215
HLH			208
HHL		106	214
HHH			234
SE	1	9	7
p-value	*ns*	*ns*	*ns*
Contrasts			
LL *vs.* HH		*ns*	
L*x vs.* H*x*		*ns*	
LL*x vs.* LH*x*			*ns*
HL*x vs.* HH*x*			*ns*
LLL *vs.* HHH			*
L*xx vs.* H*xx*			**

^{ns}, *, ** non-significant at $p < 0.10$, or significant at $p < 0.10$ or 0.05, respectively

2.2.2.1d ROOT BIOMASS

Seasonal root dry biomass (R_{dw}) accumulation was sigmoid, distinguished by a large plateau after fruit development began. Although R_{dw} accumulation did not truncate distinctly at the end of P_{d1}, most of root framework was established during this initial phase of growth; for continuity, the grouped L*xx* and H*xx* treatments were retained figuratively (Fig. 2.7). Similar patterns were also observed for the continuous low and high border treatments.

Root biomass accumulated rapidly in both treatments during P_{d1}. The small trend towards greater R_{dw} in plants initially receiving high fertility was not significant at 43 DAT (Table 2.10). Root biomass was comparatively low at 43 DAT and high at 50 DAT; neither observation appeared related to fertility regime. Both dates fell during the phase in which root growth slowed substantially. Despite continued numerical differences between the L*x* and H*x* treatments, the overall effect of fertility was not significant at 64 DAT. The contrast between the two border regimes was however significant, with greater R_{dw} under higher fertility.

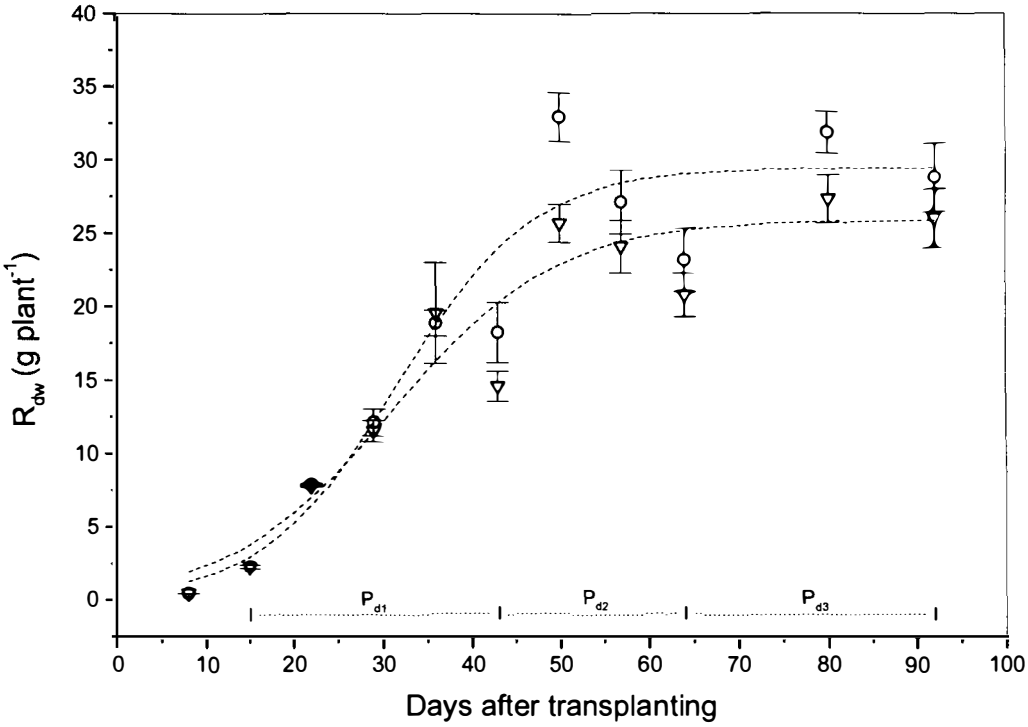


Fig. 2.7. Effect of fertility regime on seasonal root dry biomass (R_{dw}) accumulation. Treatment means are given ± standard error. Treatments were R_{dw} for L*xx* (---▽---) and H*xx* (---○---). Significant logistic growth models were fitted to both treatments ($p < 0.05$).

There was little new accumulation of R_{dw} during P_{d3}. Despite the small trend towards greater R_{dw} with high initial fertility, this effect was not significant at 92 DAT; across treatments, root biomass averaged approximately 7 % of whole-plant biomass at this time. The significance of the HL*x* *vs.* HH*x* contrast appeared overstated due to low and high R_{dw} in the HHL and HLH treatments, respectively. Such changes so late in the season were uncharacteristic of determinate tomatoes grown in a disease-free root environment. Additionally, R_{dw} did not change greatly in the two border treatments during this period (as representative of fertility 'extremes'). All other contrasts were not significant. As expected, R_{dw} at 92 DAT was not significantly correlated with F_{IN}.

Table 2.10. Effect of fertility regime on root dry biomass (R_{dw}) accumulation at the end of each defined growth period.

Fertility regime	Root dry biomass (g)		
	43 DAT (end of P_{d1})	**64 DAT** (end of P_{d2})	**92 DAT** (end of P_{d3})
LLL	15	19	21
LLH			31
LHL		23	29
LHH			23
HLL	18	20	30
HLH			36
HHL		27	21
HHH			28
SE	1	1	2
p-value	*ns*	*ns*	*ns*
Contrasts			
LL *vs.* HH		*	
L*x vs.* H*x*		*ns*	
LL*x vs.* LH*x*			*ns*
HL*x vs.* HH*x*			**
LLL *vs.* HHH			*ns*
L*xx vs.* H*xx*			*ns*

^{ns}, *, ** non-significant at $p < 0.10$, or significant at $p < 0.10$ or 0.05, respectively

2.2.2.2 Leaf Area Measurements

Seasonal leaf area (LA) expansion was sigmoid, distinguished by a large plateau as fruit developed. There was a strong correlation between LA and L_{dw} ($p < 0.01$, r = 0.92). Because leaf dynamics were largely determined during the initial period of plant growth, only the grouped L*xx* and H*xx* treatments were retained figuratively (Fig. 2.8). Similar patterns were also observed for the continuous low and high border treatments.

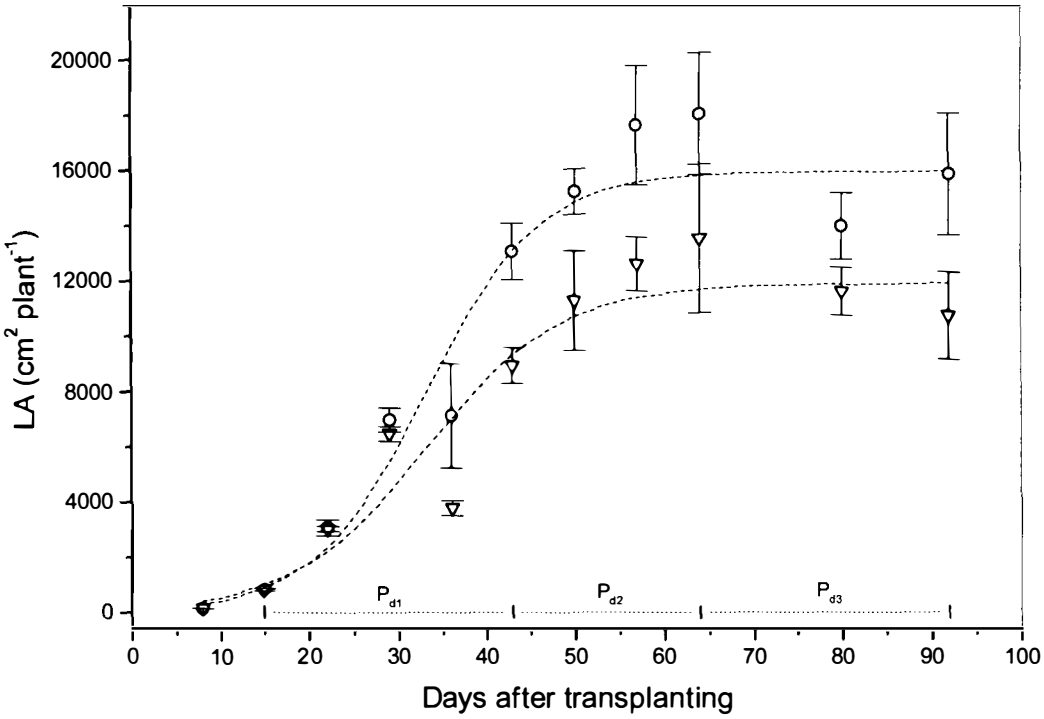


Fig. 2.8. Effect of fertility regime on seasonal leaf area (LA) expansion. Treatment means are given ± standard error. Treatments were LA for L*xx* (---▽---) and H*xx* (---○---). LA included leaf lamina only. Significant logistic growth models were fitted to both treatments ($p < 0.05$).

Leaf area expanded rapidly in both treatments during P_{d1}. Measurements were uncharacteristically low at 36 DAT, although consistent with low L_{dw} also observed; these dynamics appeared unrelated to fertility treatments. The trend towards greater LA in plants receiving high initial fertility was significant at 43 DAT (Table 2.11). After 50 DAT, there was essentially no new leaf area expansion under any treatment regime. Despite larger LA with high initial fertility, the overall effect of treatment was not significant at either 64 or 92 DAT. Contrasts on specific treatment means were also not significant. Sampling variability was large on both occasions (cv = 42 and 49 %, respectively), limiting statistical power. As previously mentioned, this was due to plant-to-plant variations rather than a large incidence of leaf die-back. Leaf area at 92 DAT was not significantly correlated with F_{IN}. As with L_{dw}, these observations confirmed that the timing of fertility was more important to LA development than the mean concentration across all periods of growth.

Table 2.11. Effect of fertility regime on leaf area (LA) accumulation at the end of each defined growth period.

Fertility regime	Leaf area (cm^2) 43 DAT (end of P_{d1})	64 DAT (end of P_{d2})	92 DAT (end of P_{d3})
LLL	8928	13742	13728
LLH			12390
LHL		13338	7519
LHH			9252
HLL	13064	19156	20164
HLH			15009
HHL		16960	12727
HHH			15478
SE	1292	1826	1470
p-value	*	*ns*	*ns*
Contrasts			
LL *vs.* HH		*ns*	
L*x vs.* H*x*		*ns*	
LL*x vs.* LH*x*			*ns*
HL*x vs.* HH*x*			*ns*
LLL *vs.* HHH			*ns*
L*xx vs.* H*xx*			*ns*

^{ns}, • non-significant at $p < 0.10$, or significant at $p < 0.10$, respectively

2.2.2.3 Plant Growth Analysis Measurements

2.2.2.3a RELATIVE GROWTH RATE

The relative growth rate (RGR) of plants declined seasonally in all treatments (Table 2.12). Across periods, RGR was numerically greater under H*xx* fertility compared to L*xx* fertility; although this difference was small, it was nevertheless consistent with total biomass accumulation (which was also greater with high initial fertility). Despite this trend, the effect of treatment on RGR was not significant for any period. As with T_{dw}, this observation appeared largely related to insufficient replication. Contrasts on specific treatment means were also not significant. Growth rates were increasingly variable late in the season; this appeared to reflect observed plant-to-plant variations (particularly in vegetative biomass) rather than important growth responses. Across periods, reinstating high fertility after a phase of low fertility had no consistent effect on RGR.

Table 2.12. Effect of fertility regime on relative growth rate (RGR) of plants across each defined period of growth.

Fertility regime	Relative growth rate (g g^{-1} $week^{-1}$)		
	P_{d1} (16-43 DAT)	P_{d2} (44-64 DAT)	P_{d3} (65-92 DAT)
LLL	0.76	0.26	0.06
LLH			0.09
LHL		0.29	0.01
LHH			0.03
HLL	0.78	0.28	0.10
HLH			0.09
HHL		0.30	0.06
HHH			0.09
SE	0.026	0.030	0.017
p-value	*ns*	*ns*	*ns*
Contrasts			
LL *vs.* HH		*ns*	
L*x vs.* H*x*		*ns*	
LL*x vs.* LH*x*			*ns*
HL*x vs.* HH*x*			*ns*
LLL *vs.* HHH			*ns*
L*xx vs.* H*xx*			*ns*

ns non-significant at $p < 0.10$

2.2.2.3b NET ASSIMILATION RATE AND LEAF AREA RATIO

The net assimilation rate (NAR) of plants declined seasonally in all treatments (Table 2.13). The effect of fertility regime on NAR was not significant, suggesting the capacity of each leaf unit to generate new biomass was similar; across treatments, NAR averaged 0.007, 0.004 and 0.002 g cm^{-2} $week^{-1}$ during P_{d1}, P_{d2} and P_{d3}, respectively. Contrasts on specific treatment means were also not significant.

Leaf area ratio (LAR) also declined seasonally in all treatments (Table 2.13). This reflected the increasing proportion of respiring (primarily fruit) to photosynthesizing (leaf) tissue. Across periods, LAR was consistently greater under H*xx* fertility compared to L*xx* fertility; this difference appeared to account for the small improvement in RGR observed under higher fertility (RGR is the product of NAR and LAR). Higher LAR was due to greater leaf weight ratio (LWR), a relative measure of leaf biomass to total plant biomass. Leaf area ratio was largely unaffected by specific leaf area (SLA), a relative measure of leaf thickness or density; across treatments and periods, SLA averaged approximately 260 cm^2 g^{-1} L_{dw}. Despite consistent numerical trends, the effect of fertility regime on LAR was only significant for P_{d3}. However, this

response appeared overstated, because LAR for the LLL and HHH border treatments was essentially identical during the final period. Significant contrasts also appeared of limited practical value, because the improvement in plant biomass and fruit yield was tied to greater growth during the initial vegetative period.

Table 2.13. Effect of fertility regime on net assimilation rate (NAR) and leaf area ratio (LAR) of plants across each defined period of growth.

	Net assimilation rate (g cm^{-2} $week^{-1}$)			Leaf area ratio (cm^2 g^{-1})		
Fertility regime	P_{d1} (16-43 DAT)	P_{d2} (44-64 DAT)	P_{d3} (65-92 DAT)	P_{d1} (16-43 DAT)	P_{d2} (44-64 DAT)	P_{d3} (65-92 DAT)
LLL	0.008	0.004	0.001	95	62	46 bc
LLH			0.002			41 cd
LHL		0.005	0.001		59	36 e
LHH			0.001			38 de
HLL	0.007	0.003	0.002	117	82	53 a
HLH			0.002			48 ab
HHL		0.004	0.001		75	43 bcd
HHH			0.002			45 bc
SE	0.0006	0.0004	0.0004	8	5	1
p-value	*ns*	*ns*	*ns*	*ns*	*ns*	***
Contrasts						
LL *vs.* HH		*ns*			*ns*	
L*x vs.* H*x*		*ns*			*ns*	
LL*x vs.* LH*x*			*ns*			***
HL*x vs.* HH*x*			*ns*			***
LLL *vs.* HHH			*ns*			*ns*
L*xx vs.* H*xx*			*ns*			***

ns, *** non-significant at $p < 0.10$, or significant at $p < 0.01$, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

2.2.3 Nutrient Analysis

2.2.3.1 Leaf Tissue

The youngest mature leaf (YML) was collected to monitor the nutrient status of the aeroponic crop. This tissue corresponded to that commonly collected and analyzed for comparison against established leaf sufficiency concentrations (Hartz *et al.*, 1998). Additionally, the concentration of N, P and K was determined on a sample of whole-plant leaves (WPL) collected from all ages and positions on the plant. The results of WPL analyses were used in calculating nutrient uptake in the leaf (as representative of all leaves, rather than just the newest leaves), but were otherwise not presented. As

expected, the concentration of N, P and K in YML and WPL tissues were consistently correlated ($p < 0.01$, r = 0.90, 0.47 and 0.88, respectively).

2.2.3.1a NITROGEN CONCENTRATION

Seasonally, YML N concentration decreased under all treatment regimes (Table 2.14). In plants initially receiving low fertility, this decline was greatest as the vegetative framework developed; in those initially receiving high fertility, decline was greatest as fruit sinks developed. During P_{d1}, YML N concentration averaged 4.5 and 5.3 % in the low and high treatments, respectively. Based on the leaf sufficiency range suggested for early bloom, N concentration was adequate in plants receiving high fertility, but fell increasingly below this threshold in plants receiving low fertility. Despite consistently greater N concentration under high fertility, on only two of the four dates during vegetative development was this effect significant (29 and 36 DAT).

Table 2.14. Effect of fertility regime on seasonal N concentration (%) in YML tissue.

	N concentration (%) in YML tissue *x* DAT								
Fertility	P_{d1} *(vegetative development)*				P_{d2} *(fruit development)*			P_{d3} *(ripening)*	
regime	*22*	*29*	*36*	*43*	50	*57*	*64*	*80*	*92*
LLL								3.7	3.5
LLH	5.7	4.5	3.9	4.0	3.6	4.0	3.8	3.6	3.3
LHL								3.7	4.0
LHH					4.0	4.1	4.0	3.8	3.9
HLL								3.6	3.6
HLH	5.8	5.2	5.1	5.2	4.7	4.6	4.2	4.4	3.4
HHL								4.0	3.5
HHH					4.2	4.1	4.2	4.2	4.2
SE	0.13	0.20	0.36	0.35	0.20	0.14	0.07	0.09	0.14
p -value	*ns*	*	***	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Sufficiency levels [z]	----------	***4.6 - 5.2 %***	----------		-------	***3.5 - 4.5 %***	-------	--	***2.7 - 3.8 %*** --
Contrasts									
LL *vs.* HH					*ns*	*ns*	*ns*		
L*x vs.* H*x*					*ns*	*ns*	*ns*		
LL*x vs.* LH*x*								*ns*	*ns*
HL*x vs.* HH*x*								*ns*	*ns*
LLL *vs.* HHH								*ns*	*ns*
L*xx vs.* H*xx*								**	*ns*

[ns], *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively

[z] sufficiency levels from Hartz *et al.* (1998)

During P_{d2}, the numerical trend towards greater N concentration with high initial fertility continued, although this difference appeared to moderate; YML N

concentration averaged 3.9 and 4.3 % in the L*x* and H*x* treatments, respectively. On no date was the effect of treatment significant. Contrasts on specific treatment means were also not significant. All treatments resulted in tissue N concentrations comparable to the sufficiency range suggested for full bloom and fruit development. During P_{d3}, tissue N concentration averaged 3.7 and 3.9 % in the L*xx* and H*xx* treatments, respectively; these values continued to reflect adequate tissue N levels based on the sufficiency range suggested for early fruit ripening. On neither sampling occasion during fruit ripening was the effect of treatment on tissue N concentration significant. However, at 80 DAT the contrast comparing N concentration between the L*xx* and H*xx* groupings was significant; higher fertility resulted in greater tissue N. All other contrasts of interest were not significant. Across periods, reinstating high fertility after a phase of low fertility did not consistently increase tissue N concentration.

2.2.3.1b PHOSPHORUS CONCENTRATION

Seasonally, YML P concentration did not vary greatly under any treatment regime, averaging approximately 0.77 % (Table 2.15). Across all three growth periods, P concentrations were very high compared to typical leaf sufficiency standards. On only one date (64 DAT) was there a significant effect of treatment on tissue P; for this sampling, the HH treatment had lower tissue P than the other treatments. However, this difference was comparatively small and was associated with unusually low sampling variability (cv = 3 %). Several contrasts were significant at 57 and 64 DAT; greater tissue P was associated with lower fertility, although the difference remained small and did not appear to be of any practical importance (values were above sufficiency standards). All other contrasts were not significant. Across periods, reinstating high fertility after a phase of low fertility did not consistently increase tissue P concentration.

Table 2.15. Effect of fertility regime on seasonal P concentration (%) in YML tissue.

	P concentration (%) in YML tissue *x* DAT								
Fertility	P_{d1} *(vegetative development)*				P_{d2} *(fruit development)*			P_{d3} *(ripening)*	
regime	*22*	*29*	*36*	*43*	*50*	*57*	*64*	*80*	*92*
LLL								0.89	0.78
LLH					0.77	0.83	0.85 a	0.85	0.82
LHL	0.71	0.78	0.77	0.78				0.73	0.82
LHH					0.79	0.78	0.79 a	0.85	0.83
HLL								0.81	0.77
HLH					0.82	0.75	0.78 a	0.84	0.76
HHL	0.75	0.79	0.78	0.68				0.65	0.73
HHH					0.67	0.69	0.68 b	0.80	0.79
SE	0.03	0.02	0.02	0.03	0.04	0.03	0.03	0.03	0.03
p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	**	*ns*	*ns*
Sufficiency levels [z]	----------	***0.32 - 0.49 %***	----------		------	***0.25 - 0.41 %***	------	--	***0.23 - 0.37 %*** --
Contrasts									
LL *vs.* HH					*ns*	*	***		
L*x* *vs.* H*x*					*ns*	*ns*	**		
LL*x* *vs.* LH*x*								*ns*	*ns*
HL*x* *vs.* HH*x*								*ns*	*ns*
LLL *vs.* HHH								*ns*	*ns*
L*xx* *vs.* H*xx*								*ns*	*ns*

[ns], *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

[z] sufficiency levels from Hartz *et al.* (1998)

2.2.3.1c POTASSIUM CONCENTRATION

There was no consistent seasonal trend in YML K concentration (Table 2.16). During P_{d1}, tissue K levels averaged 4.4 and 5.0 % in the low and high treatments, respectively; these values were well above the sufficiency range reported for early growth. Despite consistently greater K concentration under high fertility, on only one of four dates during vegetative development was this effect significant (22 DAT).

When low fertility was supplied during fruit development, tissue K generally decreased. This decline was not evident when high fertility was supplied during fruit development and ripening; tissue K concentration actually increased in several of these treatments late in the season. Across P_{d2} YML K concentration averaged 4.3 and 4.8 % in the L*x* and H*x* treatments, respectively; by comparison, across P_{d3} YML K concentration averaged 4.3 and 5.1 % in the L*xx* and H*xx* treatments, respectively. In both these periods, all treatments had tissue values that continued to reflect adequate to high K concentrations in the leaf. The effect of treatment was only significant at 64 and 80 DAT. On the first of these dates, HH fertility resulted in the greatest YML K

concentration, although this was not significantly different to LH fertility. On the second date, most treatments resulted in higher tissue K than LLL fertility. Several contrasts were also significant across these periods; a higher level of fertility generally increased tissue K concentration. However, the grouped comparisons based on initial fertility (L*x vs.* H*x*, L*xx vs.* H*xx*) were misleading due to high tissue K concentrations in the continuous high fertility treatments.

The effect of reinstating high fertility after a period of low fertility consistently increased YML K concentration compared to matching treatment combinations (i.e. LL *vs.* LH, LLL *vs.* LLH, or HLL *vs.* HLH); this apparently reflected increased availability of K in solution and the relatively high mobility of K into the plant. However, such improvements did not appear related to growth and yield outcomes, because all plants had above-normal tissue K concentrations and such increases generally came after fruit set. Across periods, the concentration of K in YML tissue was negatively correlated with the concentration of Mg and Ca in YML tissue ($p < 0.01$, r = -0.51 and -0.45, respectively); however, even the lowest concentration of Mg and Ca was within established sufficiency norms (1.0-2.2 % Mg and 1.9-2.4 % Ca; Hartz *et al.*, 1998).

Table 2.16. Effect of fertility regime on seasonal K concentration (%) in YML tissue.

	K concentration (%) in YML tissue *x* DAT								
Fertility	P_{d1} *(vegetative development)*				P_{d2} *(fruit development)*			P_{d3} *(ripening)*	
regime	*22*	*29*	*36*	*43*	*50*	*57*	*64*	*80*	*92*
LLL								3.0 b	3.4
LLH	4.4	4.6	4.3	4.4	4.5	4.1	3.4 c	4.4 a	4.1
LHL								4.8 a	4.0
LHH					4.6	4.4	5.0 ab	5.3 a	5.3
HLL								4.2 ab	4.8
HLH					5.0	4.4	4.3 bc	5.0 a	5.3
HHL	4.9	4.9	5.2	5.2				5.2 a	5.2
HHH					5.0	4.9	5.4 a	5.4 a	5.5
SE	0.14	0.15	0.33	0.35	0.13	0.14	0.30	0.23	0.27
p-value	**	*ns*	*ns*	*ns*	*ns*	*ns*	**	**	*ns*
Sufficiency levels [z]	----------	***2.2 - 3.5 %***	----------		-------	***2.0 - 3.1 %***	-------	***-- 0.8 - 2.0 % --***	
Contrasts									
LL *vs.* HH					*ns*	**	***		
L*x vs.* H*x*					*ns*	*	*		
LL*x vs.* LH*x*								**	*ns*
HL*x vs.* HH*x*								*	*ns*
LLL *vs.* HHH								***	*
L*xx vs.* H*xx*								*	*ns*

[ns], *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

[z] sufficiency levels from Hartz *et al.* (1998)

2.2.3.2 Stem and Fruit Tissue

The concentration of N, P and K were determined for both stem and fruit samples collected during the aeroponic experiment. The results of these analyses were used in calculating nutrient uptake in each respective tissue. However, with the exception of fruit concentrations at 92 DAT (Section 2.2.4.5), these results are not otherwise presented. The concentration of N, P and K in stem or fruit tissue is rarely (if ever) used in the context of determining a growth-limiting nutrient deficiency. This reflects the difficulty of standardizing sampling from these tissues. Furthermore, nutrients can accumulate in- or be redistributed from- healthy tissues as they age; analysis of such tissue may therefore simply reflect the overall fertility history of the plant rather than nutrient availability for new growth at the time of sampling.

2.2.4 Fruit Yield and Quality Measurements

The effect of fertility regime on tomato yield and fruit quality is summarized in Table 2.17.

Table 2.17. Effect of fertility regime on tomato yield and fruit quality at 92 DAT.

Fertility regime	Total yield (kg plant^{-1})	Marketable yield (kg plant^{-1})	BER yield (kg plant^{-1})	Soluble solids (°Brix)	Brix yield (kg Brix solids plant^{-1})	Adjusted Brix yield [z]
LLL	3.82	2.59	0.31	4.3	0.11	0.15
LLH	4.00	2.39	0.51	4.5	0.11	0.16
LHL	4.11	2.35	0.23	4.2	0.10	0.15
LHH	3.53	2.59	0.21	4.4	0.11	0.14
HLL	4.57	2.87	0.08	4.3	0.12	0.18
HLH	4.44	2.76	0.13	4.6	0.13	0.19
HHL	4.39	2.99	0.21	4.7	0.14	0.19
HHH	4.45	2.92	0.18	4.7	0.14	0.19
SE	0.14	0.10	0.04	< 0.1	< 0.01	< 0.01
p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Contrasts						
LL*x vs.* LH*x*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
HL*x vs.* HH*x*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
LLL *vs.* HHH	*ns*	*ns*	*ns*	*	*ns*	*ns*
L*xx vs.* H*xx*	•	*	*	**	**	**

[z] adjusted Brix yield based on 90 % of total yield considered marketable

ns, •, ** non-significant at $p < 0.10$, or significant at $p < 0.10$ or 0.05, respectively

2.2.4.1 Total, Marketable and Blossom-end Rot Fruit Yield

The overall effect of fertility regime on total yield was not significant (Table 2.17). This was despite a consistent numerical trend towards greater fruit yield under high initial fertility. However, the contrast comparing total yield in the L*xx* and H*xx* treatments was significant; total yield averaged 3.87 and 4.46 kg plant^{-1}, respectively (equivalent to a field-estimate of approximately 86 and 99 Mg ha^{-1}, respectively). Yield increase was primarily attributable to increased fruit number, as there were no significant differences in mean fruit mass. Across treatments, mean fruit mass averaged approximately 60 g fruit^{-1}. All other contrasts were not significant. Total fruit yield at 92 DAT was not correlated to F_{IN} (Fig. 2.9); this supported earlier plant biomass observations, indicating that the timing of fertility (and in particular early fertility) was most critical in determining overall productivity.

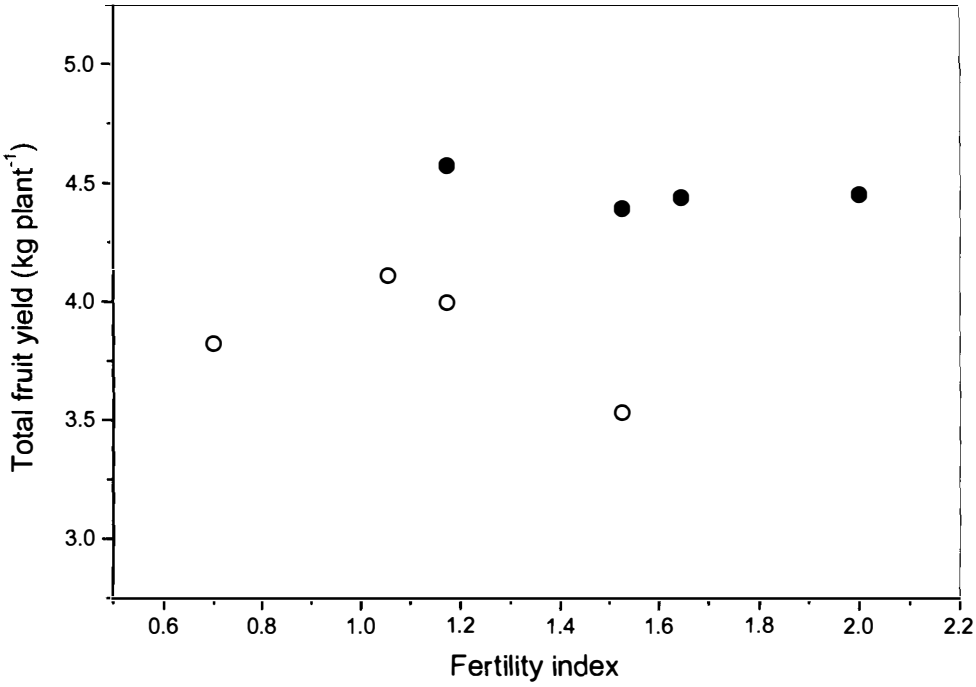


Fig. 2.9. Relationship between fertility index (F_{IN}) and total fruit yield at 92 DAT. Treatments were L*xx* (○) and H*xx* (●).

Surprisingly, T_{dw} at the end of P_{d1} and P_{d2} (end of vegetative and fruit development, respectively) was not strongly correlated with total yield. This appeared to be an anomaly (due to insufficient replication), particularly in light of the positive correlation between LA at the end of P_{d1} and total yield ($p < 0.02$, r = 0.59); larger early leaf areas were generally associated with higher fruit yields. Total yield was also

positively correlated with the average N concentration in YML tissue during P_{dl} ($p < 0.03$, r = 0.57); N concentrations below 4.6 % (the lower threshold for established sufficiency norms during early bloom) were associated with yield outcomes below 4.1 kg plant^{-1} (or less than approximately 90 Mg ha^{-1}). There was no clear correlation between fruit yield and YML N status in subsequent periods. The correlation between total yield and YML K concentration ($p < 0.07$, r = 0.47) appeared largely coincidental, because all treatments resulted in tissue K levels above established sufficiency norms.

As with total yield, the overall effect of fertility regime on marketable yield was not significant (Table 2.17). However, the contrast between the L*xx* and H*xx* treatments was significant; marketable yield averaged 2.48 and 2.88 kg plant^{-1}, respectively (equivalent to a field-estimate of approximately 55 and 64 Mg ha^{-1}, respectively). There was no difference in the percent of yield that was marketable at 92 DAT, averaging approximately 65 % of total fruit yield for both the L*xx* and H*xx* groupings. As expected, total and marketable yields were positively correlated ($p < 0.03$, r = 0.55). No attempt was made to correlate marketable yield with F_{IN} or other variables of interest because the crop was not commercially mature at 92 DAT.

The overall effect of fertility regime on the incidence of blossom-end rot (BER) was not significant (Table 2.17); BER is an imperfection that reduces marketable yields. The contrast between the L*xx* and H*xx* groupings was however significant; treatments receiving low initial fertility had approximately double the incidence of BER to those receiving high initial fertility. Very large sampling variability was associated with BER yield (cv = 70 %). Contrasts remained the same when BER incidence was adjusted to a percent of total yield (to standardize for differences in productivity). There was no correlation between F_{IN} and percent BER yield at 92 DAT. However, percent BER was negatively correlated with average Ca concentration in fruit tissue during P_{dl} ($p < 0.02$, r = -0.57); fruit concentrations below 0.11 % Ca were associated with BER levels in excess of 6 % of total yield. As expected, BER levels were not strongly correlated with fruit Ca concentrations in subsequent periods (early rather than late deficiency is thought to promote this disorder). There was no evidence to suggest that high concentrations of N or K in YML tissue were correlated to greater BER expression. Importantly, the incidence of BER overestimated that typical in the field, where levels are more commonly only 1-3 % of total yield. To some extent, cautious grading of only slightly-affected fruit may have increased observed levels under aeroponics;

commercially, fruit that exhibit some darkening at the distal end but are not deeply sunken may either be constituted as paste products or be used in some limited capacity.

Across treatments, combined BER and marketable yields (ripe fruit) still only comprised approximately 72 % of total yield at 92 DAT. There was no significant effect of fertility regime on this measure of fruit maturity. Pathological rots remained a very small constituent of total yield, averaging less than 1 % (data not shown); the predominant rot species were water mold (*Pythium ultimum*) and gray mold (*Botrytis cinerea*). Remaining fruit were unripe (green). Collectively, these observations suggested that a later harvest would have maximized the yield of ripe fruit. To estimate when commercial maturity (95 % ripe fruit) would have been reached, projections were made from 92 DAT using a ripening rate of 2.5 % colour change per day; this reflects the approximate rate of ripening for tomatoes grown for processing (T.K. Hartz, personal communication). This projected rate was also comparable to that observed under aeroponics between 64 and 92 DAT (approximately 2.6 % per day; data not shown). Based on these predictions, the LLL treatment would have reached a 95 % ripe-stage of maturity approximately 102 DAT; comparatively, the HHH treatment was projected to reach this stage of maturity only 2 days later (104 DAT). Such a small difference between the border treatments would be largely inconsequential in a commercial setting.

2.2.4.2 Fruit Soluble Solids

Across treatments SSC of marketable fruit was low, averaging < 4.5 °Brix; an acceptable target for fruit grown commercially in the field is > 5.0 °Brix. The overall effect of fertility regime on fruit SSC was not significant (Table 2.17). However, contrasts confirmed that HHH and H*xx* fertility significantly increased SSC outcomes compared to LLL and L*xx* fertility, respectively. The significant contrast between the L*xx* and H*xx* regimes appeared to be overstated, because HLL fertility resulted in identical fruit SSC to LLL fertility. An additional contrast was made specific only to the fruit ripening period (*xx*L *vs.* *xx*H); high late fertility significantly ($p < 0.08$) increased fruit SSC levels. It appeared that these effects were in part additive (i.e. high fertility during ripening increased SSC, but to a greater level when high fertility was also supplied during fruit development).

Fruit SSC was not correlated to total yield, but was to F_{IN} ($p < 0.01$, r = 0.65; Fig 2.10); a higher index generally resulted in greater fruit Brix. Leaf area (as an indicator of assimilate supply in plants) at the end of P_{d1} was positively correlated with fruit SSC at 92 DAT ($p < 0.05$, r = 0.51); LA at the end of P_{d2} and P_{d3} was an increasingly poor predictor of SSC potential. Fruit SSC was positively correlated with fruit K concentration at 92 DAT ($p < 0.05$, r = 0.52); however, the overall improvement in SSC was comparatively small (for each 0.5 % increase in fruit K concentration, fruit SSC increased by < 0.1 °Brix).

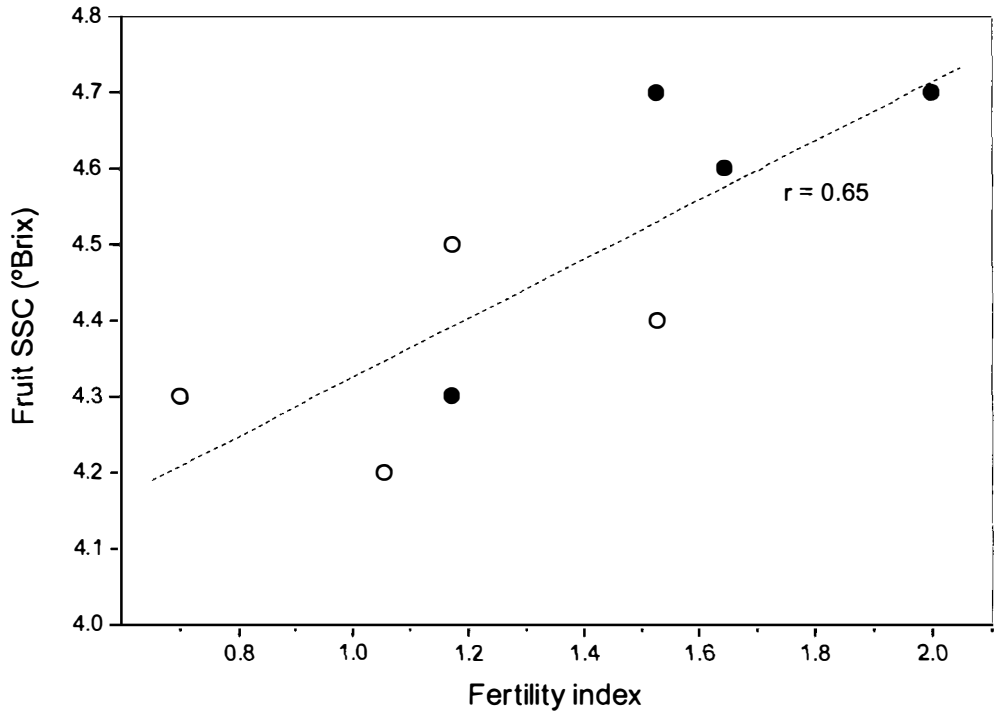


Fig. 2.10. Relationship between fertility index (F_{IN}) and fruit soluble solids concentration (SSC) at 92 DAT. Treatments were L*xx* (○) and H*xx* (●).

2.2.4.3 Brix Yield and Adjusted Brix Yield

The overall effect of fertility regime on Brix yield (marketable yield x fruit SSC) was not significant (Table 2.17). However, the contrast comparing Brix yield in the L*xx* and H*xx* treatments was significant; Brix yield was 0.11 and 0.13 kg Brix solids plant^{-1}, respectively (equivalent to a field-estimate of approximately 2.4 and 2.9 Mg Brix solids ha^{-1}, respectively). Brix yield was more closely correlated with marketable yield ($p < 0.01$, r = 0.95) than fruit SSC ($p < 0.07$; r = 0.47).

Across treatments, Brix yields were underestimated because the final harvest at 92 DAT occurred before full maturity (i.e. > 95 % ripe fruit). An adjustment of Brix

yield was subsequently made to reflect a typical field maturity; marketable yield was considered as 90 % of the total yield measured at 92 DAT (assuming 5 % greens and 5 % culls, normal field levels). Although consistently higher, adjusted Brix yield remained unaffected by fertility regime (Table 2.17). Contrast trends were identical to those for the unadjusted data. Adjusted Brix yield for the L*xx* and H*xx* treatments was 0.15 and 0.18 kg Brix solids plant^{-1}, respectively (equivalent to a field-estimate of approximately 3.7 and 4.1 Mg Brix solids ha^{-1}, respectively). Original and adjusted Brix yields were both positively correlated with F_{IN} ($p < 0.05$ and 0.08, r = 0.51 and 0.49, respectively; Fig. 2.11a, b).

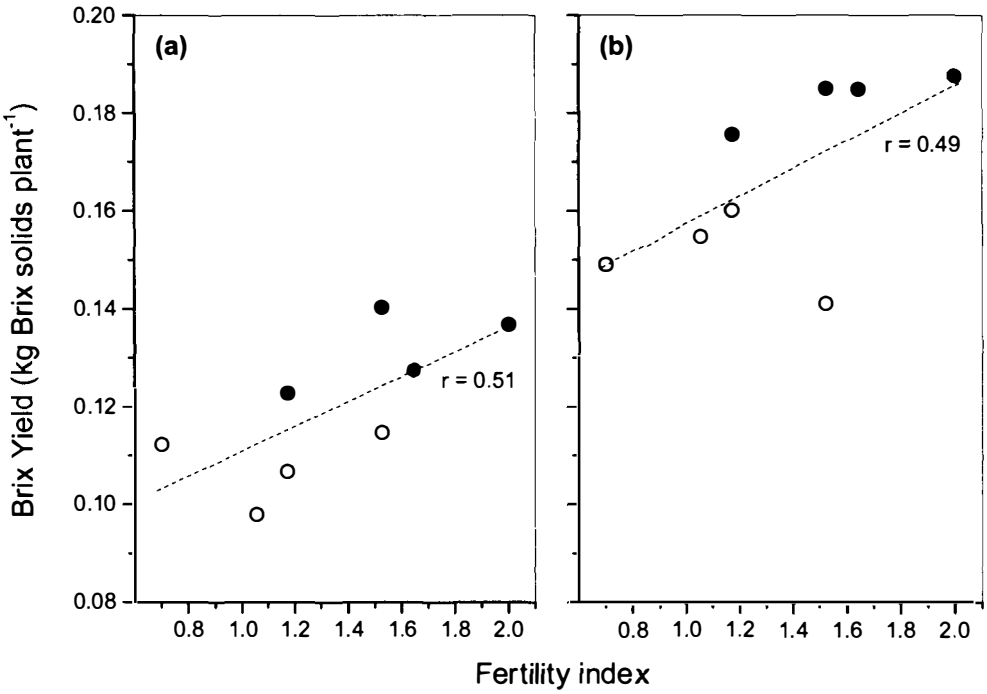


Fig. 2.11. Relationship between fertility index (F_{IN}) and actual Brix yield (a) and adjusted Brix yield (b) at 92 DAT. Treatments were L*xx* (○) and H*xx* (●). Adjusted Brix yields were calculated using a revised marketable yield estimate (90 % of total yield at 92 DAT).

2.2.4.4 Titratable Acidity and Lycopene Content

Titratable acidity (TA) was not significantly affected by fertility regime, varying over a comparatively narrow range (Table 2.18). Across treatments, TA averaged 0.43 %; high acidity combined with high sugars is generally associated with ideal fruit flavour. The contrast comparing TA between the two border treatments was not significant, despite a small numerical increase (approximately 0.04 %) under continuous

high fertility. The contrast between L*xx* and H*xx* fertility was not considered relevant because it averaged fruit quality response during P_{d2} and P_{d3} (these are the periods in which fruit development and ripening occur, and therefore when fertility regime would most likely have affected TA). Two additional contrasts were made to specifically detail the effect of late season fertility (*xx*L *vs. xx*H, and *x*LL *vs. x*HH). Despite numerically greater TA with higher late-season fertility, neither contrast was significant. However, $F_{INAdj.}$ was positively correlated to TA at 92 DAT ($p < 0.05$, r = 0.53). Fruit K concentration at 92 DAT was not significantly correlated to TA; other minerals are not thought to be directly associated with fruit acidity.

Table 2.18. Effect of fertility regime on titratable acidity (TA) and lycopene content of fruit at 92 DAT.

Fertility regime	Titratable acidity [z] (%)	Lycopene content (mg kg^{-1} fresh weight)
LLL	0.40	114
LLH	0.43	109
LHL	0.44	100
LHH	0.46	103
HLL	0.40	99
HLH	0.43	101
HHL	0.41	114
HHH	0.44	113
SE	< 0.01	4
p-value	*ns*	*ns*
Contrasts		
LLL *vs.* HHH	*ns*	*ns*
*xx*L *vs. xx*H	*ns*	*ns*
*x*LL *vs. x*HH	*ns*	*ns*

[z] expressed as the equivalent mass of citric acid as a percent of total dry mass; citric acid is the predominant organic acid in ripe tomatoes

[ns] non-significant at $p < 0.10$

The effect of fertility regime on lycopene content was also not significant (Table 2.18). Across treatments, lycopene content averaged approximately 107 mg kg^{-1} fresh weight. All contrasts of interest were not significant. Lycopene content was not significantly correlated to F_{INAdj}, nor was there any correlation to fruit K concentration at 92 DAT; other fruit minerals are not thought to be directly associated with fruit carotenoids.

2.2.4.5 Fruit Nutrient Concentrations

The overall effect of fertility regime on the concentration of N, P, K, Ca and Mg in fruit at 92 DAT was not significant (Table 2.19); across treatments, fruit concentrations averaged 3.0 %, 0.65 %, 4.9 %, 0.16 % and 0.29 % for each nutrient, respectively. Several contrasts were significant; with the exception of that for fruit K concentration (HHH resulted in greater fruit K than LLL fertility), the remaining contrasts reflected comparatively small differences in nutrient concentration. Fruit tissue concentrations at 92 DAT were not significantly correlated to total yield.

Table 2.19. Effect of fertility regime on N, P, K, Ca and Mg concentration (%) in fruit tissue at 92 DAT.

Fertility regime	Fruit tissue concentrations (%)				
	N	P	K	Ca	Mg
LLL	2.9	0.62	4.0	0.19	0.25
LLH	2.8	0.59	4.4	0.18	0.25
LHL	2.9	0.71	4.8	0.18	0.27
LHH	2.8	0.63	5.5	0.15	0.27
HLL	2.8	0.60	4.6	0.15	0.28
HLH	3.1	0.66	5.0	0.15	0.34
HHL	3.2	0.69	5.3	0.13	0.33
HHH	3.2	0.68	5.9	0.15	0.34
SE	0.07	0.01	0.18	< 0.01	0.01
p-value	*ns*	*ns*	*ns*	*ns*	*ns*
Contrasts					
LLL *vs.* HHH	*ns*	*ns*	**	*	*ns*
L*xx vs.* H*xx*	*ns*	*ns*	*ns*	**	*

^{ns}, *, ** non-significant at $p < 0.10$, or significant at $p < 0.10$ or 0.05, respectively

2.2.5 Nutrient Uptake

Nutrient uptake in leaf, stem and fruit tissue was calculated using the biomass and N, P and K concentration of each respective constituent; total uptake was then combined uptake into these three plant tissues. Root uptake could not be calculated because of previously mentioned difficulties in determining nutrient concentrations in this tissue. However, root uptake (as distinct from the process of absorption) is generally considered to constitute only a very small percentage of total nutrient accumulation in processing tomato (Ward, 1964). This primarily reflects the small contribution of roots to overall plant biomass at harvest.

Cumulative uptake of N, P and K was calculated at the end of each defined growth period. This approach provided a convenient basis on which results could be applied in the field, where from a practical stand-point growers would have some consistency in fertilizer applications (rather than a new regime every week). Because plant growth and subsequent fruit yield was largely determined according to fertility regime during the initial period, nutrient uptake appeared best matched to the grouped L*xx* and H*xx* treatments; given the limited number of replications per treatment, this also improved the overall accuracy of uptake estimates for maximum productivity.

2.2.5.1 Nitrogen Uptake

Seasonally, total N uptake increased under all treatments (Table 2.20). Nitrogen uptake was strongly correlated with total plant biomass ($p < 0.01$, r = 0.98); greater total biomass resulted in higher cumulative N uptake. Across periods, there was a consistent numerical trend towards greater total N uptake resulting from high initial fertility. However, the overall effect of treatment was only significant at 92 DAT. On this date, cumulative N uptake was greatest in plants that had received HHH fertility, and lowest in those that had received LLL, LHL and LHH fertility. Contrasts simplified the general trends observed at 92 DAT; both HHH and H*xx* fertility regimes resulted in significantly greater N uptake than LLL and L*xx* fertility, respectively. Seasonally, total N uptake was approximately 8.6 and 12.1 g plant^{-1} for the grouped L*xx* and H*xx* treatments, respectively; this was equivalent to field uptake in the above-ground constituents of approximately 191 and 269 kg N ha^{-1}, respectively. For maximum productivity (i.e. H*xx* fertility), the plant required approximately 2.7 kg N per megagram of fresh fruit yield.

Greater total uptake was the result of increased N accumulation in both vegetative (leaf and stem) and fruit tissues. However, across periods the percent of total plant N in either vegetative or fruit tissue was not significantly different between the L*xx* and H*xx* fertility regimes. Across treatments, vegetative uptake averaged 94, 60 and 41 % of total N accumulated at 43, 64 and 92 DAT, respectively; fruit uptake therefore accounted for 6, 40 and 59 % of total N accumulated, also respectively.

Individually, there remained a strong correlation between leaf, stem and fruit biomass and N uptake into each separate constituent ($p < 0.01$, r = 0.96, 0.98 and 0.98, respectively). Uptake of N into leaf and stem tissues largely stopped when vegetative

Table 2.20. Effect of fertility regime on cumulative N uptake (total, leaf, stem and fruit) at the end of each defined period of growth.

Fertility regime	Cumulative uptake at the end of each growth period (g N plant^{-1})											
	Total			Leaf			Stem			Fruit		
	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT
LLL	3.5	6.5	8.6 bc	2.5	2.3	2.3	0.8	1.1	1.0 c	0.2	3.1	5.3
LLH			9.6 abc			2.5			1.6 bc			5.5
LHL		7.9	8.0 c		2.9	1.4		1.7	1.1 c		3.3	5.5
LHH			8.2 bc			1.7			1.6 bc			4.9
HLL	4.7	9.0	11.8 abc	3.2	3.8	3.2	1.2	2.3	2.5 ab	0.3	2.9	6.1
HLH			12.0 ab			2.3			3.3 a			6.4
HHL		9.7	11.3 abc		3.8	1.9		2.3	2.6 ab		3.6	6.8
HHH			13.1 a			3.3			2.3 ab			7.5
SE	0.48	0.65	0.56	0.32	0.36	0.27	0.16	0.24	0.22	0.05	0.20	0.28
p-value	*ns*	*ns*	*	*ns*	*ns*	*ns*	*ns*	*ns*	**	*ns*	*ns*	*ns*
Contrasts												
LL *vs.* HH		*ns*			*ns*			*ns*			*ns*	
L*x vs.* H*x*		*ns*			*ns*			*ns*			*ns*	
LL*x vs.* LH*x*			*ns*			*ns*			*ns*			*ns*
HL*x vs.* HH*x*			*ns*			*ns*			*ns*			*ns*
LLL *vs.* HHH			**			*ns*			**			*
L*xx vs.* H*xx*			***			*ns*			***			**

ns, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

growth truncated mid-season. Across periods, the effect of fertility regime on leaf uptake was not significant. This was despite a trend towards greater leaf N uptake at both 43 and 64 DAT in plants that had initially received high fertility. Differences in leaf uptake at 92 DAT were confounded by variability in leaf biomass and also net redistribution of N to the fruit. The effect of fertility on stem N uptake was only significant at 92 DAT. Contrasts clarified the general response to fertility at this time; greater stem N uptake was found with HHH and H*xx* fertility compared to LLL and L*xx* fertility, respectively. Stem N uptake in the HLH treatment appeared uncharacteristically high at 92 DAT, due primarily to high stem biomass. On no date was the overall effect of fertility on fruit N uptake significant. However, contrasts at 92 DAT also confirmed the trend towards higher N uptake with HHH and H*xx* fertility compared to LLL and L*xx* fertility, respectively.

2.2.5.2 Phosphorus Uptake

Seasonally, total P uptake increased under all treatments (Table 2.21). Phosphorus uptake was strongly correlated with total plant biomass ($p < 0.01$, $r = 0.98$); greater total biomass resulted in higher cumulative P uptake. Differences in total P uptake were comparatively small at 43 and 64 DAT. However, the overall effect of treatment on P uptake was significant at 92 DAT. On this date, cumulative P uptake was greatest in plants that had received HLH, HHH and HLL fertility, and lowest in those that had received LLL and LHL fertility. Contrasts simplified the general trends observed at 92 DAT; both HHH and H*xx* fertility regimes resulted in significantly greater P uptake than LLL and L*xx* fertility, respectively. Seasonally, total P uptake was approximately 2.1 and 3.0 g plant^{-1} for the grouped L*xx* and H*xx* treatments, respectively; this was equivalent to field uptake in the above-ground constituents of approximately 47 and 67 kg P ha^{-1}, respectively. For maximum productivity, the plant required approximately 0.67 kg P per megagram of fresh fruit yield.

Greater total uptake was the result of increased P accumulation in both vegetative and fruit tissues. However, across periods the percent of total plant P in either vegetative or fruit tissue was not significantly different between the L*xx* and H*xx* fertility regimes. Across treatments, vegetative uptake averaged 89, 66 and 48 % of total P accumulated at 43, 64 and 92 DAT, respectively; fruit uptake accounted for 11, 34 and 52 % of total P accumulated, also respectively.

Table 2.21. Effect of fertility regime on cumulative P uptake (total, leaf, stem and fruit) at the end of each defined period of growth.

Fertility regime	Cumulative uptake at the end of each growth period (g P plant^{-1})											
	Total			Leaf			Stem			Fruit		
	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT
LLL	0.9	1.8	2.0 c	0.5	0.7	0.5	0.3	0.4	0.4 c	0.1	0.7	1.1
LLH			2.4 abc			0.6			0.6 bc			1.2
LHL		2.0	2.0 c		0.7	0.3		0.6	0.4 c		0.7	1.3
LHH			2.1 bc			0.4			0.6 bc			1.1
HLL	1.0	2.1	3.0 ab	0.6	0.8	0.8	0.3	0.7	0.9 ab	0.1	0.6	1.3
HLH			3.1 a			0.6			1.1 a			1.4
HHL		2.2	2.7 abc		0.8	0.4		0.7	0.8 ab		0.7	1.5
HHH			3.0 a			0.7			0.7 bc			1.6
SE	0.06	0.14	0.13	0.03	0.08	0.06	0.03	0.06	0.06	0.01	0.04	0.05
p-value	*ns*	*ns*	*	*ns*	*ns*	*ns*	*ns*	*ns*	**	*ns*	*ns*	*ns*
Contrasts												
LL *vs.* HH		*ns*			*ns*			*ns*			*ns*	
L*x vs.* H*x*		*ns*			*ns*			*ns*			*ns*	
LL*x vs.* LH*x*			*ns*			*ns*			*ns*			*ns*
HL*x vs.* HH*x*			*ns*			*ns*			*			*ns*
LLL *vs.* HHH			**			*ns*			*			*
L*xx vs.* H*xx*			***			*ns*			***			**

^{ns}, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

Individually, there remained a strong correlation between leaf, stem and fruit biomass and P uptake into each separate constituent ($p < 0.01$, r = 0.96, 0.98 and 0.99, respectively. As with N, uptake of P into leaf and stem tissues largely stopped when vegetative growth truncated mid-season. Despite a small numerical trend towards greater leaf P uptake in plants that had initially received high fertility, on no date was this effect significant. The effect of fertility on stem P uptake was only significant at 92 DAT. Contrasts clarified the general response to fertility at this time; greater stem P uptake was found with HHH and H*xx* fertility compared to LLL and L*xx* fertility, respectively. The significant contrast between HL*x* and HH*x* fertility appeared to be of little practical relevance, and was influenced by the higher stem biomass (and therefore uptake) observed for the HLH treatment. On no date was the overall effect of fertility on fruit P uptake significant. However, contrasts at 92 DAT confirmed the trend towards higher P uptake with HHH and H*xx* fertility compared to LLL and L*xx* fertility, respectively.

2.2.5.3 Potassium Uptake

Seasonally, total K uptake increased under all treatments (Table 2.22). Potassium uptake was strongly correlated with total plant biomass ($p < 0.01$, r = 0.96); greater total biomass resulted in higher cumulative K uptake. Across periods, there was a consistent numerical trend towards greater total K uptake resulting from high initial fertility. However, the overall effect of treatment was only significant at 92 DAT. On this date, cumulative K uptake was greatest in plants that had received HHH, HHL, HLH and HLL fertility and lowest in those that had received LLL and LHL fertility. Contrasts simplified the general trends observed at 92 DAT; both HHH and H*xx* fertility regimes resulted in significantly greater K uptake than LLL and L*xx* fertility, respectively. Seasonally, total K uptake was approximately 13.8 and 20.8 g plant^{-1} for the grouped L*xx* and H*xx* treatments, respectively; this was equivalent to field uptake in the above-ground constituents of approximately 307 and 462 kg K ha^{-1}, respectively. For maximum productivity, the plant required approximately 4.7 kg K per megagram of fresh fruit yield. The ratio of total K : N uptake in the plant was approximately 1.7 : 1 under H*xx* fertility.

Greater total uptake was the result of increased K accumulation in both vegetative and fruit tissues. However, across periods the percent of total plant K in

Table 2.22. Effect of fertility regime on cumulative K uptake (total, leaf, stem and fruit) at the end of each defined period of growth.

Fertility regime	Cumulative uptake at the end of each growth period (g K plant^{-1})											
	Total			Leaf			Stem			Fruit		
	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT	43 DAT	64 DAT	92 DAT
LLL	4.4	9.0	12.4 c	2.7	2.6	2.7	1.4	1.8 b	2.3 c	0.3	4.7	7.4 b
LLH			14.9 bc			3.1			3.3 bc			8.5 b
LHL		11.8	12.9 c		4.0	1.8		2.5 ab	2.3 c		5.3	8.8 b
LHH			15.1 bc			2.6			3.1 bc			9.4 b
HLL	5.9	13.0	19.4 ab	3.6	5.8	5.0	2.0	3.1 ab	4.4 ab	0.4	4.1	10.0 b
HLH			20.0 ab			3.7			5.9 a			10.4 ab
HHL		14.6	19.3 ab		5.7	3.0		3.9 a	5.1 a		5.0	11.2 ab
HHH			24.4 ab			5.3			5.1 a			14.0 a
SE	0.54	1.08	1.08	0.30	0.63	0.41	0.21	0.34	0.35	0.05	0.39	0.57
p-value	*ns*	*ns*	**	*ns*	*ns*	*ns*	*ns*	*	***	*ns*	*ns*	*
Contrasts												
LL *vs.* HH		*ns*			*ns*			**			*ns*	
L*x vs.* H*x*		*ns*			*ns*			**			*ns*	
LL*x vs.* LH*x*			*ns*			*ns*			*ns*			*ns*
HL*x vs.* HH*x*			*ns*			*ns*			*ns*			*
LLL *vs.* HHH			***			*ns*			***			***
L*xx vs.* H*xx*			***			*			***			**

^{ns}, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

either vegetative or fruit tissue was not significantly different between the L*xx* and H*xx* fertility regimes. Across treatments, vegetative uptake averaged 93, 59 and 42 % of total K accumulated at 43, 64 and 92 DAT, respectively; fruit uptake accounted for 7, 41 and 58 % of total K accumulated, also respectively.

Individually, there remained a strong correlation between leaf, stem and fruit biomass and K uptake into each separate constituent ($p < 0.01$, r = 0.96, 0.91 and 0.97, respectively). As with N and P, uptake of K into leaf and stem tissues largely stopped when vegetative growth truncated mid-season. Across periods, the effect of fertility regime on leaf uptake was not significant. This was despite a trend towards greater leaf K uptake at both 43 and 64 DAT in plants that had initially received high fertility. Differences in leaf uptake at 92 DAT were confounded by variability in leaf biomass and also uptake of K not apparently associated with a critical growth requirement. However, at 92 DAT the contrast between the grouped L*xx* and H*xx* treatments was significant, with greater overall leaf K uptake with higher fertility. The effect of fertility on stem K uptake was significant at both 64 and 92 DAT. On both dates, contrasts simplified the general response to fertility; HHH and H*xx* treatments resulted in greater stem K uptake than LLL and L*xx* treatments, respectively. As with both N and P, high stem biomass at 92 DAT inflated stem K uptake for the HLH treatment. The effect of fertility regime on fruit uptake was only significant at 92 DAT. Contrasts confirmed that HHH and H*xx* fertility resulted in greater fruit K uptake than LLL and L*xx* fertility, respectively. The significant contrast between HL*x* and HH*x* fertility appeared to be of little practical relevance, driven primarily by very high K uptake under the HHH treatment.

2.3 Discussion

2.3.1 Effect of Fertility on Plant Biomass and Growth

High fertility during the initial period of growth increased the vegetative framework established. This difference in early vegetative growth largely determined subsequent yield outcomes. Fruit biomass was maximized with high initial fertility, primarily due to greater fruit number. Improved fruit number likely resulted from greater assimilate supply in plants that established larger leaf canopies; the main source of assimilates for fruit growth come from the leaf (Ho and Hewitt, 1986). This

appeared supported by the positive correlation between fruit yield and leaf area at the end of the first period of growth. These observations under aeroponic conditions were consistent to those made in the field; Colla *et al.* (1999) found that higher fertility resulted in a larger leaf canopy, which increased flowering, fruit number and subsequent fruit yield.

The relationship between fruit yield and assimilate capacity reflected the growth habit in processing tomato. Determinate cultivars have been bred to flower and set fruit over a short period of time (Atherton and Harris, 1986). Whilst this maximizes the yield of ripe fruit during once-over destructive harvesting, plants rarely have excess assimilate supply (Stevens, 1976). Because assimilates are preferentially directed to developing fruit (Ho, 1984; Wardlaw, 1990), when demand equals or exceeds supply not only does new vegetative growth stop, but later-setting flowers may abort (reducing fruit number). This phenomenon appears to be reflected in the fact that the majority of fruit yield is carried on earlier rather than later flower trusses (Julian, 1990; Renquist and Reid, 1998). Not surprisingly then, reinstating adequate fertility after vegetative growth had stopped and fruit number had been determined did not improve yield. A complete discussion of fruit yield parameters is provided in Section 2.3.3.

Greater accumulation of vegetative biomass with high initial fertility was attributed to an increased RGR in plants. Although this difference was comparatively small, it nonetheless was consistent with the overall increase in plant biomass. Growth rates of plants during this initial phase of vegetative development were lower than reported previously under N.Z. conditions; Pan *et al.* (1999) found that during the first 8 weeks after field transplanting RGR averaged approximately 1.4 g g^{-1} $week^{-1}$; under aeroponics, this rate was closer to 0.8 g g^{-1} $week^{-1}$. This in part reflected the omission of biomass gain during the first 15 DAT in aeroponics (the initial treatment period was between 16-43 DAT). The relative gain per unit of established plant biomass is greatest early in the season and declines thereafter. The difference in RGR may have also reflected solar radiation levels under glass, which were most likely lower than in the field; plant growth rates are strongly linked to radiation interception (Bruggink and Heuvelink, 1987). In a well maintained modern glasshouse, transmittance may only be reduced by 10-15 %, while in older glasshouses with greater structural interferences this reduction may be closer to 20-30 % (T.K. Hartz, personal communication). No measurements of solar radiation levels inside the glasshouse were made during this experiment.

Higher RGR was itself related to a higher LAR early in the season. These observations were consistent with the larger leaf area that developed with high initial fertility. Greater leaf area is thought to improve radiation interception and therefore photosynthetic activity (Greenwood, 2001; Sinclair and Horie, 1989; Tei *et al.*, 2002); it is through the process of photosynthesis that new assimilates are made for continued growth and development. These findings under aeroponics were similar to those reported in the field by Cavero *et al.* (1999) and Pan *et al.* (1999); both found that increased growth was primarily the result of a higher LAR.

Early-season LAR dynamics appeared strongly related to the N status of plants; low initial fertility resulted in a mild N deficiency when compared to established sufficiency norms (Hartz *et al.*, 1998). This deficiency was apparently growth-limiting to plants. A number of other studies have also documented the importance of adequate N availability (Adams, 1986, Cavero *et al.*, 1997, 1998; Cerne, 1990; Clark *et al.*, 1999; Colla *et al.*, 1999, 2001; Greenwood *et al.*, 1991); all reported that where N was limiting, plant growth declined resulting in lower fruit yields. The P and K status of plants appeared unrelated to differences in productivity under aeroponics. A complete discussion of leaf nutrient concentrations is provided Section 2.3.2.

2.3.2 Effect of Fertility on Leaf Nutrient Concentrations

2.3.2.1 Nitrogen Concentration

Seasonally, leaf N concentrations declined as assimilates were redistributed to developing fruit. This observation was consistent with previous studies conducted in the field (Colla *et al.*, 2001; Hartz *et al.*, 1998; Hochmuth *et al.*, 1991; Lorenz and Tyler, 1983; Tei *et al.*, 2002). Provided fruit demand does not result in extensive mining of nutrients from leaves early in the season (when vegetative growth is still important), management to allow for such a seasonal decline may reduce the need for mid- and late-season N applications. However, the ability to accurately predict such dynamics appears difficult; seasonal sufficiency norms have been developed as 'indicators' of overall crop nutrient status, although by the time a deficiency is detected, new growth may already have been limited.

In plants receiving low fertility during vegetative development, the concentration of N in leaf tissue fell increasingly below such sufficiency norms. Hartz

et al. (1998) suggested that maximum fruit yields are typically associated with leaf N concentrations during early bloom between 4.6-5.2 %; under aeroponics, tissue values were as low as 3.9 % with low initial fertility, appearing to be at least mildly deficient. These observations were consistent with reduced vegetative growth; N is a key constituent in chlorophyll and amino-acids, and therefore plays a critical role in leaf development (Mengel and Kirkby, 1987). Early N deficiency appeared to primarily reflect high demand for this nutrient during the intensive period of vegetative growth; the low fertility regime was unable to meet this demand. During fruit development and ripening, tissue N concentrations were above established sufficiency norms for all treatments. However, fruit yield dynamics had already been largely determined by this time.

2.3.2.2 Phosphorus Concentration

Seasonally, the concentration of P in leaf tissue remained very high for all treatments; values were well above established sufficiency norms recommended by Hartz *et al.* (1998) for maximum yield. Leaf P did not decline during fruit development, as has been commonly reported in the field (Hartz *et al.*, 1998; Hochmuth *et al.*, 1999; Lorenz and Tyler, 1983). This observation suggested that P availability in solution was sufficient for optimal growth, even under low fertility; irrespective of the concentration in solution, P was continuously available in highly-soluble plant forms. This is in contrast to many field settings, where soil dynamics largely control P availability; factors such as soil temperature, soil moisture, pH, salinity, compaction and aeration can all influence equilibrium reactions and therefore plant-available P (Brady, 1990).

This 'ready' availability throughout the season may also account for the high concentrations found under aeroponics. Typical leaf P concentrations in processing tomatoes range from 0.2-0.5 % (Hartz *et al.*, 1998), while under aeroponics concentrations consistently exceeded 0.7 %. Although Hochmuth *et al.* (1999) found early-season tissue P concentrations as high as 0.9 %, this appeared to not only reflect the very high fertilization rates used (up to 200 kg P ha^{-1}), but also the type of tomato grown (fresh market rather than processing); the two have dissimilar growth habits, and can therefore have differing nutrient requirements. There was no evidence to suggest that such high concentrations in plants grown under aeroponics reflected an actual

critical growth requirement. Differences in plant growth and fruit yield therefore appeared unrelated to P status in the plant.

2.3.2.3 Potassium Concentration

Seasonally, the concentration of K in leaf tissue remained very high for all treatments; values were well above established sufficiency norms recommended by Hartz *et al.* (1998). There was no evidence to suggest that differences in vegetative biomass and subsequent fruit yields were related to tissue K status. This indicated that K availability in solution was sufficient for optimal growth, even under low fertility.

For most treatments, leaf K concentration did not decline as fruit developed. This was in contrast to findings reported in the field, where remobilization of K to the developing fruit causes leaf concentrations to decrease (Besford and Maw, 1975; Hartz *et al.*, 1998, 1999, 2005; Pan *et al.*, 1999; Widders and Lorenz, 1982). In some treatments (particularly those receiving high late fertility), leaf K concentrations actually increased as fruit developed and ripened. This increase likely reflected luxury absorption of K due to its higher availability in solution rather than an actual plant demand; fruit yields were determined before such increases. A number of crops including tomato are known to continue to absorb K well in excess of critical requirements (Bartholomew and Janssen, 1929; Brady, 1990; Fisher *et al.*, 2002; Pan *et al.*, 1999; Pujos and Morard, 1997); while it does not typically result in K toxicity, it may overestimate plant requirements for this nutrient.

2.3.3 Effect of Fertility on Fruit Yield and Quality

2.3.3.1 Total, Marketable and Blossom-end Rot Fruit Yield

Fruit yields were greatest with high initial fertility. Higher yield was due to greater fruit number rather than mean individual fruit mass. Increased fruit number was previously attributed to greater assimilate capacity in plants receiving high initial fertility, although no measurements were made to distinguish whether this effect was related to increased flower number and/or an improvement in the percent of flowers that successfully set. Colla *et al.* (1999) suggested the former, reporting that flower number per unit area increased with higher fertility; subsequent fruit number per unit area

increased by a similar amount. Importantly, fruit rots (excluding BER) remained a very small constituent of yield (< 1 % across treatments). This confirmed that differences in fruit number were not likely due to fruit that had disintegrated and were not otherwise counted (if this were problematic, rots in general would have been higher). Marketable yields were low for all treatments because the final harvest occurred before full maturity. However, because high initial fertility did not increase fruit culls nor did it cause a significant delay in crop maturity, maximizing total yield would therefore also have maximized marketable yield.

Blossom-end rot incidence was high across treatments. This apparently reflected the glasshouse production environment. Higher temperatures may have promoted rapid cell expansion and fruit growth, while elevated humidity likely reduced transpiration and water movement (with dissolved Ca) into developing fruit; both of these events have been previously associated with localized Ca deficiency at the distal-end of fruit, which has resulted in greater BER (Adams and Ho, 1992; Paiva *et al.*, 1998). Blossom-end rot levels in the field are typically much lower, and more commonly aggravated by intermittent water stress rather than low soil Ca availability; such water stress did not appear related to BER incidence under aeroponics, because plant roots received continual misting.

Importantly, there was no evidence to suggest that high fertility caused greater BER. The incidence of this disorder was in fact further aggravated under low fertility, particularly during the initial period. Tissue Ca concentrations in early developing fruit grown under low fertility were similar to those suggested by Grierson and Kader (1986) to cause an increase in BER symptoms (< 0.08 % Ca). This apparently reflected low Ca availability in solution. Massey *et al.* (1984) suggested that BER incidence increased with solution concentrations below 70 mg L^{-1} Ca; under aeroponics, the low fertility regime supplied only 60 mg L^{-1} Ca. All nutrients ratios were otherwise considered to be appropriately balanced for successful greenhouse production (Tregidga *et al.*, 1986).

2.3.3.2 Fruit Soluble Solids

Across treatments, fruit SSC was low; high SSC (> 5.0 °Brix) is desirable, as it improves paste yield and overall processing efficiency (Linden, 2004). Renquist and Reid (1998) and Dadomo *et al.* (1994b) both reported high SSC for 'Cannery Row' at maturity (5.4-6.3 °Brix), indicating a good SSC potential in this variety. High yields did

not appear to cause low fruit SSC observed under aeroponics; this phenomenon has been previously reported by Dumas *et al.* (1994).

Poor SSC therefore apparently reflected an earlier than ideal harvest (before full maturity) and also a lack of significant osmotic stress during fruit ripening. Late-season water stresses are commonly imposed in the field to increase SSC levels (Cahn *et al.*, 2001; Calado *et al.*, 1990; Lowengart-Aycicegi *et al.*, 1999; May *et al.*, 1990; May and Gonzales, 1999; Murray, 1999; Renquist and Reid, 2001), while in glasshouse culture high solution conductivity often achieves the same result (Cuartero and Fernández-Munoz, 1999; Ehret and Ho, 1986; Ho *et al.*, 1987; Sakamoto *et al.*, 1999). Under aeroponics, plants received continual misting of solutions directly onto the root surface, effectively eliminating the potential for controlled water deficits. Roots had no surrounding medium to absorb water from, so a water cutback or cutoff would have almost certainly killed the plants. Similarly, many studies that have found large improvements in fruit SSC by manipulating solution conductivity have done so at levels considerably greater (> 8 dS m^{-1}) than the high treatment used under aeroponics (2 dS m^{-1}). Whilst improving fruit quality, solution conductivities above 2.5 dS m^{-1} can reduce tomato growth and therefore yield (Maas, 1986).

It was unclear whether the small improvement in SSC with high fertility (particularly when supplied during fruit ripening) was the result of modestly higher conductivity (0.7 *vs.* 2.0 dS m^{-1}) or higher K availability as suggested by Lachover (1972). Although higher fruit K concentration was associated with fruit SSC, this may have simply reflected its elevated availability in solution (as noted, K is known for luxury uptake). Also, the improvement in fruit SSC per increase in fruit K concentration was very small; to have any notable impact on fruit quality, the increase in fruit K concentration required appeared not only uneconomical under field conditions, but also impractical. Applied K can be fixed at large quantities in many agricultural soils (Cassman *et al.*, 1990).

Although K fertility is undoubtedly related to other fruit quality factors such as internal and external blotchy ripening (Ozbun *et al.*, 1967; Picha and Hall, 1981) and yellow shoulder (Hartz *et al.*, 2001, 2005), the effectiveness of high fertility as fruit ripened appeared poor; plant nutrient demand after most growth stopped was low, and fruit yield was not improved by high late-season fertility. In the field, achieving high SSC therefore appears best addressed by late-season irrigation practices; the effect of such techniques is summarized in Chapter 4.

2.3.3.3 Brix Yield

Brix yields were low across treatments because of poor SSC (< 5.0 °Brix) and low marketable yields. Renquist and Reid (1998) reported high yields and fruit SSC in 'Cannery Row', with an overall productivity close to 6 Mg Brix solids ha^{-1}; the commercial norm is at least 5 Mg Brix solids ha^{-1} (based on a yield of 100 Mg ha^{-1} and fruit SSC of 5.0 °Brix). The adjustment made to marketable yields to reflect a 'typical' commercial maturity increased Brix yields, but levels were still below 5 Mg Brix solids ha^{-1}; no correction could be made for fruit SSC.

Despite being low, Brix yields were maximized with high initial fertility. This was consistent with improved yield productivity, and to a lesser extent higher fruit SSC. These findings were similar to those made in the field by Colla *et al.* (1999), who concluded that Brix yields were maximized with high N applications rates compared to plants that received no fertilizer; this was due to both higher yield and fruit SSC. The strategy then of maximizing early growth for high yield appeared critical in maximizing Brix yield outcomes. Nutrient deficiencies during vegetative growth and fruit development not only have the potential to decrease yield, but may also reduce leaf area and therefore assimilate capacity of the plant, potentially lowering fruit SSC.

2.3.3.4 Fruit Titratable Acidity

High late-season fertility numerically increased titratable acidity of fruit, although this improvement was small. Similar increases with either high fertility or high conductivity have been reported elsewhere (Colla *et al.*, 1999, 2001; Cuartero and Fernández-Munoz, 1999; Mitchell *et al.*, 1991a, b). A number of researchers have suggested that greater K availability increases fruit TA (Adams *et al.*, 1978; Carangal *et al.*, 1954; Davies, 1964; Davies and Winsor, 1967; Stevens, 1972). The two were not directly correlated under aeroponics, despite generally greater fruit K concentrations with increasing fertility. However, the positive correlation between the adjusted fertility index and TA may have reflected K availability rather than overall solution conductivity; K availability increased at a rate directly proportional to this index (i.e. a higher index provided high K concentration in solution for a longer duration of fruit development and ripening).

Whilst there appears to be some potential to favourably influence fruit TA with late-season fertility, it does not represent a practical field option. Under controlled glasshouse conditions it is possible to manipulate the conductivity or fertility of a small soil volume (i.e. pot) or solution with relative ease and affordability; in the field however, fertilizer applications required to improve fruit quality often far exceed that expected for agronomic yield response. A similar observation was made by Hartz *et al.* (2005); although the incidence of the colour disorder yellow shoulder was reduced with higher K fertility, without a yield increase such applications were considered uneconomical. Because there is no price premium offered for fruit with high TA, there is little incentive to apply fertilizer at rates above those required for maximum yield. Furthermore, unlike fresh market tomatoes, processed tomato products can be supplemented with citric acid if levels are too low. It would also appear that TA is influenced by other factors at least equally, if not more so than soil fertility; these may include fruit age, cultivar selection and the production environment (Colla *et al.*, 1999, 2001; Davies and Hobson, 1981; Davies and Winsor, 1969).

2.3.3.5 Fruit Lycopene Content

There was no effect of fertility regime on the lycopene content of ripe fruit. Levels were comparable to those reported for processing tomatoes grown in the field (Barrett and Anthon, 2001; López *et al.* 2001). Some studies have suggested a positive link between K fertility and lycopene content (Amable and Sinnadurai, 1977; Flores *et al.*, 2004; Trudel and Ozbun, 1970, 1971), although under aeroponics the two were not correlated. This observation may have been influenced by high fruit K concentrations, which averaged 4.9 % across treatments; typical fruit K concentrations are more commonly in the range of 4.0-4.5 % (Hartz *et al.*, 1999).

There was little evidence supporting the use of high late-season K fertility to improve lycopene content. The best grower option still remains cultivar selection; Barrett and Anthon (2001) reported that some commercial cultivars have almost double the lycopene content of others. Furthermore, while fruit colour and colour uniformity are important quality attributes for processing, they are not entirely analogous to lycopene content; therefore, achieving acceptable and uniform colour is the pre-requisite rather than achieving high lycopene content per se. In addition to cultivar

selection, scheduling harvesting for when the majority of fruit are ripe (i.e. < 5 % greens) commonly achieves acceptable fruit colour.

2.3.3.6 Fruit Nutrient Concentrations

The concentration of N, P and Mg in fruit at 92 DAT appeared to be largely inconsequential; these nutrients were not correlated to fruit quality variables of interest (SSC, TA or lycopene content). Despite its purported association with fruit quality (Usherwood, 1985), K concentration in fruit was only weakly correlated to SSC, and not directly correlated to TA or lycopene content. Higher fruit K concentrations therefore appeared to largely reflect overall availability in treatment solutions. Although Ca levels in early-developing fruit were correlated with BER incidence, by 92 DAT such concentration differences had disappeared; all fruit had tissue concentrations well above the 0.08 % Ca threshold thought to aggravate the symptom (Grierson and Kader, 1986). This observation was not surprising, because BER typically develops on the earliest fruit (Saure, 2001). Tissue sampling at 92 DAT for mineral analysis also excluded those fruit that were most severely affected by the disorder; additionally, BER is a localized deficiency at the distal end of fruit (Adams and Ho, 1993), whereas collected tissue was cut longitudinally from the whole-fruit (effectively eliminating any concentration gradient).

2.3.4 Effect of Fertility on Nutrient Uptake

Current fertilizer recommendations have been largely based on determinations made in the field, where supply of nutrients directly at the root surface can be limited by a number of production and environmental factors. Not all applied fertilizers in such field experiments may therefore be available to the plant, although they often become part of the overall fertilizer requirement suggested for maximum tomato yield and/or fruit quality. Aeroponic supply of nutrients effectively eliminated such constraints by optimising the root environment for growth; nutrient uptake as determined using this system may therefore represent the most appropriate measure of plant demand from which seasonal applications can be derived. Under aeroponics, nutrient uptake associated with the H*xx* treatment (the HLL, HLH, HHL and HHH treatments)

represented that closest to 'optimal' plant demand for maximum yield and to a lesser extent fruit quality.

Seasonal plant uptake of N, P and K was sigmoidal, closely following the pattern of biomass accumulation. Greatest nutrient uptake was therefore during the period of rapid fruit biomass accumulation (under aeroponics, this was approximately 36 to 80 DAT). Similar observations have been reported in the field (Dumas, 1990; Halbrooks and Wilcox, 1980; Wilcox, 1993); despite differences in cultivars, growth patterns, and growing environments, all found that nutrient uptake was greatest during fruit growth. Matching nutrient supply more closely with plant demand is an important step in improving fertilizer efficiency in the field (Dumas, 1990; Hartz and Hochmuth, 1996; Stark *et al.*, 1983). Because the concentration of nutrients in surface runoff and leachate is directly correlated with their availability in the soil (Blackmer, 1987; Hartz and Johnstone, 2005; McDowell and Sharpley, 2001; Sharpley, 1995, 1997), reducing supply during periods when demand is low will also reduce the potential for environmental loss.

Although adequate fertility is still required for full vegetative growth, plant nutrient demand during this phase is invariably lower than during fruit growth. Where practical, fertilizer application should therefore be concentrated as fruit develop. However, in conventionally-managed fields it is difficult to side-dress fertilizers later than approximately 60 days after emergence without causing extensive root and vine damage and possibly reducing yields (banding fertilizers by tractor shanks requires 'open' bed-tops).

One option currently practiced is to water-run fertilizers (particularly N) with furrow irrigation, although the efficiency of this practice is directly related to the uniformity and efficiency of irrigation. In fields where irrigation uniformity and efficiency is poor due to slow infiltration rates or excessive slope, this practice may not evenly distribute nutrients. The use of drip irrigation technology offers a more effective alternative to match supply with crop uptake, free from many of the cultural constraints that characterize other production systems (Hartz and Hochmuth, 1996). Drip fertigation also enables the delivery of fertilizers directly to the active root-zone, which is typically confined to the region wetted by the drip tape. Improving the efficiency and timeliness of such applications may reduce the need for high fertilizer rates.

Seasonal plant nutrient uptake for high fruit yield (> 90 Mg ha^{-1}) was equal to 12.1, 3.0 and 20.8 g $plant^{-1}$ for N, P and K, respectively; this was equivalent to

approximately 270, 64 and 460 kg ha^{-1}, respectively. Plant N uptake was similar to fertilizer applications made in high-yielding commercial fields; growers commonly apply between 140-280 kg N ha^{-1} (Hartz and Miyao, 1997; Krusekopf *et al.*, 2002). Although Halbrooks and Wilcox (1980) found lower N uptake per plant (9.4 g N $plant^{-1}$) than under aeroponics, much of this disparity appeared related to differences in biomass productivity. In the field, Halbrooks and Wilcox (1980) reported a total biomass of 314 g $plant^{-1}$, while under aeroponics, the H*xx* treatment resulted in a total biomass of approximately 416 g $plants^{-1}$. Adjusted for biomass, the percent of N per unit of dry plant biomass were similar (approximately 3 % N).

Plant P and K uptake were above typical fertilizer application levels. Although aeroponic culture provided the ideal root environment for plant growth and allowed manipulation of fertility directly at the root surface, the interpretation of nutrient uptake results obtained from this method appeared confounded by its own unique limitations. All nutrients were supplied in highly absorbable forms, so although nutrients varied in concentration, they were readily available. In this system there was apparently luxury uptake of both P and K. Eymar *et al.* (2001) concluded similarly, suggesting that in an ideal growing environment (where water and nutrients are not limiting and roots are healthy) nutrients can continue to accumulate in plant tissue beyond levels normally expected or required for growth.

Even adjusted for differences in biomass productivity, P and K uptake determined by aeroponics was still greater than that suggested by Halbrooks and Wilcox (1980); in the field, they found P and K uptake was 1.2 and 14.2 g $plant^{-1}$, respectively. Differences in tissue concentrations reflected the greater P and K uptake per unit of plant biomass under aeroponic conditions. Under aeroponics, the percent of P and K per unit of dry plant biomass was approximately 0.72 % and 5.0 %, respectively, while Halbrooks and Wilcox (1980) found approximately 0.38 % and 4.5 %, respectively. Although P uptake for high yield under aeroponics (67 kg P ha^{-1}) was not greatly dissimilar to commercial application norms (30-60 kg P ha^{-1}; Hartz and Miyao, 1997), many growers supply P at such high rates as an 'insurance' for early growth. It is early-season P status which is often most critical to successful growth (Strand, 1998), particularly in fields that are planted in spring when low soil temperatures can greatly reduce native P availability (Johnstone *et al.*, 2005a).

By comparison, current grower K applications (< 110 kg K ha^{-1}; Hartz and Miyao, 1997) rely on a large amount of plant K being supplied by the soil; plant K

demand often exceeds 300 kg K ha^{-1} (Widders and Lorenz, 1979). Although K accumulation by tomato is greater than N accumulation, the K : N ratio is typically 1.5 : 1 (Adams, 1986). In this study, H*xx* fertility had a ratio closer to 1.7 : 1. Plant P and K demand for maximum fruit yield as determined by aeroponics may therefore have overestimated that typical in the field environment. Field-testing is required to validate the necessity of such high applications under normal production conditions.

CHAPTER 3: 1999-2000 Field Nutrition Trial

A field experiment was conducted at the Fruit Crops Unit (long. 175° 37'E; lat. 40° 23'S), Massey University, Palmerston North, during the summer growing season of 1999-2000. The aim was to evaluate under field conditions nutrient uptake results that had been determined previously using aeroponic culture; based on this prior study, plant nutrient uptake for maximum fruit yield and quality was quantified. Closely matching supply with plant demand was tested as a means of maintaining high yield in processing tomato while improving fertilizer efficiency (applying nutrients continuously throughout the season is thought to be more efficient than single applications). Drip fertigation was selected as the most effective and practical means to supply nutrients to plants in small but regular amounts. Drip also offers the ability to more closely regulate irrigation. However, the influence of water supply on fruit yield and quality was considered in a separate series of experiments (Chapter 4).

3.1 Materials and Methods

3.1.1 Experimental Site

The experimental site was selected in Palmerston North because of proximity to the University; although most commercial production in N.Z. occurs in the Hawkes Bay, the continuous fertigation required for this trial made such a location impractical. Palmerston North has a temperate climate with warm, windy summers and cool, moist winters (Burgess, 1988). Daily meteorological data for pan evaporation, air and soil temperatures and rainfall were collated from the nearest weather station (AgResearch Grasslands Centre); this station was less than 1 km from the Fruit Crops Unit. A full summary of climate data for the 1999-2000 season is provided in Appendix II.

Soil type was a *Manawatu sandy loam* (mixed, mesic, Dystric Eutrochrept). The soil was formed on loamy alluvium over gravels, characterized with moderate fertility and high permeability. The field had recently been converted from a long-term apple orchard. A representative soil sample was collected before planting (0-30 cm depth). The sample was air-dried before being ground to pass through a 2 mm screen. Soil pH was determined potentiometrically by pH electrode on a 1:2 (v/v) soil:water slurry (Blakemore *et al.*, 1987). Available N was determined colorimetrically following

extraction with 2 M potassium chloride (Hinds and Lowe, 1980). Bicarbonate-extractable P was determined using the Olsen method for available P (Olsen and Sommers, 1982). Exchangeable cations (X-K, X-Ca, X-Mg and X-Na) were extracted using 1 M neutral ammonium acetate (Thomas, 1982); determination of X-K and X-Na was by atomic emission and X-Ca and X-Mg by atomic absorption. Soil fertility is summarized in Table 3.1.

Table 3.1. Soil fertility status of the top 30 cm depth.

Fertility analysis	Level found	Nutrient status [z]
pH	6.2	medium
Olsen P (mg kg^{-1})	80	high
Available N (kg ha^{-1})	115	medium
Exchangeable K (cmol kg^{-1})	0.41	low
Exchangeable Ca (cmol kg^{-1})	9.2	medium
Exchangeable Mg (cmol kg^{-1})	1.39	medium
Exchangeable Na (cmol kg^{-1})	0.08	medium

[z] as determined by a commerical laboratory

3.1.2 Production Details

The hybrid cultivars 'Morse' and 'H225' were used in this study (seed of 'Cannery Row' was not available); both were selected as popular N.Z. standards. 'Morse' was considered to be most similar to 'Cannery Row'. Seed was supplied by Heinz Wattie's Ltd. (Hawkes Bay, N.Z.). Seed was sown and seedlings raised in a greenhouse. Four weeks prior to transplanting, seedlings were hardened in an outdoor shade house. Plants were liquid fed as required using a solution containing 100, 34 and 100 mg L^{-1} of N, P and K, respectively. Uncharacteristically high summer rainfall during November delayed planting; standard bed preparation techniques were made after the soil had dried out sufficiently. A rotary-hoe was used to form slightly-raised 1.5 m wide beds, although these settled with heavy rainfall.

Transplants were hand-planted into single rows with in-row spacing of 30 cm; this was equivalent to a density of 22,222 plants ha^{-1} (Fig. 3.1a, b). Surface drip irrigation was used to establish transplants. All plants received a small liquid feed (equivalent to less than 1 kg ha^{-1} of N, P or K) immediately following planting, a common commercial practice when transplanting. Heavy rain and strong winds during the initial week after transplanting slowed early plant growth. Temperature sensors

were installed at 15 cm above- and below the soil surface in plant rows, with four replicates per height and depth. Measurements were recorded every 15 minutes by data-logger (Squirrel SQ, Grant Instruments, Dundee, UK). Heavy rainfall flooded the data-logger mid-season and site-specific data was lost. Important production and phenological dates are summarized in Table 3.2.

Table 3.2. Production and phenological dates, 1999-2000.

		Phenological stage		
Sown	*Transplanted*	*First flowering*	*First fruit set*	*First ripe fruit*
October 20	December 9	January 28	February 9	March 17

Control for broad-leaf weed species consisted of post-plant application with Sencor® (Bayer Crop Science Ltd.) at 0.67 kg a.i ha^{-1}. During the season regular in-row hand weeding was required. Weed control with Roundup® (Monsanto Co.) was also used carefully between rows early in the season (due to poor control with Sencor). Insecticide control for tomato fruit worm (*Helicoverpa armigera*) consisted of a single mid-season application with Attack® (Nufarm Ltd.) at 0.7 kg a.i ha^{-1}. Multiple early-, mid- and late-season fungicide applications were made alternating between Bravo® (Syngenta Crop Protection, Inc.) at 1.8 kg a.i ha^{-1} and Dithane® (DowAgro Science) at 1.5 kg a.i ha^{-1}. Heavy rainfall provided ideal conditions (free moisture, cool and humid after rain storms) for development of early blight (*Alternaria solani*) and late blight (*Phytophthora infestans*). High moisture availability also resulted in a large incidence of pathological rots as fruit ripened.

3.1.3 Experimental Design

Experimental design was a split-plot within a randomized complete block, with the main plot representing fertilizer treatment, the split-plot representing cultivar. The two cultivars used ('Morse' and 'H225') were chosen to represent early and mid crop maturities, respectively. Individual split-plots were one bed wide and 19.8 m long,

Fig. 3.1a. Early-season vegetative growth at 26 DAT.

Fig. 3.1b. Mid-season vegetative growth at 55 DAT.

and were replicated three times. Fertilizer treatments were initiated 10 DAT, corresponding to early vegetative growth. Phosphorus was incorporated preplant (the commercial norm); only a small quantity (10 kg P ha^{-1}) was applied to all treatments equally because of the very high Olsen-P test result, which was well above the typical agronomic threshold for processing tomato (12-15 mg kg^{-1} P; Hartz and Miyao, 1997).

Seasonal application rates of N and K were based on optimum uptake that had been determined previously under aeroponics for maximum yield and fruit quality (H*xx* fertility). Based on these results, plant demand was defined for each distinct period of growth (vegetative development, 10-55 DAT; fruit development, 56-90 DAT; fruit ripening, 91-120 DAT), and then divided over the duration of each period to provide a regular application amount. Fertigation was made 3 times per week (irrespective of rainfall), with the weekly application being split evenly across these events. Irrigation volume was determined using a standardized evapotranspiration loss of 5 mm per day adjusted for crop canopy development; all treatments received the same irrigation volume. Fertilizer rates evaluated included 0 (control), 0.5, 1.0, 1.5 and 2.0x the optimal plant nutrient uptake found under aeroponics. Details of N and K field applications are summarized in Table 3.3 for the optimal treatment (1.0x). Fertigated N and K (from ammonium nitrate and potassium nitrate) were injected into the irrigation stream by water-powered proportional injectors.

Table 3.3. Optimal N and K treatments (1.0x) applied during vegetative development, fruit development and fruit ripening.

Plant growth stage	Optimal nutrient supply [z]			
	Individual plants		Field basis [y]	
	N (g)	K (g)	N (kg ha^{-1})	K (kg ha^{-1})
Vegetative development (10-55 DAT)	4.7	6.0	104	133
Fruit development (56-90 DAT)	4.7	7.8	104	173
Fruit ripening (91-120 DAT)	2.7	7.0	60	156
Cumulative	**12.1**	**20.8**	**268**	**462**

[z] reflects optimum plant uptake for high yields (> 90 Mg ha^{-1}) as determined under aeroponics (H*xx* fertility); the remaining treatments were calculated as 0 (control), 0.5, 1.5 or 2.0x these rates

[y] calculated using a density of 22,222 plants ha^{-1}

3.1.4 Data Collection

3.1.4.1 Leaf Analysis

Leaf samples (YML tissue) were collected from each split-plot at 55, 74 and 99 DAT to document the N, P and K status of the crop; these dates corresponded approximately to early bloom, full bloom and early fruit ripening (10 % of fruit showing red colour), respectively, all of which have established tissue sufficiency norms (Hartz *et al.*, 1998). On each occasion, 15-20 leaves were removed per split-plot. Leaves were rinsed to remove any surface residues, then oven dried at 65 °C for 48 hours and ground to pass through a 0.5 mm screen. Total N, P and K concentrations were determined as previously described.

3.1.4.2 Destructive Whole-Plant Sampling

There was one destructive whole-plant harvest made 55 DAT, corresponding approximately to full vegetative development (leaf and stem growth largely stops after fruit development begins). On this date, 10 consecutive plants were destructively sampled from each split-plot. Total fresh plant biomass (above-ground) of all plants was recorded. Four plants were then randomly selected and separated into leaf and stem tissue and each component weighed; there was no fruit biomass at 55 DAT. Representative leaf and stem samples were subsequently collected and weighed. A sub-sample of leaf laminae was also collected and leaf area determined as previously described. Leaf and stem samples were then oven dried at 65 °C for 48 hours before being weighed dry and ground to pass a 0.5 mm screen. Ground tissues were analyzed for Total N, P and K concentrations as previously described. Root biomass was not sampled.

3.1.4.3 Fruit Yield and Quality Measurements

One destructive fruit harvest was made 130 DAT to determine the effect of fertilizer application rate on yield and quality parameters. Fruit harvests planned for later in the season (including a final harvest at commercial maturity, > 95 % ripe) were abandoned because unseasonably high summer rains resulted in a substantial incidence

of late blight and also increasingly large rot losses. At 130 DAT, all fruit within a representative 3 m section of each split-plot was hand-harvested and weighed to determine total yield. Fruit were sorted according to three categories, including marketable, green, and culls (including pathological rots and limited-use fruit). As expected, BER incidence in the field was negligible compared to aeroponics. Blight-affected fruit were not designated as culls, because its occurrence clearly overestimated that typical of commercial production. The number and mass of fruit in each category was recorded, and mean fruit mass calculated.

A sample of approximately 20-25 intact marketable fruit per split-plot was collected for mineral analysis. Fruit were cut longitudinally, weighed fresh and then oven dried at 65 ºC before being weighed dry. Samples were subsequently ground to pass through a 0.5 mm screen and analyzed for Total N, P and K as previously described. An additional 20-25 intact marketable fruit per split-plot were juiced and filtered (using cheese-cloth) before determining SSC by temperature-compensated refractometer.

3.1.5 Statistical Analysis

Experimental data were subjected to split-plot ANOVA tests using the SAS GLM procedure. SAS regression procedures were used to test the significance of linear and quadratic effects in describing plant responses to the quantitative fertilizer variable. Relevant log and arc-sine transformations were made where appropriate. A series of orthogonal contrasts were used to compare specific fertilizer treatments combinations. Correlation analysis was used to report positive and negative linear relationships between variables of interest.

3.2 Results

3.2.1 Leaf Nutrient Sampling

3.2.1.1 Nitrogen Concentration in YML Tissue

Seasonally, N concentration in YML tissue declined in all treatments (Table 3.4). On no date was there a significant interaction between treatment and cultivar.

Table 3.4. Effect of fertilizer application rate on YML N concentration (%) at early bloom, full bloom and early fruit ripening.

Fertilizer treatment	N concentration (%) in YML tissue [z]		
	Early bloom	Full bloom	Early ripening
0 (control)	4.1	3.9	3.4
0.5	4.4	4.1	3.7
1.0	4.6	4.4	4.0
1.5	4.9	4.6	4.1
2.0	5.0	4.7	4.1
Sufficiency levels [y]	***4.6 - 5.2***	***3.5 - 4.5***	***2.7 - 3.8***
Treatment x cultivar interaction	*ns*	*ns*	*ns*
Linear effect	***	***	***
Quadratic effect	***	***	***
Contrasts			
Control *vs.* applied fertilizer	***	***	***
Optimal (1.0) *vs.* low (0 + 0.5)	***	***	***
Optimal (1.0) *vs.* high (1.5 + 2.0)	***	**	*ns*
Cultivar			
Morse	4.6	4.3	3.7
H225	4.6	4.3	3.9
p-value	*ns*	*ns*	*

[z] early bloom, full bloom and early ripening (10 % of fruit showing red colour) corresponded to 55, 74 and 99 DAT, respectively

[y] sufficiency levels from Hartz *et al.* (1998)

[ns], *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively

Both linear and quadratic fertilizer effects were highly significant at early bloom, full bloom and early fruit ripening; on each date, the quadratic effect had a slightly higher coefficient of determination (r^2; a measure of goodness of fit) value. Across dates, N concentration in YML tissue began to plateau at the highest fertilizer rate. The optimal fertilizer rate (1.0x) generally resulted in tissue concentrations that were intermediate to lower and higher application rates. On all three dates the no fertilizer control had significantly lower tissue N values when compared directly against grouped fertilizer application (i.e. all rates of fertilizer). The remaining contrasts that were significant followed a similar trend; a greater level of fertilizer application resulted in higher tissue N concentration. YML N concentration at early bloom was below established sufficiency norms for both the no fertilizer control and 0.5x treatments. On the remaining dates, tissue N concentrations were interpreted as sufficient for plant growth. Cultivar had no effect on YML N concentration during early bloom and full

bloom. However, late in the season 'H225' had significantly higher tissue N concentration than 'Morse', presumably related to differences in cultivar maturity (N is typically redistributed from the leaf as fruit develop).

3.2.1.2 Phosphorus Concentration in YML Tissue

There was no P fertilizer treatment during the field study. This reflected the very high soil test P value at the experimental site (bicarbonate-extractable P was 80 mg kg^{-1}). As expected, there was no effect of N and K fertilizer application on YML P levels. Across treatments, P concentration declined seasonally, averaging 0.45, 0.39 and 0.33 % during early bloom, full bloom and early fruit ripening, respectively. On all dates, these values reflected tissue concentrations interpreted as sufficient. All contrasts were not significant. YML P concentrations were essentially identical for 'Morse' and 'H225'.

3.2.1.3 Potassium Concentration in YML Tissue

Seasonally, K concentration in YML tissue declined in all treatments (Table 3.5). On no date was there a significant interaction between treatment and cultivar. Both linear and quadratic fertilizer effects were highly significant at all growth stages; across dates, the quadratic response had a higher r^2 value. On all dates, K concentration in YML tissue had a notable plateau at the higher application rates. The no fertilizer control had consistently lower tissue K values when compared directly against grouped fertilizer application. The remaining contrasts that were significant followed a similar trend; a greater level of fertilizer application resulted in higher tissue K concentration. YML K concentration at all growth stages appeared to be above established sufficiency norms, even in the no fertilizer control. Cultivar had no effect on YML K concentration during early bloom and full bloom. However, late in the season 'H225' had significantly higher tissue K concentration than 'Morse'. As with N, this was presumably related to differences in cultivar maturity.

Table 3.5. Effect of fertilizer application rate on YML K concentration (%) at early bloom, full bloom and early fruit ripening.

	K concentration (%) in YML tissue [z]		
Fertilizer treatment	Early bloom	Full bloom	Early ripening
0 (control)	4.3	3.9	2.7
0.5	4.7	4.1	3.8
1.0	4.8	4.3	4.1
1.5	4.9	4.5	4.2
2.0	4.9	4.6	4.4
Sufficiency levels [y]	***2.2 - 3.5***	***1.6 - 4.1***	***0.8 - 2.0***
Treatment x cultivar interaction	*ns*	*ns*	*ns*
Linear effect	***	***	***
Quadratic effect	***	***	***
Contrasts			
Control *vs.* applied fertilizer	***	**	***
Optimal (1.0) *vs.* low (0 + 0.5)	**	*ns*	***
Optimal (1.0) *vs.* high (1.5 + 2.0)	*ns*	*ns*	*ns*
Cultivar			
Morse	4.7	4.2	3.6
H225	4.7	4.4	4.1
p-value	*ns*	*ns*	**

[z] early bloom, full bloom and early ripening (10 % of fruit showing red colour) corresponded to 55, 74 and 99 DAT, respectively

[y] sufficiency levels from Hartz *et al.* (1998)

[ns], **, *** non-significant at $p < 0.10$, or significant at $p < 0.05$ or 0.01, respectively

3.2.2 Destructive Whole-Plant Biomass Sampling

One destructive whole-plant sampling was made 55 DAT, corresponding approximately to flowering and early fruit set. Most vegetative development was thought to have occurred by this date; because of the determinate growth habit in processing tomato, there is generally little new 'structural' (leaf and stem) biomass developed once fruit sinks establish. Based on the previous aeroponic study, it also appeared that fruit yield was influenced most significantly by this period of early plant growth (i.e. once the vegetative framework was formed and fruit number established, yield outcomes were largely determined). As expected, there was no substantial fruit biomass at 55 DAT.

No variable had a significant interaction between treatment and cultivar. Total plant biomass and leaf biomass response to fertilizer application was significantly

described by both linear and quadratic effects (Table 3.6); in both instances, the quadratic response had higher r^2 values. Leaf biomass began to plateau more distinctly at the highest application rate than total biomass. For stem biomass, the linear response had a slightly higher r^2 value. Contrasts confirmed that fertilizer application increased all three biomass measures when compared collectively against the control treatment. Less than optimal fertility (no fertilizer control and 0.5x treatments) resulted in significantly lower total plant and leaf biomass when compared directly against the optimal treatment. There was no effect of fertilizer application rate on partitioning between the leaf and stem, across treatments representing approximately 70 and 30 % of total biomass at 55 DAT, respectively.

Table 3.6. Effect of fertilizer application rate on plant dry biomass (total, leaf and stem) and leaf area at 55 DAT.

Fertilizer treatment	Total biomass (g plant^{-1})	Leaf biomass (g plant^{-1})	Stem biomass (g plant^{-1})	Leaf area (cm^2 plant^{-1})
0 (control)	61	43	19	8240
0.5	72	52	20	10057
1.0	77	54	23	10477
1.5	83	59	24	11551
2.0	87	61	26	11960
Treatment x cultivar interaction	*ns*	*ns*	*ns*	*ns*
Linear effect	***	***	**	***
Quadratic effect	***	***	*	***
Contrasts				
Control *vs.* applied fertilizer	***	***	**	***
Optimal (1.0) *vs.* low (0 + 0.5)	*	*	*ns*	*ns*
Optimal (1.0) *vs.* high (1.5 + 2.0)	*ns*	*ns*	*ns*	*ns*
Cultivar				
Morse	69	49	20	9470
H225	83	58	25	11444
p-value	***	***	***	***

^{ns}, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively

The effect of cultivar on biomass measures (total, whole-leaf and stem) was strongly significant; in all instances 'H225' had greater biomass than 'Morse'. As with treatment, there was no substantial difference in relative biomass partitioning to the leaf and stem between cultivars. Across cultivars, total plant biomass was positively

correlated with N and K concentration in YML tissue at 55 DAT ($p < 0.01$, r = 0.57 and 0.56, respectively), but not P concentration.

Leaf area response to fertilizer application was also significantly described by both linear and quadratic effects; the quadratic response had a higher r^2 value, although again this difference was small. Leaf area began to plateau at the highest application rates. Fertilizer application increased leaf area when compared collectively against the control treatment. The remaining contrasts were not significant. As with plant biomass, the effect of cultivar on leaf area was highly significant; 'H225' had a larger leaf area than 'Morse'. Leaf area was strongly correlated with leaf biomass ($p < 0.01$, r = 0.89). Leaf area was also positively correlated with N and K concentration in YML tissue at 55 DAT ($p < 0.01$ and 0.02, r = 0.65 and 0.43, respectively), but not P concentration. Leaf area index (LAI, the proportion of leaf area per unit area of individual plant space) ranged from between 1.8 for the no fertilizer control to 2.7 for 2.0x the optimal fertilizer application rate; a higher index indicates improved vegetative cover, and may allow for greater interception of solar radiation (and therefore increased plant productivity).

3.2.3 Fruit Yield and Quality Measurements

Although the final harvest was not made at full commercial maturity (i.e. > 95 % ripe fruit), yield results did not appear to be greatly compromised. In a separate maturity experiment (using a glasshouse solely as a rain-shelter) conducted parallel to the field study, ripening rates (expressed as percent colour change per day) were established for 'Morse' and 'H225'. Using these ripening rates (both were approximately 2.5 % colour change per day) an estimation of expected commercial maturity was made for the control and 2.0x border treatments; 'Morse' would have required an extra 3-10 days to reach a 95 % ripe-stage of maturity (134-141 DAT), while 'H225' would have required an extra 11-20 days (142-151 DAT). Importantly, fruit set within the final six weeks do not typically mature by harvest; therefore, all fruit that would have contributed to commercial yields were established well in advance of the destructive fruit harvest at 130 DAT.

The effect of fertilizer application rate and cultivar on tomato yield and fruit quality is summarized in Table 3.7. No variable had a significant interaction between treatment and cultivar.

Table 3.7. Effect of fertilizer application rate on tomato yield and fruit at 130 DAT.

Fertilizer treatment	Total yield (Mg ha^{-1})	Marketable yield (Mg ha^{-1})	Soluble solids (°Brix)	Brix yield (Mg Brix solids ha^{-1})	Adjusted Brix yield [z] (Mg Brix solids ha^{-1})	% Ripe [y]
0 (control)	68	42	4.09	1.71	2.50	77
0.5	82	47	4.11	1.93	3.00	73
1.0	92	48	4.24	2.04	3.53	63
1.5	100	51	4.42	2.27	3.98	62
2.0	103	51	4.42	2.27	4.09	59
Treatment x cultivar interaction	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*
Linear effect	***	***	***	***	***	***
Quadratic effect	***	**	**	***	***	***
Contrasts						
Control *vs.* applied fertilizer	***	**	**	*	***	*ns*
Optimal (1.0) *vs.* low (0 + 0.5)	*	*ns*	*ns*	*ns*	**	*ns*
Optimal (1.0) *vs.* high (1.5 + 2.0)	*ns*	*ns*	**	*ns*	*ns*	*ns*
Cultivar						
Morse	78	51	4.34	2.22	3.04	79
H225	101	45	4.17	1.86	3.79	55
p-value	***	**	**	***	***	***

[z] adjusted Brix yield based on 90 % of total yield considered marketable

[y] ripe fruit included both marketable and cull constituents

^{ns}, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively

3.2.3.1 Total and Marketable Yield

Total and marketable yield response to fertilizer application was significantly described by both linear and quadratic effects (Table 3.7). However, in both instances, the quadratic response had a higher r^2 value. Total yield began to plateau more distinctly at the highest fertilizer application rates than marketable yield, presumably related to the fact that the final harvest occurred before full maturity (across treatments, marketable yield only averaged 54 % of total yield at 130 DAT). Total fruit yield was low (< 70 Mg ha^{-1}) in control plots that received no fertilizer. Fertilizer application significantly increased total fruit yield when compared collectively against the control treatment. Less than optimal fertility (control and 0.5x treatments) resulted in lower total yield when compared directly against the optimal treatment (1.0x). Higher total fruit yield was more strongly correlated to total fruit number than mean fruit mass ($p <$ 0.01, r = 0.92 and 0.79, respectively). The effect of fertilizer application on cultivar

was also significant; total yield was greatest for 'H225', reflecting both a larger number of fruit per plant and larger mean fruit mass. Significant quadratic regressions (p < 0.01) were fitted to total yield against fertilizer application for both 'Morse' and 'H225' (Fig. 3.2).

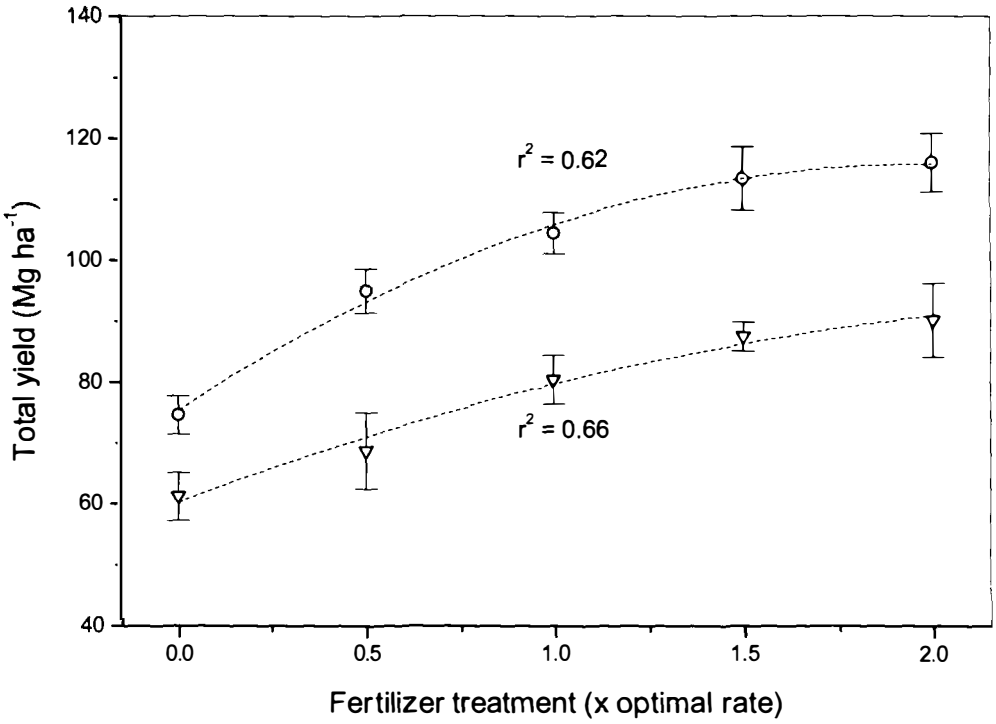


Fig. 3.2. Effect of fertilizer application rate on the total yield of 'Morse' and 'H225' at 130 DAT. Fertilizer treatments represented 0 (control), 0.5, 1.0, 1.5 and 2.0x the optimal fertilizer rate (268 kg N ha^{-1} and 462 kg K ha^{-1}). Treatment means are given ± standard error. Cultivars were 'Morse' (▽) and 'H225' (○). From replicated data, the equation of the fitted quadratic regression line (···) for 'Morse' was $y = 60 + 23.2x - 4.0x^2$ and for 'H225' $y = 75 + 40.8x - 10.3x^2$.

Total plant dry biomass at 55 DAT (comparable with full vegetative growth) was positively correlated with total fruit yield (p < 0.01, r = 0.64). Leaf area index at 55 DAT was also positively correlated with total yield (p < 0.01, r = 0.83); an index above approximately 2.3 was generally associated with fruit yields greater than 90 Mg ha^{-1} (an acceptable commercial benchmark). Total yield was positively correlated with N concentration in YML tissue during early bloom (p < 0.01, r = 0.63); tissue levels ≥ 4.6 % N (the minimum sufficiency value for this phase of growth) were associated with fruit yields above 90 Mg ha^{-1}. YML N concentration at full bloom and early fruit ripening was also associated with final fruit yield (r = 0.59 and 0.74, respectively); however, these correlations did not appear noteworthy, because both samplings occurred after most vegetative growth had stopped (it was vegetative growth during the

initial period that determined fruit number). Although YML K concentration at early bloom, full bloom and early fruit ripening was significantly correlated with total yield ($p < 0.05$, r = 0.41, 0.40 and 0.54, respectively), in all instances tissue K levels were above established sufficiency norms. YML P concentration was not correlated with yield outcomes.

The effect of fertilizer application on fruit culls was not significant. Across treatments, culls averaged approximately 10 %, although in some individual plots they were as high as 30 % (data not shown). Culled fruit were almost exclusively due to pathological rots, in particular water mold; this apparently reflected the very wet conditions in the field. Although not significant, culls were marginally higher for 'Morse' compared to 'H225' (12 and 9 %, respectively); this appeared related to the earlier maturity of 'Morse', as ripe fruit are more susceptible to rots (Strand, 1998).

3.2.3.2 Fruit Soluble Solids

Across treatments, SSC of marketable fruit was low, averaging < 4.5 °Brix (Table 3.7); as previously suggested, an acceptable target for fruit grown commercially is > 5.0 °Brix. Fruit SSC response to fertilizer application was significantly described by both linear and quadratic effects, although neither was superior to the other. Fertilizer application significantly improved fruit SSC when compared collectively against the control treatment. Similarly, above optimal fertility (1.5 and 2.0x treatments) resulted in higher SSC when contrasted directly to the optimal treatment. In both instances, the improvement in SSC was only modest.

Fruit SSC was significantly higher for 'Morse', although this difference was also comparatively small (< 0.2 °Brix). Fruit SSC was not significantly correlated to total yield; high yields can cause a 'dilution' of fruit SSC. Leaf area index (as an indicator of assimilate supply in plants) at 55 DAT was also not significantly correlated to subsequent SSC potential; this was despite a numerical trend towards higher SSC with larger early-season LAI values. Fruit SSC was not correlated with K concentration in fruit at 130 DAT.

3.2.3.3 Brix Yield and Adjusted Brix Yield

Across treatments Brix yields were low, averaging approximately 2 Mg Brix solids ha^{-1} (Table 3.7); as previously suggested the commercial norm is at least 5 Mg Brix solids ha^{-1}. This not only reflected the earlier than ideal harvest date (and therefore a low percent of marketable fruit), but also poor fruit SSC levels (< 4.5 °Brix). Despite this, Brix yield response to fertilizer application rate was still significantly described by linear and quadratic effects; the quadratic response had a slightly higher r^2 value. Brix yields appeared to plateau at the highest application rates. Fertilizer application significantly improved Brix yield outcomes when compared collectively against the control treatment. The remaining contrasts were not significant. Brix yield was more closely correlated with marketable yield than with fruit SSC ($p < 0.01$, r = 0.97 and 0.61, respectively). Brix yields were significantly higher for 'Morse' rather than 'H225'; however, this observation appeared to be overstated, as 'H225' had significantly higher total fruit yields but delayed maturity.

Because the final harvest occurred before fruit were fully ripe, an adjustment of Brix yield was made to reflect a typical field maturity; marketable yield was considered as 90 % of the total yield measured at 130 DAT (assuming 5 % greens and 5 % culls). Although higher, adjusted Brix yields still remained below 5 Mg Brix solids ha^{-1}. Similar statistical patterns were found to the original data. The effect of cultivar remained significant, although as expected, with the adjustment 'H225' had greater Brix yield outcomes than 'Morse' (because of higher total yield).

3.2.3.4 Percent Ripe Yield

Percent ripeness is an indicator of crop maturity; a lower value reflects fewer ripe fruit. As noted, the typical crop maturity at which commercial fields are harvested is approximately 95 % ripe fruit; this compared to only 67 % across treatments in the current study. Plans for destructive sampling later in the season were abandoned because of heavy summer rainfall and increasing late-blight pressure and fruit rot concerns. Ripe fruit included those that were either marketable or culls (culls were overwhelmingly ripe fruit). At 130 DAT, the percent of fruit that were ripe in response to fertilizer application rate was significantly described by linear and quadratic effects (Table 3.7); the quadratic response had a marginally higher r^2 value. The highest

fertilizer application rates resulted in the lowest percent of ripe fruit. However, all contrasts were not significant.

The percent of ripe fruit was significantly higher for 'Morse' rather than 'H225'. This difference was consistent with the growth patterns of the two cultivars ('Morse' is early-maturing, while 'H225' is mid-maturing). Percent ripe fruit was negatively correlated with YML N concentration at early boom, full bloom and early fruit ripening ($p < 0.05$, r = -0.39, -0.48 and -0.63, respectively). Although YML K concentration was also negatively correlated with percent ripeness on these dates, coefficients were consistently weaker.

3.2.3.5 Fruit Nutrient Concentrations

There was no interaction between treatment and cultivar for any fruit nutrient measured (Table 3.8).

Table 3.8. Effect of fertilizer application rate on the concentration of N, P and K (%) in fruit at 130 DAT.

	Fruit tissue concentrations (%)		
Fertilizer treatment	N	P	K
0 (control)	3.1	0.48	4.4
0.5	3.3	0.50	5.1
1.0	3.4	0.50	5.3
1.5	3.5	0.49	5.4
2.0	3.5	0.51	5.6
Treatment x cultivar interaction	*ns*	*ns*	*ns*
Linear effect	***	*ns*	***
Quadratic effect	**	*ns*	***
Contrasts			
Control *vs.* applied fertilizer	**	*ns*	***
Optimal (1.0) *vs.* low (0 + 0.5)	*ns*	*ns*	***
Optimal (1.0) *vs.* high (1.5 + 2.0)	*ns*	*ns*	*
Cultivar			
Morse	3.5	0.48	5.2
H225	3.2	0.51	5.1
p-value	***	*ns*	*

ns, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively

The effect of fertilizer application rate on both fruit N and K concentration was significantly described by linear and quadratic effects; in both instances, the quadratic response had a higher r^2 value. There was no effect of N and K fertilizer application on tissue P levels in fruit; across treatments, P concentration averaged approximately 0.50 %. Collectively, fertilizer application significantly improved fruit N and K concentrations when compared against the control treatment. Less than- and above-optimal fertility resulted in lower and higher fruit K concentrations when compared separately against the optimal treatment, respectively. All other contrasts were not significant. The concentration of N and K in fruit tissue was significantly greater in 'Morse' compared to 'H225'; this difference was however comparatively small. There was no effect of cultivar on fruit P concentration.

3.2.3.6 Nutrient Removal and Fertilizer Efficiency

Nutrient removal rates in the harvested fruit were calculated using an adjusted marketable yield (90 % of total yield at 130 DAT). Because the final harvest occurred before full maturity, this standardized all treatments to a comparable level of fruit ripeness. Based on adjusted marketable yields, the effect of fertilizer application rate on the removal of N, P and K in fruit was significantly described by linear and quadratic effects (Table 3.9); in all instances, the quadratic response had a marginally higher r^2 value. For all significant contrasts, a higher level of fertilizer application resulted in greater removal of N, P or K in marketable fruit. The effect of cultivar was also significant for each nutrient; in all instances, 'H225' had the greatest rate of removal (consistent with higher overall yields for this cultivar). Removal rates for N, P and K were strongly correlated with adjusted marketable yields ($p < 0.01$, r = 0.93, 0.89 and 0.94, respectively); although the concentration of each nutrient in fruit was correlated with removal, coefficients were weaker (r = 0.33, 0.67 and 0.56, respectively).

Fertilizer efficiency (F_e) was estimated only for N and K treatments; P was not applied differentially during the experiment. The F_e value was calculated as the mass of nutrient in marketable fruit (less that removed by the control which received no fertilizer application) expressed as a percent of the mass of fertilizer applied. To standardise for differences in maturity, the adjusted marketable yields for each treatment were used. For N, F_e values ranged from 22 – 12 % across the 0.5 and 2.0x treatments, respectively; recovery was also greater in 'H225' than 'Morse' (consistent

with higher fruit yields). Similar trends were observed for K; F_e values ranged from 20 – 13 % across the 0.5 and 2.0x treatments, respectively, with recovery also being greater in 'H225'. Efficiency values did not account for the mass of applied fertilizer that was essential in establishing the vegetative framework, but that was not redistributed to the fruit (i.e. that which is eventually returned to the soil as crop residue).

Table 3.9. Effect of fertilizer application rate on removal of N, P and K in marketable fruit at 130 DAT.

	Nutrient removal (kg ha^{-1}) in marketable fruit at 130 DAT[z]		
Fertilizer treatment	**N**	**P**	**K**
0 (control)	84	13	120
0.5	109	17	167
1.0	130	19	200
1.5	140	20	218
2.0	146	22	236
Treatment x cultivar interaction	*ns*	*ns*	*ns*
Linear effect	***	***	***
Quadratic effect	***	***	***
Contrasts			
Control *vs.* applied fertilizer	***	**	***
Optimal (1.0) *vs.* low (0 + 0.5)	***	*ns*	***
Optimal (1.0) *vs.* high (1.5 + 2.0)	*ns*	*ns*	*ns*
Cultivar			
Morse	112	15	166
H225	131	21	210
p-value	***	***	***

[z] calculated using adjusted marketable yields which were 90 % of total fruit yield

^{ns}, **, *** non-significant at $p < 0.10$, or significant at $p < 0.05$ or 0.01, respectively

3.3 Discussion

3.3.1 Effect of Fertilizer Application on Leaf Nutrient Concentrations

3.3.1.1 Nitrogen Concentration

Leaf N concentrations declined seasonally as assimilates were redistributed to developing fruit. This trend was similar to that observed under aeroponics, and is also

consistent with that commonly reported in the literature (Colla *et al.*, 2001; Hartz *et al.*, 1998; Lorenz and Tyler, 1983; Tei *et al.*, 2002). Optimal fertility and above resulted in tissue N values interpreted as sufficient for high yield (Hartz *et al.*, 1998). In plants receiving above optimal fertility, tissue N concentrations were not supra-optimal despite very large N applications of up to 540 kg N ha^{-1} (as much as double typical commercial applications; Hartz and Miyao, 1997); this suggested plant demand was not as high as these rates supplied. Tissue N concentration was low during early bloom in treatments receiving less than optimal fertility; tissue values appeared to be mildly deficient, and were comparable to concentrations found under aeroponics to reduce plant growth and fruit yields. However, late-season tissue N concentration in treatments receiving less than optimal fertility was not below sufficiency values. This suggested that N application after most active fruit growth has stopped was unnecessary.

3.3.1.2 Phosphorus Concentration

All treatments resulted in adequate tissue P status compared to established sufficiency norms (Hartz *et al.*, 1998). This apparently reflected the high soil test P value at the experimental site (80 mg kg^{-1} P); a bicarbonate-extractable value of > 15 mg kg^{-1} P is generally interpreted as sufficient for maximum yield (Hartz and Miyao, 1997). Leaf P concentration declined seasonally, as P was redistributed to fruit. This was in contrast to aeroponics (where tissue P levels remained high throughout the season), but consistent with prior field observations (Hartz *et al.*, 1998; Hochmuth *et al.*, 1999; Lorenz and Tyler, 1983). Tissue P concentrations were also considerably lower than found under aeroponics (0.7-0.8 % P), even at what was considered to be a high soil test P level. This confirmed that there was luxury uptake of P in the aeroponics experiment. As previously noted, while excessive P fertilization generally does not cause serious agronomic problems, it can be a significant contributor to P pollution of surface waterways (Pote *et al.*, 1996).

3.3.1.3 Potassium Concentration

All treatments resulted in adequate to high tissue K status compared to established sufficiency norms (Hartz *et al.*, 1998). Seasonal decline was observed in all treatments, even those supplying large amounts of fertilizer K; this reflected

redistribution of K to the fruit, and was consistent with prior studies (Besford and Maw, 1975; Hartz *et al.*, 1999, 2005; Pan *et al.*, 1999; Widders and Lorenz, 1982). It also suggested that K uptake by the roots could not match fruit demand during this active period of growth; fruit are the major sink for absorbed K (Adams, 1986). Although K application during fruit ripening resulted in greater leaf K concentrations, such applications were unnecessary for maximum yield and fruit quality. Even the control treatment which applied no K fertilizer resulted in tissue concentrations above sufficiency values. This suggested that K application after most active fruit growth has stopped was unnecessary. Field results confirmed that the high late-season tissue K concentrations (> 5.0 %) under aeroponics represented luxury levels; K uptake in these conditions therefore over-estimated actual plant demand.

3.3.2 Effect of Fertilizer Application on Whole-Plant Biomass

Plants receiving optimal fertility and above established the greatest total biomass and leaf area by flowering. The N status of plants was most important in accounting for these differences; plants with low biomass and small leaf area (the no fertilizer control and the 0.5x treatments) had leaf tissue N concentration below sufficiency norms at early bloom. The role of N in vegetative growth has been previously documented; when deficient, canopy development can be limited (Cavero *et al.*, 1999; Colla *et al.*, 1999, 2001; Pan *et al.*, 1999) and radiation interception and photosynthetic activity reduced (Greenwood, 2001; Sinclair and Horie, 1989; Tei *et al.*, 2002). The P and K status of plants were adequate for all treatments. The positive correlation between YML K concentration and plant biomass and leaf area appeared then to be largely coincidental, apparently reflecting increased K availability with increased N supply.

These findings were consistent to those made under aeroponics, and further reinforced the importance of establishing a strong vegetative framework early in the season for subsequent flowering and fruit development. Once vegetative growth stops and fruit number is determined, yield outcomes are largely set (i.e. only fruit size can be positively influenced). These results were consistent to commercial fertilizer trials conducted in the Hawkes Bay during 1994-95 (the major production region of N.Z.); conclusions from this work advised growers to maximize early growth in order to achieve a large vegetative framework for flowering (BASF, unpublished data).

3.3.3 Effect of Fertilizer Application on Fruit Yield and Quality

3.3.3.1 Total and Marketable Fruit Yield

High total fruit yield was achieved with treatments that supplied optimal fertility and above. Although application rates above optimal resulted in the numerically greater fruit yields, these were not statistically different to those achieved with the optimal treatment. Higher yield was due primarily to greater fruit number rather than mean fruit mass. Improved fruit number was associated with the larger vegetative frameworks established early in the season; this apparently reflected an improved assimilate capacity in plants. These findings were consistent to those made under aeroponics, and were also related to early-season N status in plants rather than to P or K.

Marketable yields were not maximized for any treatment; this reflected an early harvest date due to an increasing incidence of plant disease and fruit rots. Above-optimal fertility resulted in the lowest percent of total yield that was marketable. This was linked to high tissue N status which delayed maturity. Similar observations have been made by May and Gonzales (1994) and Nicklow and Downes (1971); both found larger green fruit yields within increasing N application rates. However, there was no effect of high fertility on fruit culls. If all treatments had been grown to commercial maturity, marketable yields would have been greatest in plants receiving optimal fertility and above. As expected, the incidence of BER was almost non-existent in the field compared to levels found under glasshouse aeroponic culture. This apparently reflected high moisture supply in the soil during fruit growth and development; intermittent water stress during this critical period is the most common cause of BER in the field.

Due to heavy summer rainfall and light-textured soil type, the likelihood of N (and possibly K) leaching out of the active root zone was high; plants were already receiving full replacement of ET by irrigation water (which was necessary to fertigate on nutrient treatments). Because fruit yields were comparable at application rates of optimal fertility and above, optimal fertility itself would most likely have been sufficient to maximize growth and subsequent yields under normal field conditions (i.e. a drier season). This was supported by the fact that typical grower N applications for high yields are considerably less than that for the above optimal treatments; the 2.0x

treatment supplied approximately 540 kg N ha^{-1}, while maximum grower applications do not commonly exceed 280 kg N ha^{-1}.

Fertilizer applications made during fruit ripening were not effective in increasing yield, as mean fruit mass was not greatly improved. Maximum yields therefore appeared attainable at rates equivalent to optimal plant uptake as determined for only the initial two periods of growth under aeroponics (vegetative and fruit development); at a density of 22,222 plants ha^{-1} this was equal to approximately 210 and 310 kg ha^{-1} of N and K, respectively. This type of N application was consistent with current grower applications (140-280 kg N ha^{-1}; Hartz and Miyao, 1997), although is still greater than estimates suggested by Krusekopf *et al.* (2002). Although K application amount appeared considerably higher than current grower levels (< 110 kg K ha^{-1}; Hartz and Miyao, 1997), it was comparable to a 'typical' plant requirement of approximately 300 kg K ha^{-1} as suggested by Widders and Lorenz (1979); the apparent disparity between grower supply and plant demand is balanced by high K supply from the soil.

3.3.3.2 Fruit Soluble Solids

Across treatments, low fruit SSC reflected high soil moisture availability during ripening and also a final harvest before full maturity; both factors can substantially reduce SSC outcomes. These observations were confirmed in a separate study that ran concurrently to the field trial (production details are provided by Nichols *et al.*, 2001); using a glasshouse solely as a rain-shelter, fruit SSC at commercial maturity was 5.6 and 5.0 °Brix for 'Morse' and 'H225', respectively (in the field, fruit SSC was consistently < 4.5 °Brix). This confirmed that low SSC was not inherently related to these two cultivars, but to the production environment in which they were grown.

Higher fertility resulted in greater fruit SSC. This improvement may have been associated with the larger plant canopies established with higher fertilizer rates; larger canopies often have improved assimilate capacity (SSC is in part reflective of dry matter content in fruit resulting from assimilate import). Surprisingly, there was not a stronger correlation between early-season LAI values and fruit SSC; this may have reflected variability in the leaf area measure which was determined on only a sub-sample of tissue (LAI was subsequently calculated from leaf area).

Fruit tissue K concentration did not positively affect fruit SSC. Combined with the weak effect under aeroponics, these observations were largely consistent with those made by Hartz *et al.* (2001, 2005); across trials and seasons, they found no relationship between fruit SSC and K fertility (even when fruit K concentrations increased). The results of Lachover (1972) suggesting a positive relationship between fruit SSC and K status therefore appeared to be an anomaly, perhaps related to production in small pots where rooting was restricted. Hartz *et al.* (2005) suggested such an environment may be substantially different to the field setting. Application of K fertilizer during fruit ripening was therefore neither a reliable nor cost effective means to favourably influence SSC, and did not appear to offer any further benefit beyond appropriate late-season water management; considerably higher fruit SSC levels were achieved without excessive K application but where late-season soil moisture stress was imposed by rain-shelter.

3.3.3.3 Brix Yield and Adjusted Brix Yield

Low Brix yields reflected both modest-low fruit yield and poor SSC; even when total yield was adjusted to a standardized commercial maturity (based on 90 % of total yield considered marketable), adjusted Brix yields remained < 5 Mg Brix solids ha^{-1} (the commercial norm). These observations appeared to primarily reflect the growing environment in Palmerston North during the 1999-2000 season; heavy rainfall combined with regular irrigation provided the ideal environment for disease, which appeared to limit yields. Similarly, high moisture availability during fruit ripening certainly appeared to reduce SSC. Given the positive effect of at least optimal fertility on total yield and fruit SSC, Brix yield was also maximized for these treatments.

3.3.3.4 Fruit Mineral Concentrations

The concentration of N, P and K in fruit reflected the overall availability of each nutrient in the plant, but otherwise appeared unimportant. Although fruit K concentration was higher with increased K fertilizer rates, there was no improvement in fruit SSC detected.

3.3.3.5 Fruit Nutrient Removal and Fertilizer Efficiency

Nutrient removal in the harvested marketable product was closely associated with fruit yields; higher yields resulted in greater removal of N, P and K. However, the majority of applied N and K were not removed in the harvested fruit, and either remained in the soil, was leached or returned to the soil as crop residue. Fertilizer efficiency was poor, less than 25 % of applied N and K for all fertilizer treatments. The very low efficiency at above optimal fertility confirmed that such applications were not only unjustified, but extremely wasteful; these applications exceeded plant demand under normal field conditions. Despite poor efficiency, fertigation technology still offered the potential to closely match plant demand with supply compared to conventional pre-plant and side-dressing fertilization techniques.

CHAPTER 4: 2001 and 2002 Irrigation Management Trials

Irrigation experiments were conducted at the Vegetable Crops Field Headquarters (long. 121° 47′ W; lat. 38° 32′ N), University of California, Davis, California during the summer of 2001 and 2002. The aim was to evaluate the effects of irrigation management during fruit ripening on yield and SSC of drip-irrigated processing tomatoes; water deficits prior to ripening (i.e. vegetative and fruit development) can dramatically reduce fruit set, decrease fruit size, and substantially increase the incidence of fruit rots, and should therefore be avoided.

4.1 Materials and Methods

4.1.1 Experimental Site

Davis has a Mediterranean-type climate with warm, dry summers and cool, moist winters (Andrews, 1972). No rainfall was received in either season during the final 60 days preharvest. Daily reference evapotranspiration (ET_o) and air and soil temperature were collated from the nearest computerized weather station of the California Irrigation Management Information System (CIMIS) network. This weather station was less than 1 km from the experimental sites. A full summary of climate data for both seasons is provided in Appendix III.

Soil type for the 2001 study was a *Reiff loam* (coarse-loamy, mixed, non-acid, thermic Typic Xerorthent) and in 2002 a *Yolo loam* (fine-silty, mixed, non-acid, thermic Typic Xerorthent). Both soils were formed from alluvial fans, characterised with high natural fertility and moderate permeability (Andrews, 1972). The available water holding capacity in the top 1.5 m depth was between 215-250 mm for the Reiff soil and 229-279 mm for the Yolo soil (Andrews, 1972).

4.1.2 Production Details

Standard commercial bed preparation techniques were made in the spring of each season. A multi-row lister was used to form 1.5 m-wide raised soil beds. A single line of high-flow drip tape was buried 20 cm deep in the centre of the bed; spacing

between emitters was 30 cm. Preplant fertilizer was banded in both years; additional side-dressed N was fertigated in the irrigation water as UN-32 (urea ammonium nitrate solution). Seasonal application rates are summarized in Table 4.1.

Table 4.1. Fertilizer application rates of N, P and K, 2001 and 2002.

Year	Applied fertilizer (kg ha^{-1})			
	Nitrogen		Phosphorus	Potassium
	Preplant	*Fertigated* [z]	*Preplant*	*Preplant*
2001	18	170	50	14
2002	31	170	19	24

[z] applied as UN-32, split evenly over 5 (2001) or 6 (2002) weekly fertigations during plant development

The hybrid cultivar 'Halley' was used in both years (Orsetti Seed Inc., Hollister, CA); 'Halley' was selected because it was a dominant industry standard in California at the time. Seed was sown and seedlings raised in a greenhouse until planting. Transplants were hand-planted into single rows with in-row spacing of 30 cm; this was equivalent to a density of approximately 22,000 plants ha^{-1} (Fig. 4.1). Sprinkler irrigation was used to establish the transplants in both years; it also provided a full moisture profile (field capacity) at the beginning of the season. Drip irrigation began on either May 20th (2001) and June 3rd (2002). Important production and phenological dates are summarized in Table 4.2.

Table 4.2. Production and phenological dates, 2001 and 2002.

Year			Phenological stage		
	Sown	*Transplanted*	*First flowering*	*First fruit set*	*First ripe fruit*
2001	February 15	April 13	May 06	May 20	July 01
2002	February 25	April 24	May 16	June 03	July 13

In both years, herbicide control consisted of pre-emergent application with Devrinol 2E® (United Phosphorus Ltd.) at 2.7 kg a.i ha^{-1}, post-plant application with Shadeout 25DF® (DuPont Chemical Co.) at 0.035 kg a.i ha^{-1}, and early season lay-by incorporation with Treflan 5E® (Dow Elanco Co.) at 1.3 kg a.i ha^{-1}. Insecticide control for tomato russet mite (*Aculops lycopersici*), potato aphid (*Macrosiphum euphorbiae*), tomato fruit worm (*Helicoverpa zea*) and stink-bug (*Eushistus conspersus*) consisted of

multiple mid- and late-season applications with Thiodan® (Universal Crop Protection Alliance Co.) at 1.1 kg a.i ha^{-1}, Warrior T® (Syngenta Crop Protection, Inc.) at 0.34 kg a.i ha^{-1} and Ben-Sul 85® dusting sulphur (Wilbur-Ellis Co.) at 8.5 kg a.i ha^{-1}.

Fig. 4.1. Early-season vegetative growth, 2001.

4.1.3 Experimental Design

Seven irrigation treatments including various cutoff and cutback approaches were evaluated in 2001 to provide a full range of soil moisture deficits during fruit ripening (Table 4.3). Experimental design was randomized complete block, with five replications. Individual plots were three beds wide, each 15 m in length. Only the centre bed was used for measurements, with the two outer beds designated as border rows (in case of lateral water movement between treatments). A smaller subset of four treatments was evaluated in 2002 (Table 4.3). Experimental design was again randomized complete block, but with six replications. Each plot comprised one bed, 9 m in length; border rows were eliminated in 2002 because prior observations at this site had confirmed no lateral water movement. The control treatment (full irrigation cutoff 20 days preharvest) used in both seasons represented the standard commercial practice under drip. All treatments were designed to primarily target fruit ripening (water stress prior to ripening can reduce fruit yields).

Table 4.3. Description of irrigation treatments, 2001 and 2002.

Treatment schedule
2001
Full cutoff implemented 20 days preharvest *(control)*
Full cutoff implemented 30 days preharvest
Full cutoff implemented 40 days preharvest
Full cutoff implemented 60 days preharvest *(severe stress)*
Cutback to 50 % of ET_o implemented 40 days preharvest (full cutoff at 20 days)
Cutback to 25 % of ET_o implemented 40 days pre harvest (full cutoff at 20 days)
Cutback to 25 % of ET_o implemented 60 days preharvest (full cutoff at 20 days)
2002
Full cutoff implemented 20 days preharvest *(control)*
Full cutoff implemented 30 days preharvest
Full cutoff implemented 50 days preharvest *(severe stress)*
Cutback to 25 % of ET_o implemented 50 days preharvest (full cutoff at 20 days)

Full irrigation (*I*; Eq. 4.1) was determined by multiplying daily ET_o, the crop coefficient (K_c value x plant canopy cover), and a system inefficiency factor. Reference ET_o was calculated automatically by the CIMIS network using a modified-Penman equation and hourly weather data (Goldhamer and Snyder, 1989); closely clipped, actively growing grass was the reference crop. The K_c value used for processing tomato was 1.1 (Phene *et al.*, 1986). Plant canopy cover was estimated using a ruler placed laterally across the bed, and calculated as the proportion of 1.5 m soil bed covered by leaf (Hartz, 1996); multiple measures were made to account for within field variability. System inefficiency was set at 1.15, a standard grower correction in drip-irrigated fields (Hartz, 1996); this value was higher than would have been expected in the comparatively small plots lengths used for these experiments, where uniformity and pressure loss were unlikely to be problematic.

$$I = ET_o \times (K_c \times P_{cc}) \times S_f \qquad \textit{(Eq. 4.1)}$$

Where:

I = full replacement irrigation amount (mm)

ET_o = reference evapotranspiration (mm)

K_c = crop constant

P_{cc} = plant canopy cover

S_f = system inefficiency factor

Water was applied three times per week and the amount verified by flow meters. All treatments received 100 % of the calculated irrigation volume until each respective cutoff/cutback was imposed. In both years, water supply to cutback treatments was fully terminated at the same time as the control treatment (20 days preharvest). The harvest date used to determine when to implement treatments was estimated using the modified phenological growth model of Zalom and Wilson (1999).

4.1.4 Data Collection

4.1.4.1 Plant Canopy Cover Measurements

An infrared digital camera (Dycam Inc., Lost Hills, CA) was used to calculate percent canopy cover; imagery was not related to P_{cc} measurements made to determine irrigation amount. The camera utilized spectral reflectance properties in the red and near-infrared range to identify photosynthetically-active tissue in frame. Measurements were taken weekly beginning seven weeks preharvest in 2001. This was approximately 10 days following the implementation of the 60 d treatments. A 2 m representative section of row from the centre bed was imaged. On each date, four replications were sampled, from four treatments selected to encompass the range of water stresses imposed (60 d cutoff, 60 d cutback to 25 % of ET_o, 40 d cutoff, and the 20 d control). Plant canopy cover was not measured in 2002.

4.1.4.2 Plant Water Status

A pressure chamber instrument (Model 610, PMS Instruments, Corvallis, OR) with a 4.0 MPa operational range was used to evaluate plant water potential (ψ). Measurements were taken weekly starting either seven (2001) or six (2002) weeks preharvest, on a day when irrigation was not scheduled. Five replications per treatment were sampled in both years. All samples were collected from healthy, recently-matured leaves.

There has been little commercial application of ψ as an irrigation management tool; the practical restrictions of predawn determination (only a few fields can be monitored before sunrise) and the large variability associated with sampling exposed leaves in the early afternoon have limited its use. To investigate the effect of sampling

technique on ψ a comparison was made between leaf samples that had either been bagged for a period of time prior to sampling or those that were exposed at the time of sampling. Covering leaves with a reflective water-impervious bag allows equilibrium to be reached between the leaf and stem (by stopping transpiration), and can therefore improve the reliability of ψ measures (Fulton *et al.*, 2001; McCutchan and Shackel, 1992).

Plant water status measured on bagged leaves represented stem water potential (ψ_{Stem}), while measurements made on exposed leaves (the traditional approach) represented leaf water potential (ψ_{Leaf}). The effect of bagging technique was investigated at both 0700 HR and 1300 HR; it was thought that sampling ψ_{Stem} at 0700 HR would yield similar results to conventional predawn ψ_{Leaf}, whereas the 1300 HR measure was timed to coincide with peak solar load and highest plant water demand (and also the greatest variability in exposed leaves). For the purpose of examining sampling technique, matching samples of bagged and exposed leaves were only collected from the control treatment at 0700 HR and the two border treatments at 1300 HR (control and most severe cutoff treatment in each year).

At 0700 HR, ψ_{Stem} was measured on leaves that had been bagged the previous night (to allow adequate equilibrium before sampling). In both years, a conventional predawn (0500 HR) measurement of ψ_{Leaf} was made to determine if 0700 HR sampling of ψ_{Stem} was a reliable indicator of predawn plant water potential as predicted. This measure was made either 14 (2001) or 27 (2002) days preharvest. On all other dates, 0700 HR bagged and exposed leaf samples were collected at the same time. At 1300 HR, ψ_{Stem} was measured on leaves that had been bagged mid-morning (1100 HR), allowing an equilibrium time of two hours before sampling. Once excised, all samples were placed in sealable bags and then an ice-chest to prevent desiccation. Following collection ψ was determined on samples by replicate in the pressure chamber. The procedure took approximately one hour to complete.

In both years, ψ_{Stem} rather than ψ_{Leaf} was expected to provide a more robust indicator of plant water status. For the purpose of examining the effect of irrigation treatment, ψ_{Stem} measurements were made on selected treatments at 0700 HR and 1300 HR. Four irrigation treatments were selected in 2001 to encompass the range of water stresses imposed (60 d cutoff, 60 d cutback to 25 % of ET_o, 40 d cutoff, and 20 d control). In 2002, all treatments were monitored.

4.1.4.3 Soil Water Status

A neutron hydroprobe (Model 503, CPN Corp., Pacheco, CA) was used to evaluate soil volumetric water content (θ_V) at depths of 15, 30, 60, 90 and 120 cm. Access-tubes were offset 15 cm to the side of the drip tape. The probe utilized an encapsulated ^{241}Am/Be source. Soil water measurements were taken weekly starting either six (2001) or seven (2002) weeks preharvest, on a day when irrigation was not scheduled. Four replications were sampled in 2001, five in 2002. Four irrigation treatments were selected in 2001 to encompass the range of irrigation deficits imposed (60 d cutoff, 60 d cutback to 25 % of ET_o, 40 d cutoff, and 20 d control). All treatments were monitored in 2002.

Moisture retention was determined for both soils using the method of Klute (1986). Soil was saturated with 0.01 M calcium chloride solution, and then equilibrated under a range of atmospheric pressure potentials (-20, -30, -100, -500, -1500 kPa). Using the gravimetric water content of the soil at each pressure potential and the respective bulk density at each site, θ_V was estimated; a curve of soil matric potential (ψ_{Soil}) against θ_V was generated for each site. Available soil moisture (ASM) was calculated by first determining the maximum amount of plant available water the soil could supply; this reflected the difference in θ_V between field capacity (-20 kPa) and permanent wilting point (-1500 kPa). The actual available water content was then calculated by subtracting measured θ_V on any date from that at the permanent wilting point; this was then expressed as a percent of the maximum available water content in the soil.

4.1.4.4 Yield and Quality Measurements

A single destructive fruit harvest was taken on either August 21st (2001) or August 28th (2002), when control plots had reached approximately 95 % ripe fruit (the commercial norm). All fruit within a 5 m representative section of row were hand-harvested, and weighed to determine the total yield of each treatment. A sub-sample was collected and fruit were graded into marketable, green, cull (sunburn and limited-use) and pathological rot categories. Fifty intact marketable fruit per plot were weighed to calculate mean fruit mass.

A 5 kg sub-sample of marketable fruit per plot was mechanically juiced and deaerated under a vacuum of 0.09 MPa to assess quality. Fruit SSC was determined by temperature-compensated refractometer (RFM-80, Bellingham and Stanley Ltd, Lawrenceville, GA). Blended colour was quantified by spectrophotometer, and represented the ratio of green (566 nm) to red (650 nm) light reflected from the homogenized juice sample (Agtron E-5, Magnuson Engineers, Inc., San Jose, CA). Fruit pH was determined using a pH meter (SS-3, Beckman Coulter, Inc., Fullerton, CA).

4.1.5 Statistical Analysis

Experimental data for each season were subjected independently to ANOVA tests using the SAS GLM procedure. Separation of means was made on significant ANOVA tests using the LSD method ($p < 0.05$). Arc-sine transformations were made where appropriate. Orthogonal contrasts were used to compare the means of specific irrigation treatments primarily against the control. SAS regression procedures tested the significance of linear and non-linear models in describing the response of fruit yield and quality to the percent of ET_o applied during ripening. Correlation analysis was used to report linear associations between variables of interest.

4.2 2001 Results

The amount of water applied in the final 60 days preharvest ranged from 0 mm for the severe 60 d cutoff to 314 mm for the 20 d cutoff (Table 4.4). This was equivalent to 0 and 82 % of ET_o during this period, respectively. Based on the assumption that late-season water loss from processing tomatoes is only 80-90 % of ET_o (Phene *et al.*, 1986), all treatments represented some degree of deficit irrigation strategy during fruit ripening. The earliest ripe fruit were observed approximately one week after the 60 d treatments were initiated.

Table 4.4. Irrigation treatment schedule during the final 60 days preharvest.

Treatment schedule [z]	Treatment applied water (mm)	% of ET_o applied in last 60 days
Full cutoff implemented 20 days preharvest *(control)*	314	82
Full cutoff implemented 30 days preharvest	218	57
Full cutoff implemented 40 days preharvest	143	37
Full cutoff implemented 60 days preharvest *(severe stress)*	0	0
Cutback to 50 % of ET_o implemented 40 days preharvest	229	60
Cutback to 25 % of ET_o implemented 40 days preharvest	186	48
Cutback to 25 % of ET_o implemented 60 days preharvest	79	20

[z] all cutback treatments had full cutoff at 20 days

4.2.1 Plant Canopy Cover Measurements

Plant canopy measured using the camera technique never reached 100 %, because although adjacent rows were observed to touch, differences in leaf arrangement resulted in a small portion of bare ground showing in every instance; the computer software program associated with this technique calculated percent canopy as the proportion of photosynthetically-active tissue to that which was not (bare ground). On no date was percent canopy cover significantly affected by irrigation treatment (Table 4.5); the average difference in canopy cover between the control and severe stress plots (representative of the boundary treatments) was less than 2 %. Across treatments, canopy cover declined 15 % seasonally, most noticeably close to harvest.

Table 4.5. Effect of irrigation treatment on plant canopy cover.

Irrigation treatment	Plant canopy cover (%) by days preharvest						
	49	*42*	*35*	*28*	*21*	*14*	*7*
20 d cutoff	70	67	67	62	62	62	57
40 d cutoff	70	70	66	61	60	62	54
60 d cutoff	70	70	68	61	60	62	54
25% at 60 d	67	68	66	61	60	63	52
SE	1	2	2	2	2	1	2
p-value	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*	*ns*

[ns] non-significant at $p < 0.10$

4.2.2 Plant Water Status

4.2.2.1 Effect of Sampling Technique

At 0700 HR, ψ_{Stem} readings in control plots were generally greater (less negative) than those for ψ_{Leaf} (Fig. 4.2). Seasonally, this difference averaged approximately 0.20 MPa, and was highly significant with the exception of measurements made on two of the eight occasions. On the first of these occasions (35 days preharvest), the minimum overnight air temperature was lower than normal for this experiment (lower temperatures would reduce the impact of the bagging technique by decreasing plant transpiration during the early morning). On the second occasion (14 days preharvest), ψ_{Leaf} was measured at 0500 HR, by design earlier than on the other sampling occasions and consistent with conventional predawn determination of plant water status. As expected, on this date the two sampling techniques resulted in similar ψ.

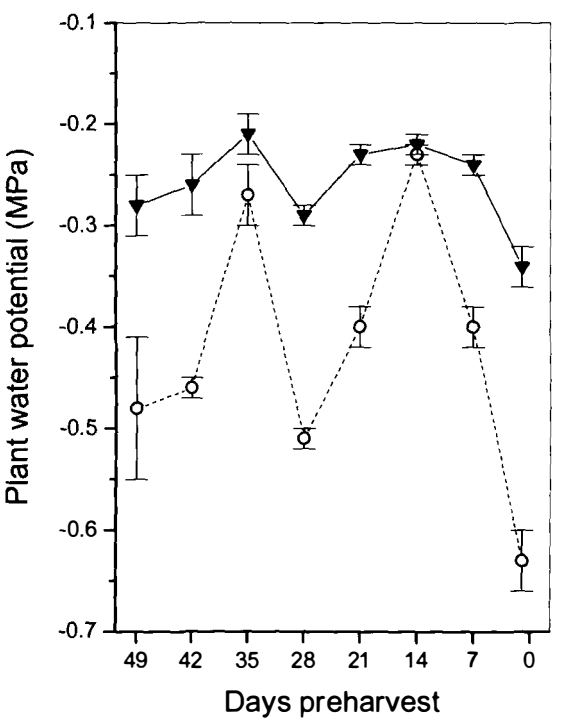


Fig. 4.2. Effect of sampling technique on plant water potential (ψ) in control plots at 0700 HR. Technique means are given ± standard error. Sampling techniques were ψ_{Stem} (—▼—) and ψ_{Leaf} (---○---). ψ_{Leaf} at 14 days preharvest was measured at 0500 HR (predawn).

As with early morning sampling, ψ_{Stem} readings taken at 1300 HR (approximately solar noon) were consistently greater than those taken simultaneously for ψ_{Leaf}. This

trend was observed in both boundary treatments (Fig. 4.3a, b). The greatest difference between ψ_{Stem} and ψ_{Leaf} was 0.67 MPa, recorded for the severe stress treatment 14 days preharvest. The largest sampling variability was associated with measuring ψ_{Leaf}.

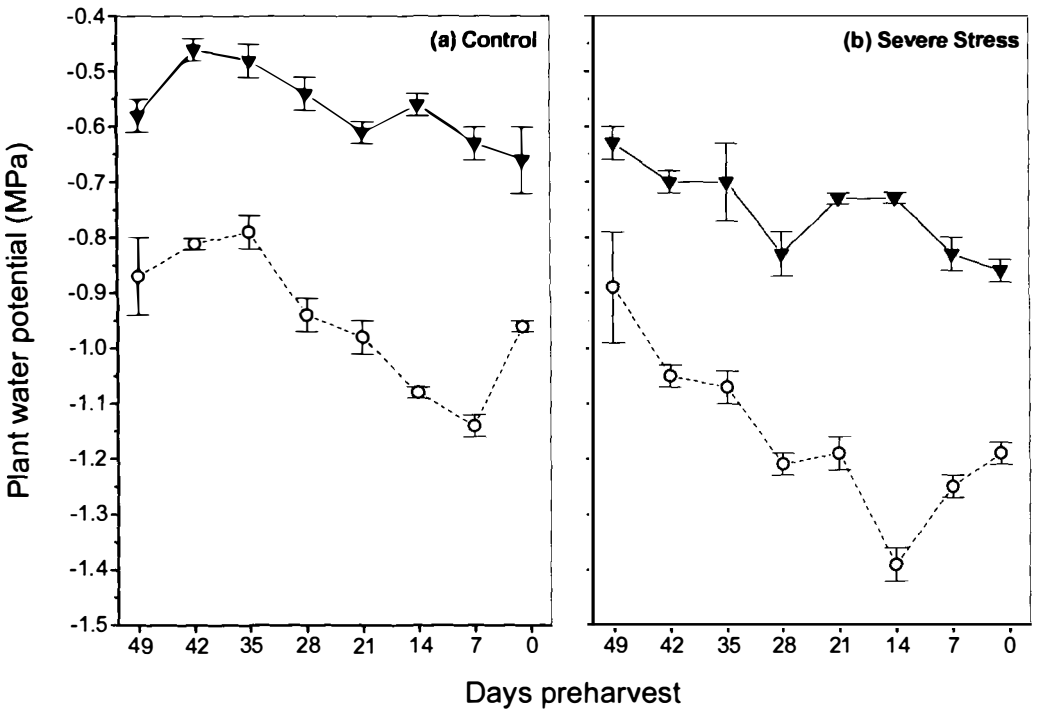


Fig. 4.3. Effect of sampling technique on plant water potential (ψ) in control plots (a) and severe stress plots (b) at 1300 HR. Technique means are given ± standard error. Sampling techniques were ψ_{Stem} (—▼—) and ψ_{Leaf} (---○---).

4.2.2.2 Effect of Irrigation Treatment

Stem water potential was adopted as the more reliable indicator of plant water status as affected by irrigation treatment. Treatments not already implemented were assumed to have ψ_{Stem} equivalent to that of the control. Decreasing water application reduced 0700 HR ψ_{Stem} during fruit ripening. This effect was generally significant with the exception of measurements taken 35 and 1 day preharvest (Table 4.6). As previously noted, a lower than normal overnight air temperature was reported on the first of these dates. Highest ψ_{Stem} was reported for control plots on all sampling dates; the 60 d cutoff treatment resulted in the lowest (most negative) ψ_{Stem}.

Similarly, decreasing water application significantly reduced 1300 HR ψ_{Stem} during fruit ripening. Again, the control treatment had consistently higher ψ_{Stem}. At harvest, the difference between the control and most severe cutoff treatment was 0.20 MPa. All treatments showed some degree of seasonal decline when measured at either

0700 HR or 1300 HR. Across the final six weeks preharvest, average ψ_{Stem} at 0700 HR was -0.25, -0.31, -0.37 and -0.33 MPa and at 1300 HR -0.57, -0.64, -0.75 and -0.68 MPa in the 20 d (control), 40 d and 60 d cutoff, and the 60 d cutback, both respectively.

Table 4.6. Effect of irrigation treatment on ψ_{Stem} measured at 0700 HR and 1300 HR.

Irrigation treatment	Stem water potential (MPa) by days preharvest							
	49	*42*	*35*	*28*	*21*	*14*	*7*	*1*
	---------- at 0700 HR ----------							
20 d cutoff	-0.28 a	-0.26 a	-0.21	-0.29 a	-0.23 a	-0.22 a	-0.24 a	-0.34
40 d cutoff				-0.30 a	-0.30 b	-0.31 bc	-0.36 b	-0.39
60 d cutoff	-0.39 b	-0.43 b	-0.29	-0.36 b	-0.35 c	-0.34 c	-0.39 b	-0.41
25% at 60 d	-0.29 a	-0.34 ab	-0.27	-0.34 ab	-0.29 b	-0.28 ab	-0.39 b	-0.41
SE	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.01
p-value	*	**	*ns*	*	***	***	***	*ns*
	---------- at 1300 HR ----------							
20 d cutoff	-0.58 ab	-0.46 a	-0.48 a	-0.54 a	-0.61 a	-0.56 a	-0.63 a	-0.66 a
40 d cutoff				-0.66 a	-0.63 a	-0.73 b	-0.76 bc	-0.79 b
60 d cutoff	-0.63 b	-0.70 c	-0.70 b	-0.83 b	-0.73 b	-0.73 b	-0.83 c	-0.86 b
25% at 60 d	-0.51 a	-0.56 b	-0.63 b	-0.56 a	-0.70 b	-0.75 b	-0.71 b	-0.79 b
SE	0.02	0.03	0.04	0.03	0.01	0.02	0.02	0.02
p-value	**	***	**	***	***	***	***	**

^{ns}, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

4.2.3 Soil Water Status

Across treatments, highest θ_V was generally observed at a depth of 30 cm; drip tape was buried at 20 cm. Although processing tomatoes are capable of very deep rooting, the majority of active water-gathering roots are located within the top 50 cm of soil (Rendon-Poblete, 1980). Volumetric water content was therefore averaged across the 15, 30 and 60 cm monitoring depths to provide an integrated indication of soil water status in the main zone of root activity. The two remaining depths (90 and 120 cm) were also averaged for comparative purposes. There was no evidence of a water table in the top 120 cm. Pressure plate analysis showed that θ_V at field capacity was equivalent to 35.2 % and at permanent wilting point 13.5 %.

The 60 d treatments were implemented approximately two weeks prior to the first measurement of θ_V; early-season dry down in these plots was therefore not well

characterized. However, water application still significantly affected θ_V in the top 60 cm during the remaining six weeks. Volumetric water content was consistently lowest in the 60 d cutoff and cutback (Fig. 4.4a). Both of the 60 d treatments lost a steady amount of soil water between six and four weeks preharvest, with a relatively slow rate of decline across the final four weeks. On all dates, the two 60 d treatments had significantly lower θ_V than control plots. Following the implementation of the 40 d cutoff, soil water availability in these plots declined rapidly, resulting in significantly lower θ_V than the control during the final 28 days preharvest. Volumetric water content did not decline at a substantial rate in the control treatment until cutoff 20 days preharvest, suggesting that irrigation was approximately equal to plant use during this period (as expected).

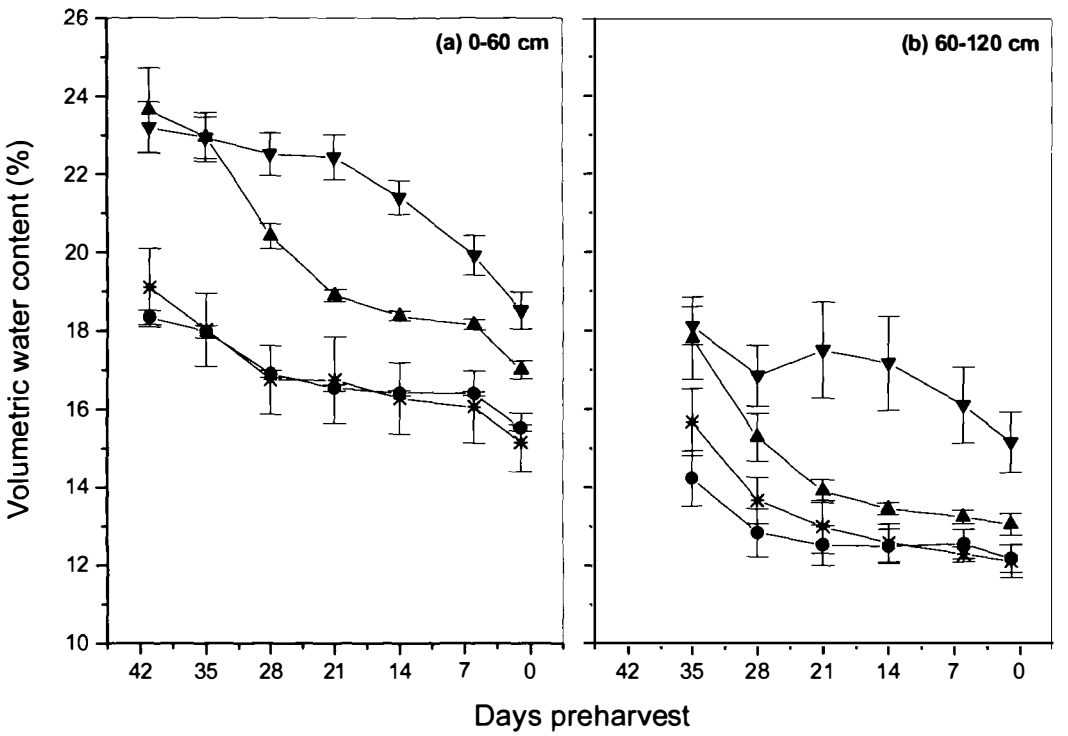


Fig. 4.4. Effect of irrigation treatment on soil volumetric water content (θ_V) in the 0-60 cm (a) and 60-120 cm (b) depth ranges. Treatment means are given ± standard error. Irrigation treatments were full cutoff at 60 days (•), 40 days (▲), 20 days (▼, control), and cutback to 25 % ET_o at 60 days (*). θ_V at field capacity was at 35.2 % and at the permanent wilting point was 13.5 %.

When averaged across the final six weeks of fruit ripening, θ_V in the top 60 cm was approximately 22, 20, 17 and 17 % in the 20 d (control), 40 d and 60 d cutoff, and the 60 d cutback, respectively. In most instances, θ_V in the top 60 cm was correlated with ψ_{Stem} (0700 HR and 1300 HR) during the final three weeks (after all treatments had been initiated); higher θ_V resulted in higher (less negative) ψ_{Stem}. Significant correlation

coefficients ranged from between 0.58 to 0.72 at 0700 HR, and 0.58 to 0.80 at 1300 HR; there was no trend over time.

Measurements were not made in the 60-120 cm depth range until the second week of monitoring (35 days preharvest). On remaining sampling occasions, soil drying patterns were similar to the top 60 cm, although θ_V was consistently less through the 60-120 cm depth range (Fig. 4.4b). A number of late season θ_V readings for the 60 d treatments were below the predicted permanent wilting point; however, as noted the majority of root activity was not expected at these depths. Available soil moisture (ASM) and soil matric potential (ψ_{Soil}) were calculated across the final six weeks of fruit ripening (Table 4.7). Across this period, the control treatment had an average ASM content of 37 %, equivalent to a ψ_{Soil} of approximately -91 kPa. This represented a more modest degree of water stress when compared to 16 % ASM in the 60 d cutoff, equivalent to a ψ_{Soil} of approximately -493 kPa.

Table 4.7. Effect of irrigation treatment on available soil moisture (ASM) and soil matric potential (ψ_{Soil}) across the final six weeks preharvest.

	Final six week average	
Irrigation Treatment	ASM (%)	Ψ_{soil} (kPa)
20 d cutoff	37	-91
40 d cutoff	30	-152
60 d cutoff	16	-493
25% at 60 d	16	-492

4.2.4 Fruit Yield and Quality Measurements

The effect of irrigation treatment on tomato yield and fruit quality is summarized in Table 4.8.

Table 4.8. Effect of irrigation treatment on tomato yield and fruit quality at harvest.

Irrigation treatment	Total yield (Mg ha^{-1})	Marketable yield (Mg ha^{-1})	Soluble solids (°Brix)	Brix yield (Brix Mg ha^{-1})	Blended colour [z]	Fruit pH
20 d cutoff	98 ab	91 ab	5.5 c	5.0	25.4	4.35
30 d cutoff	99 a	90 ab	5.5 c	4.9	23.6	4.37
40 d cutoff	88 bc	81 bc	5.9 ab	4.7	23.0	4.34
60 d cutoff	80 c	73 c	6.1 a	4.4	23.0	4.36
50% at 40 d	95 ab	87 ab	5.6 bc	4.8	24.6	4.36
25% at 40 d	97 ab	92 a	5.6 bc	5.2	24.2	4.36
25% at 60 d	91 ab	84 abc	5.9 a	4.9	22.4	4.35
SE	1.6	1.7	< 0.1	< 0.1	0.3	0.01
p-value	**	**	***	ns	ns	ns

[z] dimensionless unit, lower value indicates more intense red colour in fruit

[ns], **, *** non-significant at $p < 0.10$, or significant at $p < 0.05$ or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

4.2.4.1 Total and Marketable Fruit Yield

Irrigation application during the final 60 days preharvest significantly affected total fruit yield (Table 4.8). Yield was greatest for the 30 d cutoff treatment, although was not significantly different to the control treatment. Lowest yield was obtained under the 60 d cutoff, which compared poorly to the majority of other treatments. Separate contrasts also confirmed significantly ($p < 0.10$) lower fruit yield in both the 40 d cutoff and 60 d cutback compared to the control treatment. Treatment differences in marketable yield were largely consistent with those for total yield; the percent of yield that was marketable was approximately 93 % for both the control and 60 d cutoff. Total and marketable yield were strongly correlated ($p < 0.01$, r = 0.97).

Significant linear regression models were fitted to both total and marketable yield ($p < 0.05$, $r^2 = 0.67$ and 0.63, respectively), with similar slopes in response to percent of ET_o applied (Fig. 4.5a, b). Inclusion of quadratic or cubic terms was not statistically justified. The linear model confirmed that the percent of ET_o applied in the final 60 days preharvest had a greater effect on both yield measures than the application strategy (cutoff or cutback). For each 20 % reduction in ET_o applied during ripening, fruit yield declined by approximately 3 Mg ha^{-1}. Total yield was positively correlated to average θ_V (top 60 cm) across the final six weeks of ripening ($p < 0.01$, r = 0.56); higher soil water availability was generally associated with higher fruit yields.

Similarly, average ψ_{Stem} measured at 0700 HR and 1300 HR across the same period was also positively correlated with total yield ($p < 0.01$, r = 0.50 and 0.55, respectively); less negative plant water status was generally associated with higher fruit yields.

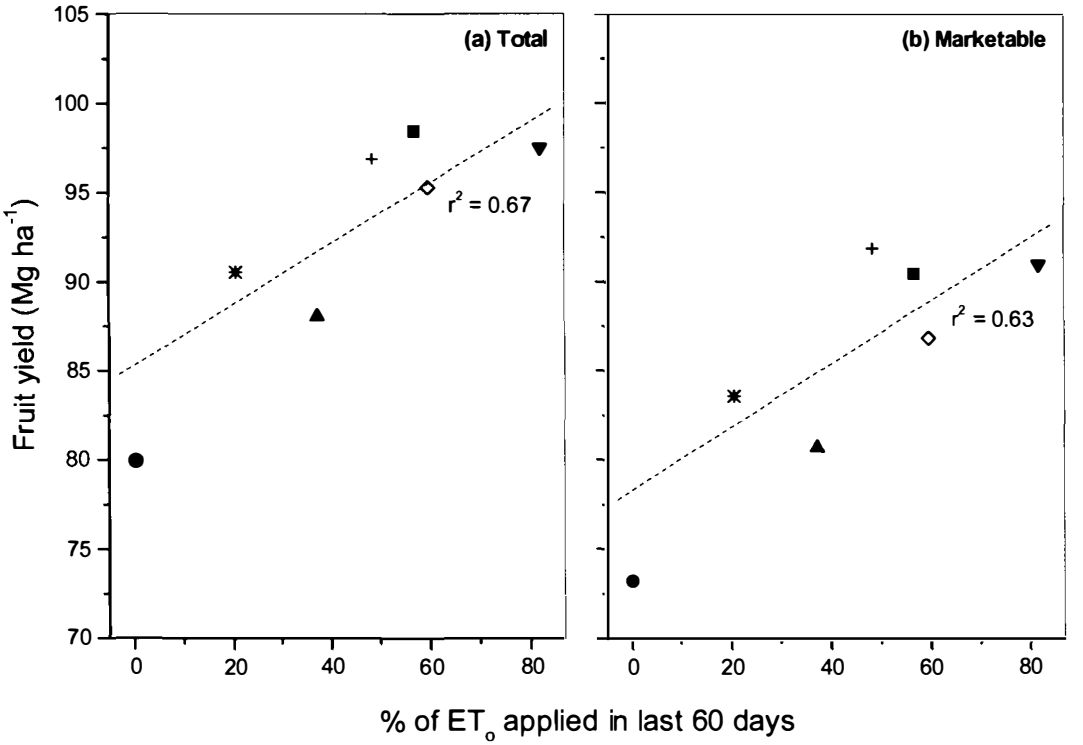


Fig. 4.5. Effect of irrigation treatment on total (a) and marketable (b) fruit yield. Treatment means are shown. Irrigation treatments were full cutoff at 60 days (•), 40 days (▲), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 60 days (✳), 25 % of ET_o at 40 days (+), and 50 % of ET_o at 40 days (◊). The equation of the fitted linear regression line (···) for total yield was y = (85.3 ±3.3) + (0.1703 ±0.0539).x and for marketable yield y = (78.3 ±3.6) + (0.1776 ±0.0614).x.

4.2.4.2 Fruit Soluble Solids

Irrigation application during the final 60 days preharvest significantly affected SSC of marketable fruit (Table 4.8). Fruit SSC was highest for the 60 d cutoff treatment, although was not significantly different to the 60 cutback or 40 d cutoff. Lowest fruit SSC was obtained with the 20 d and 30 d cutoffs. Fruit SSC was negatively correlated to total yield ($p < 0.01$, r = -0.66); for every 0.1 °Brix increase in fruit SSC there was a decline in total yield of 2 Mg ha^{-1}.

A significant linear regression model was fitted for SSC against percent of ET_o applied ($p < 0.02$, $r^2 = 0.73$); application amount appeared more important than application strategy (Fig. 4.6). The inclusion of quadratic or cubic terms was not statistically justified. For each 20 % reduction in ET_o applied during fruit ripening, fruit

SSC increased by approximately 0.15 °Brix. Fruit SSC was negatively correlated to average θ_V (top 60 cm) across the final six weeks of ripening ($p < 0.01$, r = -0.64); lower soil water availability was generally associated with higher SSC. Similarly, average ψ_{Stem} measured at 0700 HR and 1300 HR across the same period was also negatively correlated with fruit SSC ($p < 0.01$, r = -0.54 and -0.68, respectively); more negative plant water status was generally associated with higher SSC.

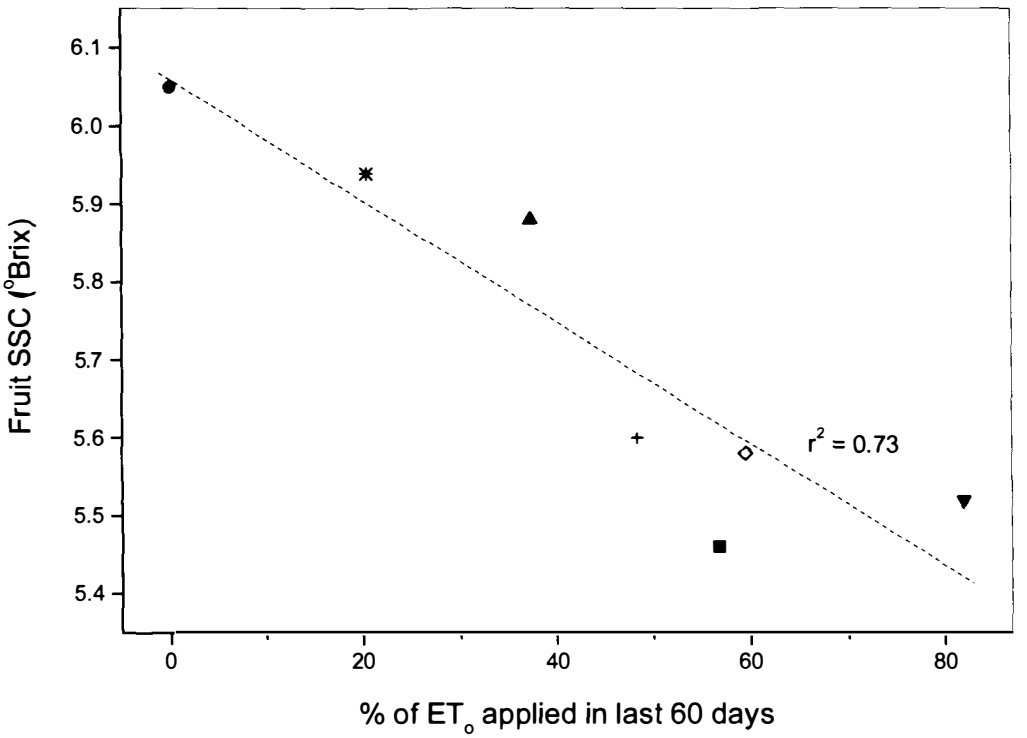


Fig. 4.6. Effect of irrigation treatment on fruit soluble solids concentration (SSC). Treatment means are shown. Irrigation treatments were full cutoff at 60 days (•), 40 days (▲), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 60 days (✳), 25 % of ET_o at 40 days (+), and 50 % of ET_o at 40 days (◊). The equation of the fitted linear regression line (···) was $y = (6.06 \pm 0.11) - (0.0077 \pm 0.0021).x$.

4.2.4.3 Brix Yield

Brix yield was not significantly affected by irrigation application, averaging 4.88 Mg Brix solids ha^{-1} across treatments (Table 4.8). This was largely consistent with the contrasting effects of water stress on the two parameters comprising Brix yield; increasing water stress reduced marketable yield but increased fruit SSC. However, this 'dilution-effect' relationship did not appear unlimited; the contrast comparing only the border treatments was significant ($p < 0.06$), confirming comparatively lower Brix yields under severe water deficit. Brix yield was more strongly correlated with marketable yield than with SSC ($p < 0.05$, r = 0.90 and -0.16, respectively).

The response of Brix yield to percent of ET_o applied was not well characterized using linear, quadratic or cubic regression. A linear plateau model appeared to provide the most logical fit of the data, although was itself limited because a large number of data points fell outside of the range at which Brix yield began to plateau. Subsequently, not all of the terms in the model could be estimated simultaneously. However, it appeared that the 'threshold' value at which Brix yield was sacrificed (i.e. where marketable yield decline was disproportionate to SSC increase) occurred between the first and second treatment levels (0-20 % of ET_o applied). Using a conservative estimate of the percent of ET_o at which the plateau began (20 %), a model was developed for illustrative purposes only (Fig. 4.7).

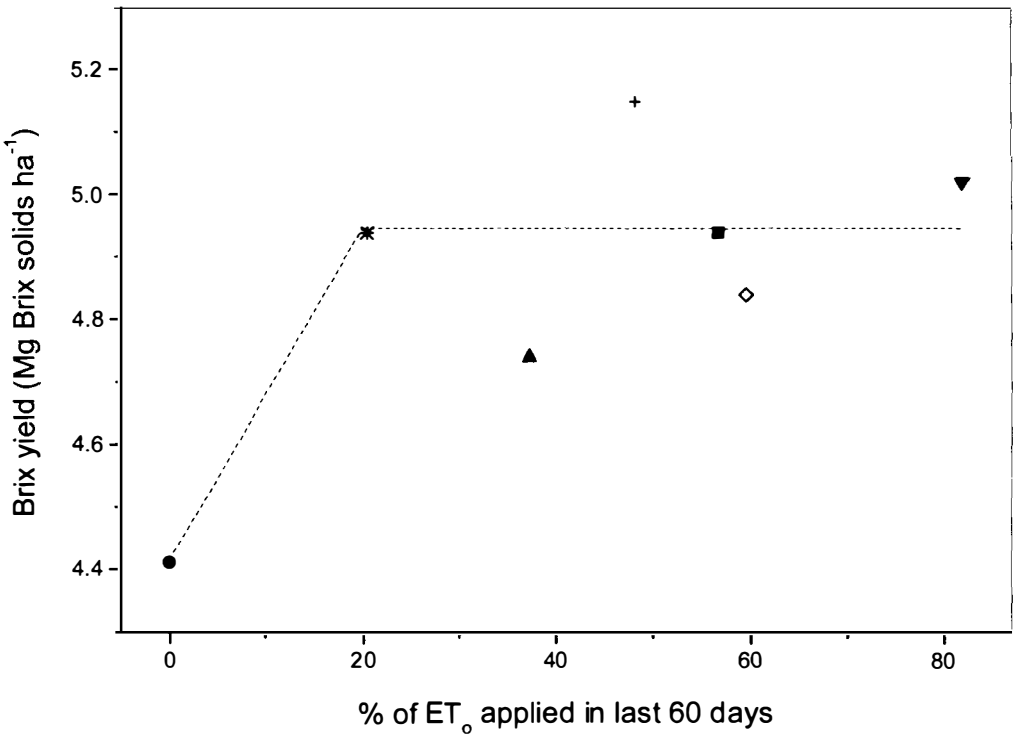


Fig. 4.7. Effect of irrigation treatment on Brix yield. Treatment means are shown. Irrigation treatments were full cutoff at 60 days (•), 40 days (▲), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 60 days (✳), 25 % of ET_o at 40 days (+), and 50 % of ET_o at 40 days (◊).

4.2.4.4 Blended Fruit Colour

Blended fruit colour was not significantly affected by irrigation application, although fruit grown under higher stress conditions appeared to have numerically lower colour scores (Table 4.8); a lower score was consistent with a higher red colour intensity. Fruit colour was not correlated to the yield or percent of green fruit observed

(consistent with harvesting at commercial maturity). A significant linear regression model was fitted for blended fruit colour against percent of ET_o applied ($p < 0.06$, $r^2 = 0.62$); application amount appeared more important than application strategy (Fig. 4.8). Inclusion of quadratic or cubic terms was not statistically justified. Despite these observations, all treatments achieved colour scores that were considered acceptable for processing (scores < 39).

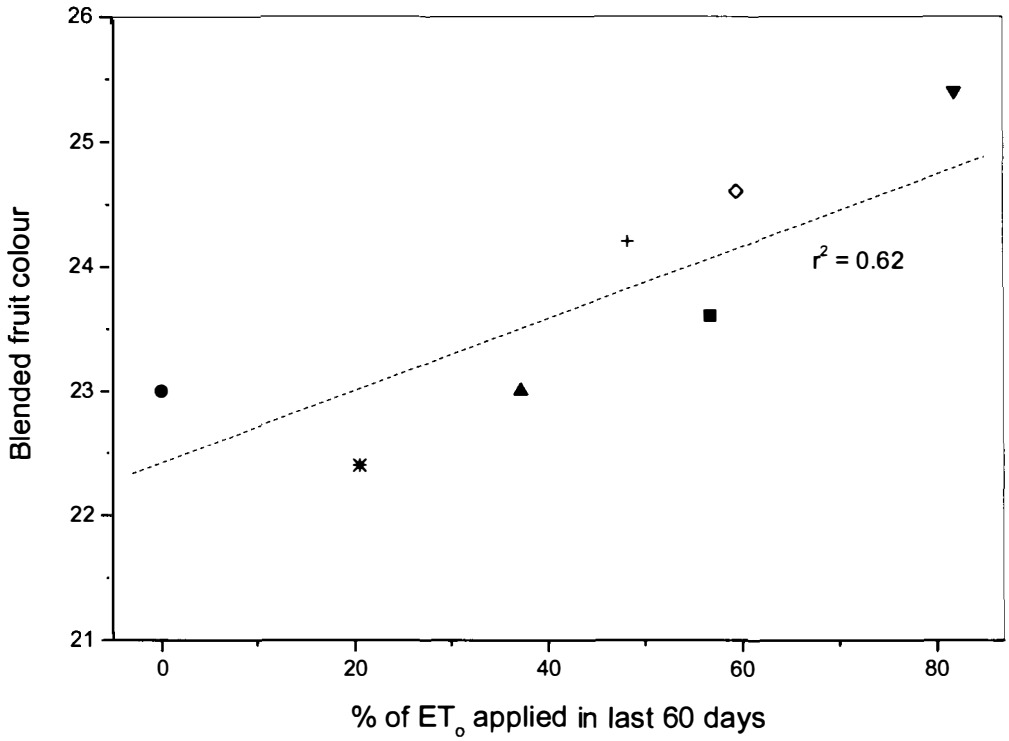


Fig. 4.8. Effect of irrigation treatment on blended fruit colour. Treatment means are shown. Irrigation treatments were full cutoff at 60 days (•), 40 days (▲), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 60 days (✳), 25 % of ET_o at 40 days (+), and 50 % of ET_o at 40 days (◊). The equation of the fitted linear regression line (···) was $y = (22.4 \pm 0.6) + (0.0289 \pm 0.0114).x$.

4.2.4.5 Fruit pH

Fruit pH was not significantly affected by irrigation treatments imposed during the final 60 days preharvest (Table 4.8). Across treatments, fruit pH averaged 4.36.

4.2.4.6 Mean Marketable Fruit Mass and Fruit Number

The effect of irrigation treatment on the mean mass of marketable fruit (M_{Ff}) was not significant. However, a consistent trend resulting in declining M_{Ff} with reduced water application was observed for all cutoff treatments. Contrasts between the control

and 60 and 40 d cutoffs were both significant ($p < 0.03$ and 0.06, respectively), while there was no difference between the control and 30 d cutoff. Marketable yield was positively correlated with M_{Ff} ($p < 0.02$, r = 0.42); greater fruit mass generally resulted in higher yield outcomes. A significant linear regression model was fitted for M_{Ff} against percent of ET_o applied ($p < 0.02$, $r^2 = 0.70$); application amount appeared more important than application strategy (Fig. 4.9). The inclusion of quadratic or cubic terms was not statistically justified.

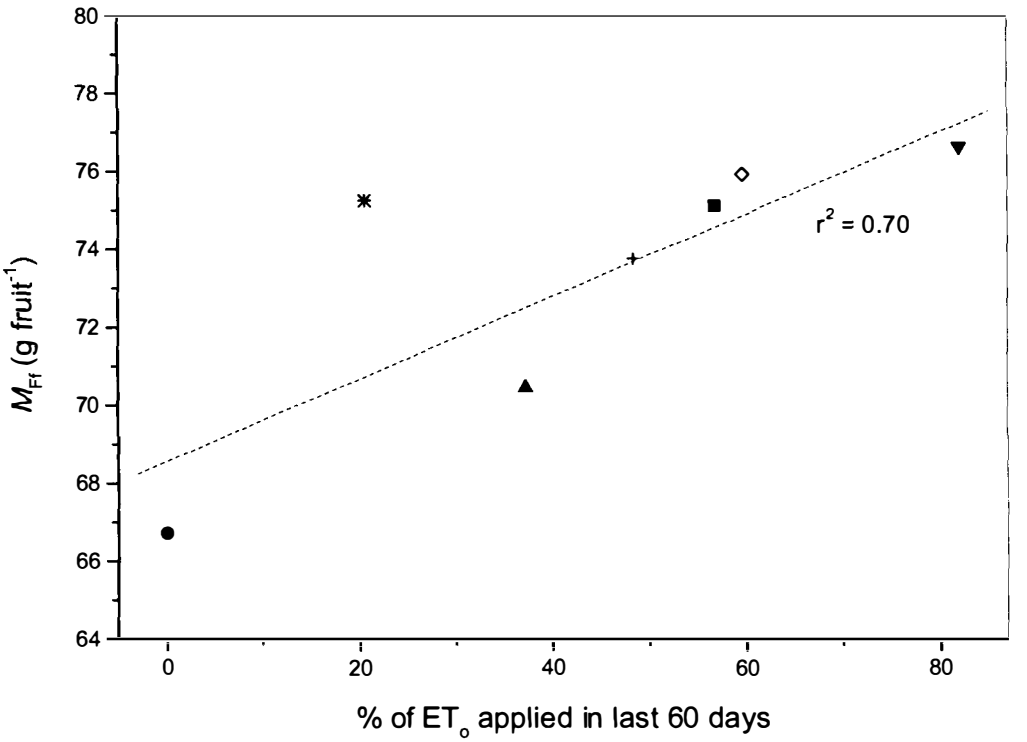


Fig. 4.9. Effect of irrigation treatment on mean marketable fruit mass (M_{Ff}). Treatment means are shown. Irrigation treatments were full cutoff at 60 days (•), 40 days (▲), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 60 days (✳), 25 % of ET_o at 40 days (+), and 50 % of ET_o at 40 days (◊). The equation of the fitted linear regression line (···) was $y = (68.6 \pm 1.7) + (0.1058 \pm 0.0307).x$.

The number of marketable fruit per plant (as estimated from marketable yield and M_{Ff}) was not significantly affected by the irrigation treatments imposed (data not shown). Although the 60 d cutoff had numerically lower fruit number than the control, the contrast between these border treatments was not significant.

4.2.4.7 Yield Components

Yield components were adjusted to a percent of total fruit yield to allow a standardized comparison of crop maturity unaffected by treatment-related differences in productivity (Fig. 4.10).

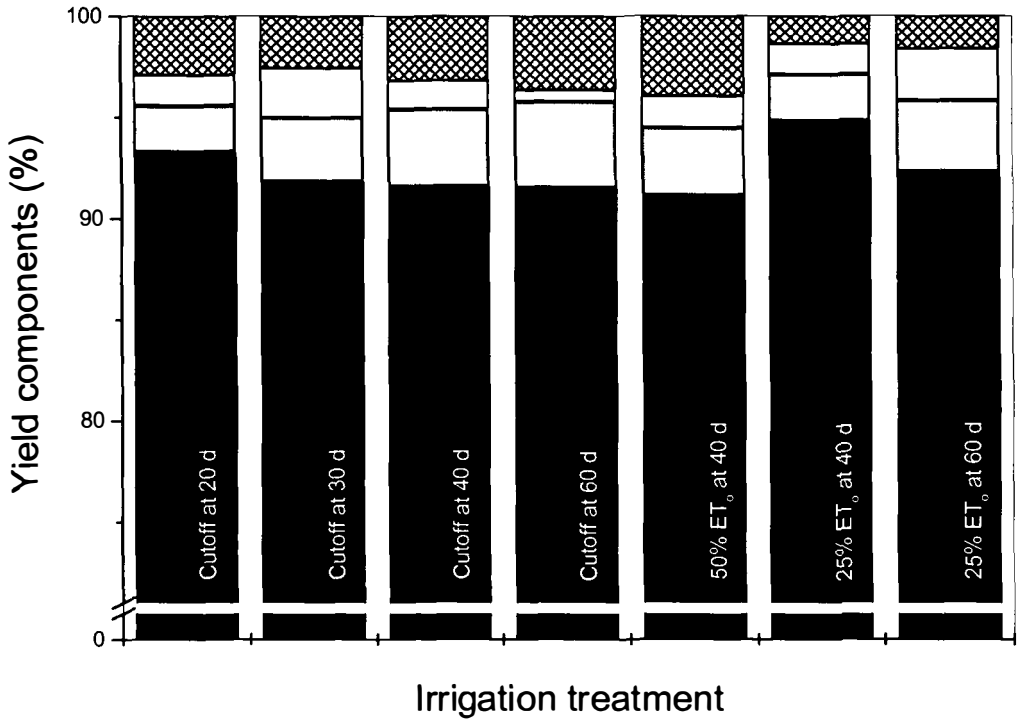


Fig. 4.10. Effect of irrigation treatment on yield components at maturity. Yield components were marketable (■), rots ( ), culls (□) and greens (☒).

Irrigation treatments did not significantly affect the percent of fruit in any yield category (marketable, rot, cull and green). Across treatments, marketable yield averaged approximately 93 % of total yield. The predominant rot species was water mold. The contrast comparing only the percent rots between border treatments was significant ($p < 0.06$); rot incidence was approximately 2 % greater under severe water deficit. However, rots remained a small constituent of total yield, averaging less than 3 % across treatments. Percent culls averaged less than 2.5 % of total yield. Across treatments, sunburn-affected fruit accounted for approximately 75 % of total culls; the remainder was limited-use fruit (fruit that were over ripe). Separately, there was no effect of irrigation treatment on the incidence of either sunburn or limited-use fruit. There was also no correlation between percent canopy cover during ripening and sunburn incidence on fruit at maturity. Green fruit comprised less than 3 % of total yield; this level was comparable to that in commercial fields at maturity. Large

sampling variability within treatments was observed for the rot, cull and green components (cv = 50, 81 and 74 %, respectively).

4.3 2002 Results

The amount of water applied in the final 50 days preharvest ranged from 0 mm for the severe 50 d cutoff to 253 mm for the 20 d cutoff (Table 4.9). This was equivalent to 0 and 77 % of ET_o during this period, respectively. All treatments therefore represented some degree of deficit irrigation strategy during fruit ripening (Phene *et al.*, 1986). In the 10 days before treatments were implemented (50-60 days preharvest) 71 mm of water was applied to all plots. First ripe fruit were observed concurrently with the implementation of the early stress treatments.

Table 4.9. Irrigation treatment schedule during the final 50 days preharvest.

Treatment schedule [z]	Treatment applied water (mm)	% of ET_o applied in last 50 days
Full cutoff implemented 20 days preharvest *(control)*	253	77
Full cutoff implemented 30 days preharvest	172	52
Full cutoff implemented 50 days preharvest *(severe stress)*	0	0
Cutback to 25 % of ET_o implemented 50 days preharvest	63	19

[z] cutback treatment had full cutoff at 20 days

4.3.1 Plant Water Status

4.3.1.1 Effect of Sampling Technique

Unlike the previous season, bagging leaves overnight in control plots for 0700 HR sampling did not consistently increase ψ_{Stem} compared to ψ_{Leaf} (Fig. 4.11). Seasonally, the difference between the two sampling techniques varied from 0.02 to 0.18 MPa, although measurements made on four of the seven sampling occasions were not significantly different. On the first of these occasions (27 days preharvest) ψ_{Leaf} was measured at 0500 HR, consistent with conventional predawn determination of ψ. No difference was therefore expected on this date. On the second occasion (20 days preharvest), the air vapour pressure and relative humidity were lower than normal for

this experiment (lower pressure and humidity would reduce the impact of the bagging technique by decreasing plant transpiration). On the third and fourth occasions (13 and 7 days preharvest) overnight and early morning weather observations were within the normal range expected. Leaf water potential readings were not taken 41 days preharvest.

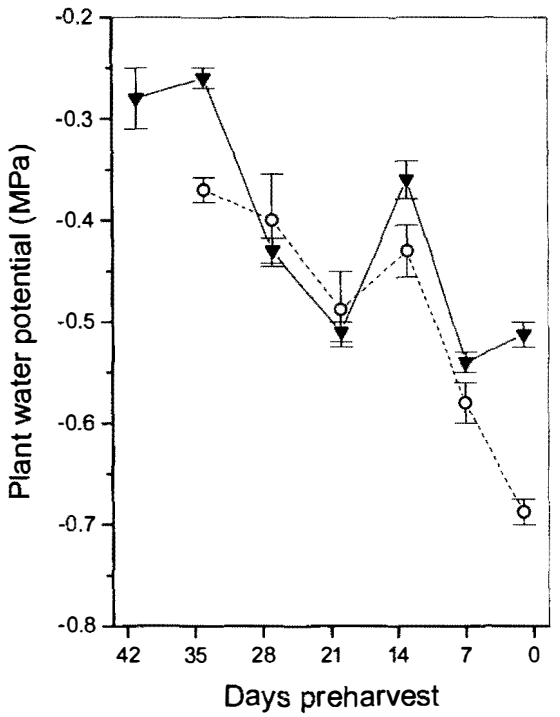


Fig. 4.11. Effect of sampling technique on plant water potential (ψ) in control plots at 0700 HR. Technique means are given ± standard error. Sampling techniques were ψ_{Stem} (—▼—) and ψ_{Leaf} (---○---). ψ_{Leaf} at 27 days preharvest was measured at 0500 HR (predawn).

When measured at 1300 HR, ψ_{Stem} was consistently higher than ψ_{Leaf}; this trend was observed in both boundary treatments (Fig. 4.12a, b). The greatest difference between ψ_{Stem} and ψ_{Leaf} was 0.55 MPa, recorded for the control treatment 41 days preharvest. Surprisingly, variability associated with sampling ψ_{Leaf} was often similar to ψ_{Stem}.

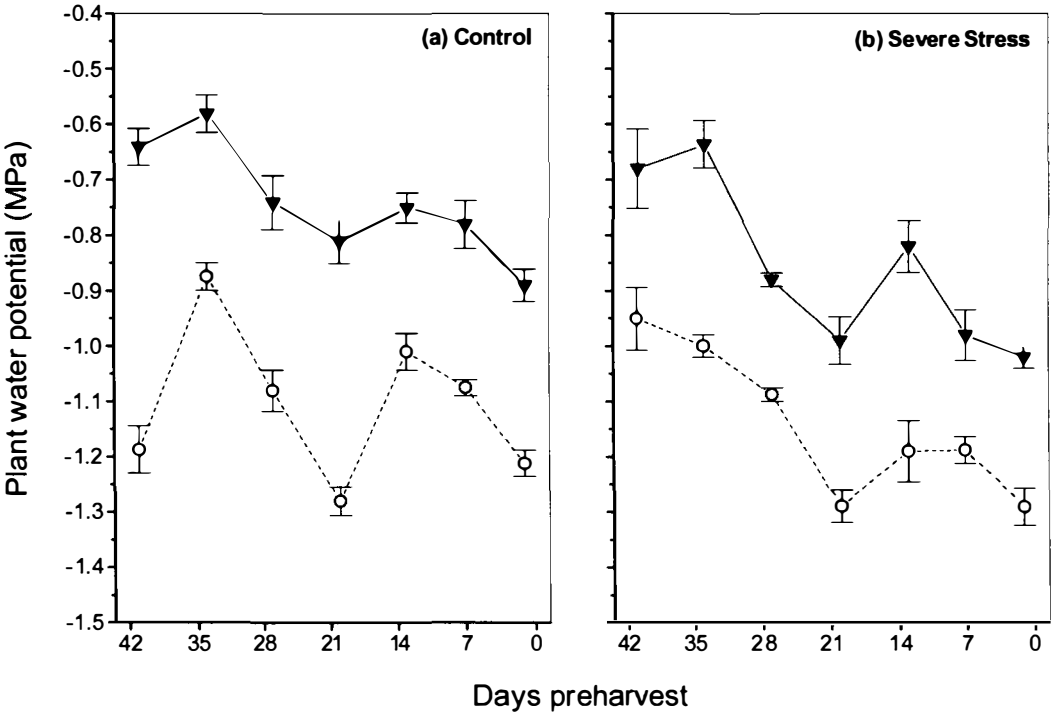


Fig. 4.12. Effect of sampling technique on plant water potential (ψ) in control plots (a) and severe stress plots (b) at 1300 HR. Technique means are given ± standard error. Sampling technique were ψ_{Stem} (—▼—) and ψ_{Leaf} (---o---).

4.3.1.2 Effect of Irrigation Treatment

In following the 2001 practice, ψ_{Stem} was adopted as the more reliable indicator of plant water status as affected by irrigation treatment. Decreasing water application reduced 0700 HR ψ_{Stem} during fruit ripening. This effect was generally significant, with the exception of measurements taken 41 and 7 days preharvest (Table 4.10). Overnight and early morning weather observations on these two sampling dates were within the normal range observed for this experiment. Highest ψ_{Stem} was generally reported for control plots; the 50 d cutoff treatment consistently resulted in the lowest ψ_{Stem}.

Similarly, decreasing water application reduced 1300 HR ψ_{Stem} during fruit ripening. As with morning sampling, this effect was generally significant, with the exception of measurements taken 41 and 13 days preharvest. On these occasions, mid-morning and early afternoon weather observations were within the normal range observed for this experiment. The control treatment had the highest ψ_{Stem}, although this was not different to 30 d cutoff until late in the season. At harvest, the difference between the control and most severe cutoff treatment was 0.18 MPa. All treatments showed some degree of seasonal decline when measured at either 0700 HR or 1300 HR.

Across the final six weeks preharvest, average ψ_{Stem} at 0700 HR was -0.41, -0.44, -0.53 and -0.47 MPa and at 1300 HR -0.74, -0.77, -0.92 and -0.88 MPa in the 20 d (control), 30 d and 50 d cutoff, and the 50 d cutback, both respectively.

Table 4.10. Effect of irrigation treatment on ψ_{Stem} measured at 0700 HR and 1300 HR.

Irrigation treatment	Stem water potential (MPa) by days preharvest						
	41	*34*	*27*	*20*	*13*	*7*	*1*
	---------- at 0700 HR ----------						
20 d cutoff	-0.28	-0.26 a	-0.43 a	-0.51 a	-0.36 a	-0.54	-0.51 a
30 d cutoff	-0.31	-0.25 a	-0.40 a	-0.55 a	-0.43 ab	-0.57	-0.59 b
50 d cutoff	-0.35	-0.38 b	-0.59 b	-0.62 b	-0.47 b	-0.65	-0.66 c
25% at 50 d	-0.33	-0.34 b	-0.49 a	-0.55 a	-0.39 ab	-0.58	-0.58 b
SE	0.01	0.01	0.02	0.01	0.02	0.02	0.02
p-value	*ns*	***	***	***	**	*ns*	***
	---------- at 1300 HR ----------						
20 d cutoff	-0.64	-0.58 a	-0.74 a	-0.81 a	-0.75	-0.78 a	-0.89 a
30 d cutoff	-0.61	-0.60 a	-0.68 a	-0.86 ab	-0.78	-0.90 ab	-0.95 ab
50 d cutoff	-0.72	-0.76 a	-0.90 b	-1.02 b	-0.88	-1.06 c	-1.07 c
25% at 50 d	-0.68	-0.64 b	-0.88 b	-0.99 b	-0.82	-0.98 bc	-1.02 bc
SE	0.02	0.02	0.03	0.03	0.02	0.03	0.02
p-value	*ns*	**	***	*	*ns*	***	***

ns, *, **, *** non-significant at $p < 0.10$, or significant at $p < 0.10$, 0.05 or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

4.3.2 Soil Water Status

Across treatments, highest θ_V was generally observed at a depth of 60 cm; drip tape was buried at 20 cm. In following the 2001 practice, θ_V was averaged across the 15, 30 and 60 cm depths to provide an integrated indication of soil water status in the main zone of root activity, and also across the two remaining depths (90 and 120 cm). There was no evidence of a water table in the top 120 cm. Pressure plate analysis showed that θ_V at field capacity was equivalent to 39.0 % and at permanent wilting point 16.7 %.

A calibration error in the standard count data (integral to calculating θ_V) was found on the first three sampling occasions (48, 41 and 34 days preharvest); θ_V determinations on these dates were subsequently omitted. However, unadjusted neutron counts during this initial three week period remained consistent with trends established

in 2001; following the implementation of the 50 d treatments, there was a rapid initial decline in neutron count in the top 60 cm depth (lower neutron count is consistent with comparatively less soil water on a given date). As expected, 20 d and 30 d cutoff treatments had similar neutron counts through this initial three week period. When the inconsistency with standard counts was corrected, water application during the remaining four weeks preharvest still significantly affected θ_V in the top 60 cm. During this period, θ_V was consistently lowest in the 50 d cutoff (Fig. 4.13a). On all dates, the 50 cutoff had lower significantly θ_V than control plots. The 50 d cutback treatment also had significantly lower θ_V than the control plots, with the exception of the final sampling 1 day preharvest. Volumetric water content did not decline at a substantial rate in the control treatment until cutoff 20 days preharvest; as in 2001, this suggested that irrigation was approximately equal to plant use during this period.

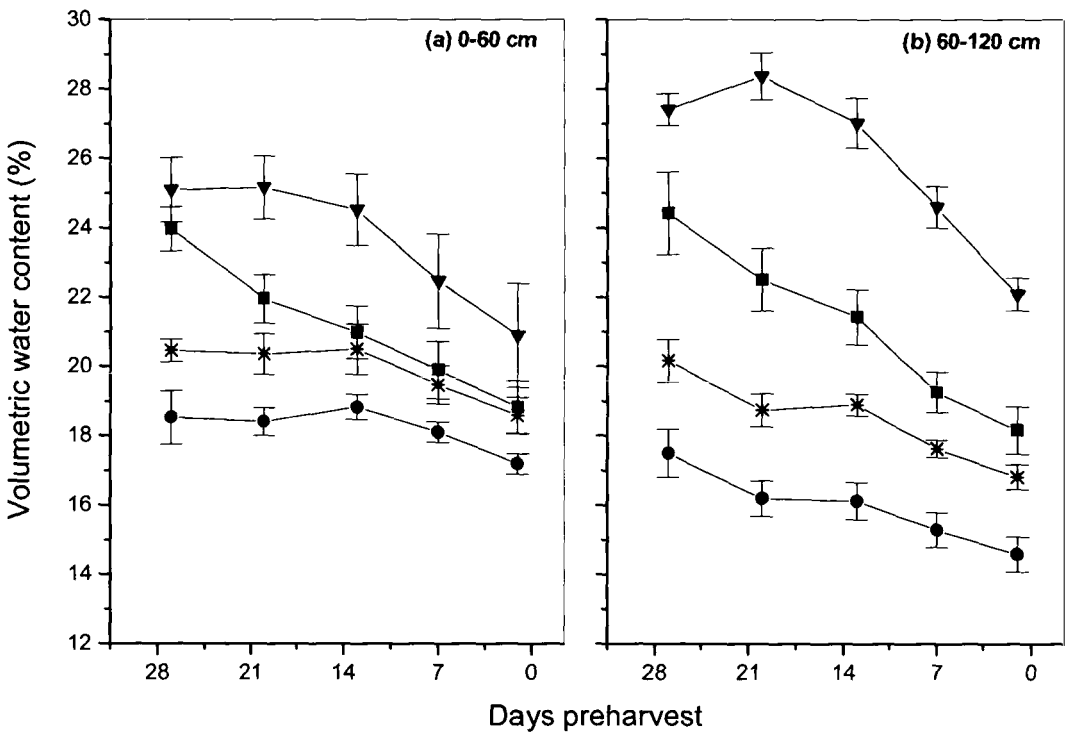


Fig. 4.13. Effect of irrigation treatment on soil volumetric water content (θ_V) in the 0-60 cm (a) and 60-120 cm (b) depth ranges. Treatment means are given ± standard error. Irrigation treatments were full cutoff at 50 days (■), 30 days (•), 20 days (▼, control), and cutback to 25 % ET_o at 50 days (*). θ_V at field capacity was at 39.0 % and at the permanent wilting point was 16.7 %.

When averaged across the final four weeks of fruit ripening, θ_V in the top 60 cm was approximately 24, 21, 18 and 20 % in the 20 d (control), 30 d and 50 d cutoff, and the 50 d cutback, respectively. Volumetric water content in the top 60 cm was consistently correlated with ψ_{Stem} (0700 HR and 1300 HR) during the final three weeks

(after all treatments had been initiated); higher θ_V resulted in higher (less negative) ψ_{Stem}. Significant correlation coefficients ranged from between 0.40 to 0.71 at 0700 HR, and 0.46 to 0.75 at 1300 HR; there was no trend over time.

Both the 20 d and 30 d cutoff had slightly higher θ_V in the 60-120 cm depth range than the top 60 cm; drying patterns were however generally similar (Fig 4.13b). With the exception of the 50 d cutoff, all other treatments had θ_V higher than the predicted permanent wilting point. Little root activity was expected at the lower soil depths.

As in 2001, calculations of ASM and ψ_{Soil} were made (Table 4.11); however, because of the calibration error during early monitoring, both variables could only be estimated across the final four weeks of fruit ripening rather than six. Across this truncated period, the control treatment had an average ASM content of 31 %, equivalent to a ψ_{Soil} of approximately -248 kPa. This represented a considerably more modest degree of water stress when compared to 7 % ASM in the 50 d cutoff, equivalent to a ψ_{Soil} of approximately -1096 kPa. The absence of reliable θ_V measures during the six to four week monitoring period clearly misrepresented water availability in both the control and severe stress treatments during fruit ripening.

Table 4.11. Effect of irrigation treatment on available soil moisture (ASM) and soil matric potential (ψ_{Soil}) across the final four weeks preharvest.

	Final four week average	
Irrigation Treatment	ASM (%)	Ψ_{soil} (kPa)
20 d cutoff	31	-248
30 d cutoff	20	-514
50 d cutoff	7	-1096
25% at 50 d	14	-724

4.3.3 Fruit Yield and Quality Measurements

The effect of irrigation treatment on tomato yield and fruit quality is summarized in Table 4.12.

Table 4.12. Effect of irrigation treatment on tomato yield and fruit quality at harvest.

Irrigation treatment	Total yield (Mg ha^{-1})	Marketable yield (Mg ha^{-1})	Soluble solids (°Brix)	Brix yield (Brix Mg ha^{-1})	Blended colour [z]	Fruit pH
20 d cutoff	125 a	109 a	5.3 b	5.7	25.5 a	4.36
30 d cutoff	119 a	103 a	5.3 b	5.5	25.3 a	4.34
50 d cutoff	103 b	88 b	5.9 a	5.2	23.0 b	4.34
25% at 50 d	117 a	106 a	5.5 b	5.8	24.2 ab	4.30
SE	2.3	2.6	< 0.1	0.1	0.4	0.01
p-value	***	**	***	*ns*	**	*ns*

[z] dimensionless unit, lower value indicates more intense red colour in fruit

ns, **, *** non-significant at $p < 0.10$, or significant at $p < 0.05$ or 0.01, respectively; means within columns separated using the Least Significant Difference (LSD) test, $p < 0.05$

4.3.3.1 Total and Marketable Fruit Yield

Irrigation application during the final 50 days preharvest significantly affected total fruit yield (Table 4.12). Yield was greatest for the control treatment, although was not significantly different to 30 d cutoff or 50 d cutback. Lowest yield was obtained under the 50 d cutoff, which compared poorly to all other treatments. Treatment differences in marketable yield were largely consistent to those for total yield; the percent of yield that was marketable was approximately 86 % for both the control and 50 d cutoff treatments. Total and marketable yield were strongly correlated ($p < 0.01$, r = 0.93).

A significant linear regression model was fitted to total yield ($p < 0.03$, r^2 = 0.92) but not marketable yield in response to the percent of ET_o applied (Fig. 4.14a, b). Inclusion of quadratic or cubic terms was not statistically justified. The linear model confirmed that the percent of ET_o applied in the final 50 days preharvest had a greater effect on total yield than the application strategy. For each 20 % reduction in the ET_o applied during ripening, fruit yield declined by approximately 6 Mg ha^{-1}. Total yield was positively correlated to average θ_V (top 60 cm) across the final four weeks of ripening ($p < 0.01$, r = 0.62); higher soil water availability was generally associated with higher fruit yields. Similarly, average ψ_{Stem} measured at 0700 HR and 1300 HR across the final six weeks was also positively correlated with total yield ($p < 0.01$, r = 0.82 and 0.81, respectively); less negative plant water status was generally associated with higher fruit yields.

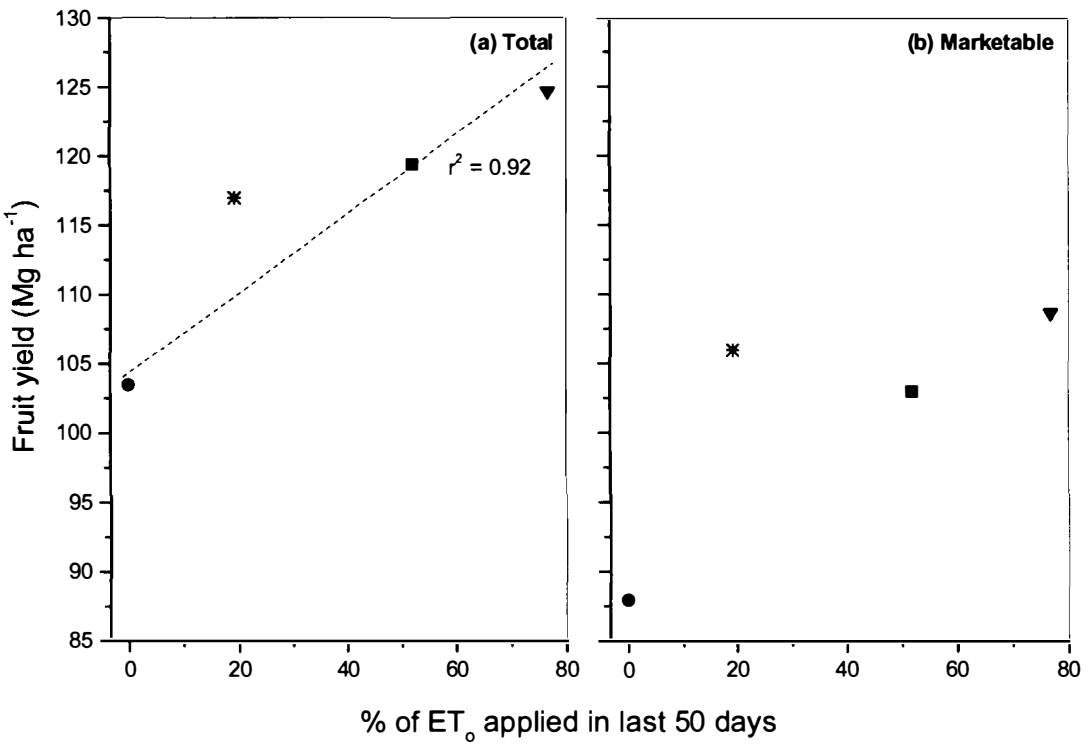


Fig. 4.14. Effect of irrigation treatment on total (a) and marketable (b) fruit yield. Treatment means are shown. Irrigation treatments were full cutoff at 50 days (•), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 50 days (✳). The equation of the fitted linear regression line (···) for total yield was y = (104.3 ±2.1) + (0.2883 ± 0.0024).x.

4.3.3.2 Fruit Soluble Solids

Irrigation application during the final 50 days preharvest significantly affected SSC of marketable fruit (Table 4.12). Fruit SSC was highest for the 50 d cutoff treatment. Lowest fruit SSC was obtained with the 20 d and 30 d cutoffs. Fruit SSC was negatively correlated to total yield ($p < 0.01$, r = -0.69); for every 0.1 °Brix increase in fruit SSC there was a decline in total yield of approximately 2 Mg ha^{-1}.

A significant linear regression model was fitted for SSC against percent of ET_o applied ($p < 0.08$, $r^2 = 0.72$); application amount appeared more important than application strategy (Fig. 4.15). The inclusion of quadratic or cubic terms was not statistically justified. For each 20 % reduction in ET_o applied during fruit ripening, fruit SSC increased by approximately 0.15 °Brix. Fruit SSC was negatively correlated to average θ_V (top 60 cm) across the final four weeks of ripening ($p < 0.04$, r = -0.49); lower water availability was associated with higher SSC. Similarly, average ψ_{Stem} measured at 0700 HR and 1300 HR across the six week period preceding harvest was also

negatively correlated with fruit SSC ($p < 0.01$, r = -0.75 and -0.82, respectively); more negative plant water status was generally associated with higher SSC.

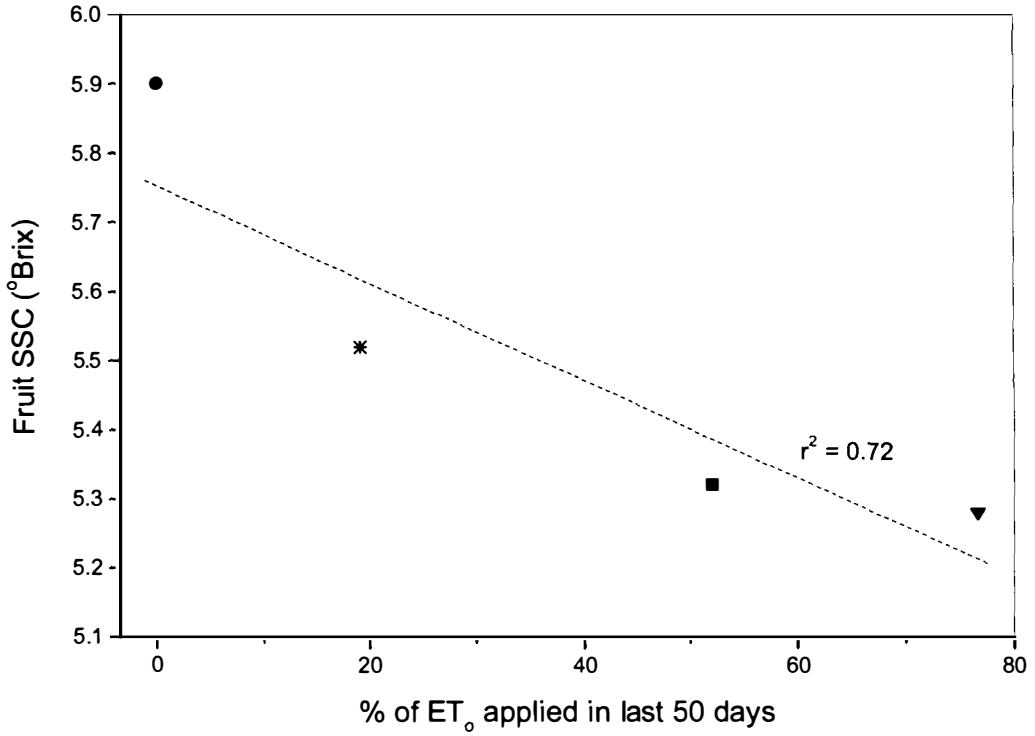


Fig. 4.15. Effect of irrigation treatment on fruit soluble solids concentration (SSC). Treatment means are shown. Irrigation treatments were full cutoff at 50 days (•), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 50 days (✳). The equation of the fitted linear regression line (···) was y = (5.75 ±0.13) - (0.0071 ±0.0024).x.

4.3.3.3 Brix Yield

Brix yield was not significantly affected by irrigation application, averaging 5.55 Mg Brix solids ha^{-1} across treatments (Table 4.12). Unlike 2001, the contrast comparing only the border treatments was not significant, despite a similar numerical increase of approximately 0.5 Mg Brix solids ha^{-1} in the control. Brix yield was significantly correlated with marketable yield ($p < 0.01$, r = 0.88) but not fruit SSC. The response of Brix yield to percent of ET_o applied was not well characterized using linear, quadratic or cubic regression. A linear plateau model was successfully fitted to the data ($p < 0.06$; Fig. 4.16). The inflection point at which a further reduction in percent of ET_o applied was predicted to reduce Brix yield was approximately 15 %.

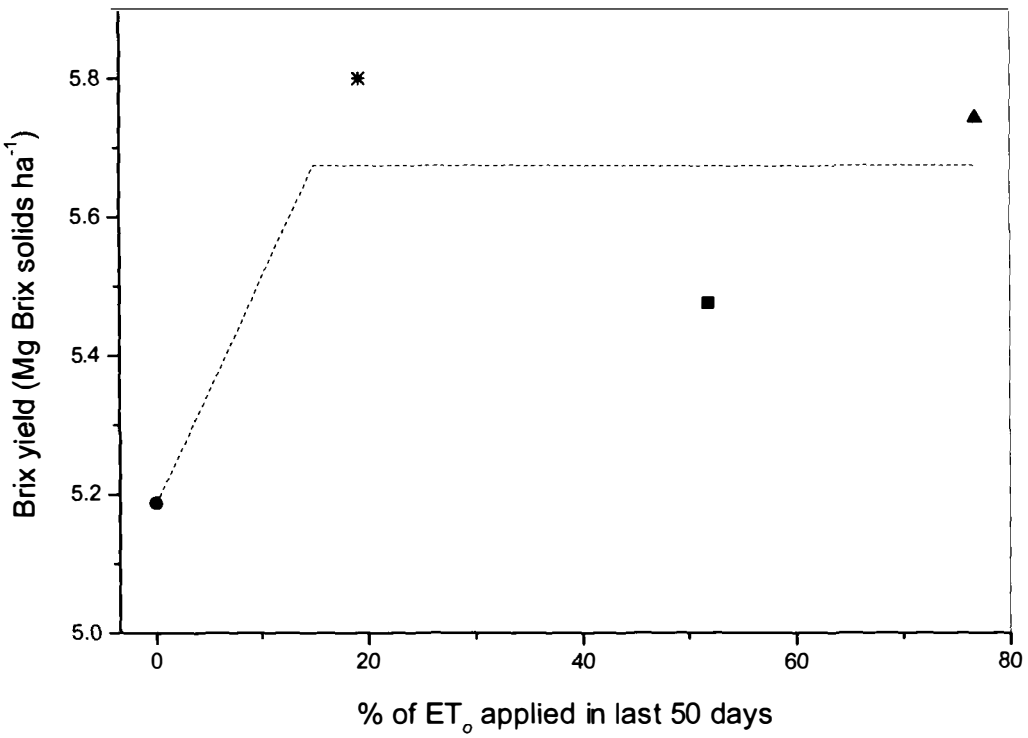


Fig. 4.16. Effect of irrigation treatment on Brix yield. Treatment means are shown. Irrigation treatments were full cutoff at 50 days (•), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 50 days (✳). The equation of the fitted linear plateau regression line (···) was $y = (5.19 \pm 0.21) + (0.0327 \pm 0.0164).x$ where $x < 14.9$, and $y = 5.67$ where $x \geq 14.9$.

4.3.3.4 Blended Fruit Colour

Blended fruit colour was significantly affected by irrigation application in the final 50 days preharvest (Table 4.12). Colour scores were lowest (most red) in the 50 d cutoff and highest in the 20 d and 30 d cutoffs. Fruit colour was not correlated to the yield or percent of green fruit observed. A significant linear regression model was fitted for blended colour against percent of ET_o applied ($p < 0.05$, $r^2 = 0.88$); application amount appeared more important than application strategy (Fig. 4.17). Inclusion of quadratic or cubic terms was not statistically justified. Despite these observations, all treatments achieved colour scores that were considered acceptable for processing.

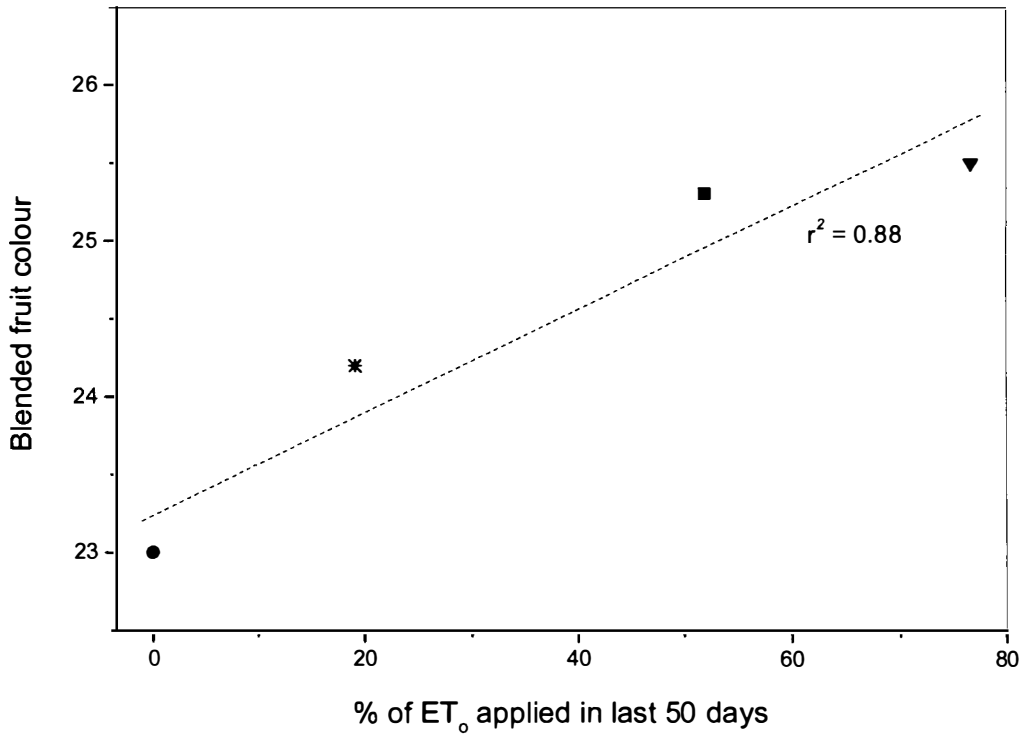


Fig. 4.17. Effect of irrigation treatment on blended fruit colour. Treatment means are shown. Irrigation treatments were full cutoff at 50 days (•), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 50 days (✳). The equation of the fitted linear regression line (···) was $y = (23.2 \pm 0.3) + (0.0332 \pm 0.0069).x$.

4.3.3.5 Fruit pH

Fruit pH was not significantly affected by irrigation treatments imposed during the final 50 days preharvest (Table 4.12). Across treatments, fruit pH averaged 4.34.

4.3.3.6 Mean Marketable Fruit Mass and Fruit Number

Mean mass of marketable fruit was significantly ($p < 0.07$) affected by irrigation application in the final 50 days preharvest; M_{Ff} was greatest in the 20 d and 30 d cutoff treatments, and lowest in the severe 50 d cutoff. Marketable yield was positively correlated with M_{Ff} ($p < 0.02$, r = 0.55); greater fruit mass generally resulted in higher yield outcomes. A significant linear regression model was fitted for M_{Ff} against percent of ET_o applied ($p < 0.06$, $r^2 = 0.83$); application amount appeared more important than application strategy (Fig. 4.18). The inclusion of quadratic or cubic terms was not statistically justified. The number of marketable fruit per plant was not significantly affected by the irrigation treatments imposed (data not shown). However, the 50 d

cutoff had significantly ($p < 0.06$) lower fruit number when compared directly against the control treatment.

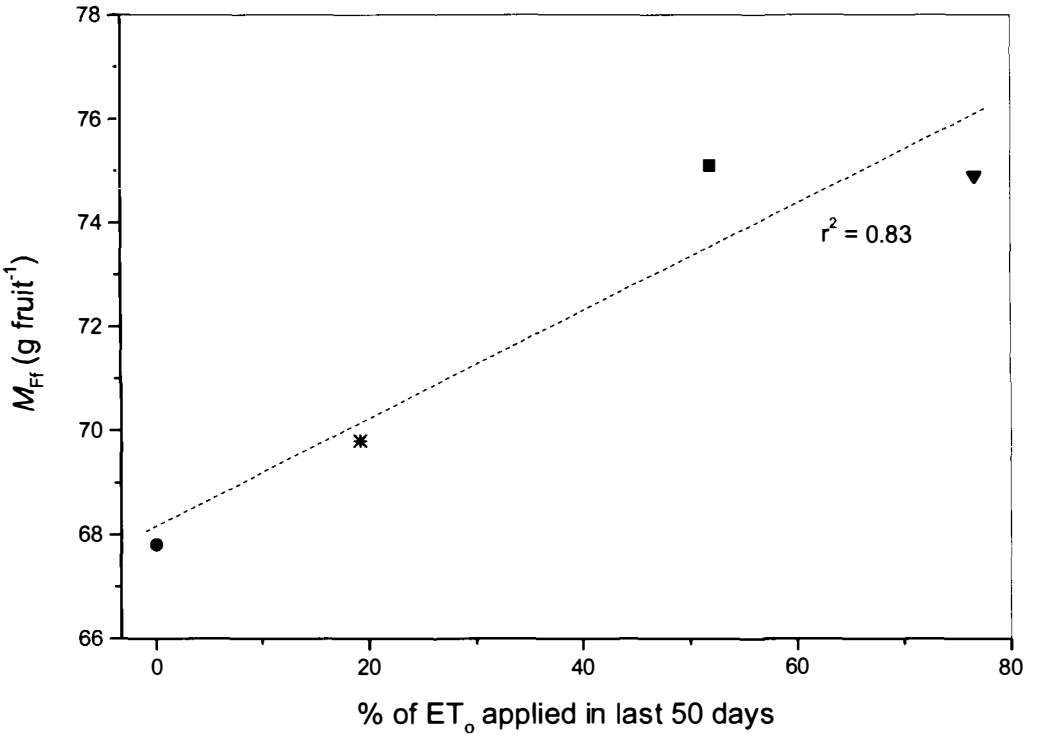


Fig. 4.18. Effect of irrigation treatment on mean marketable fruit mass (M_{Ff}). Treatment means are shown. Irrigation treatments were full cutoff at 50 days (•), 30 days (■), 20 days (▼, control), and cutback to 25 % of ET_o at 50 days (✳). The equation of the fitted linear regression line (···) was $y = (68.2 \pm 1.3) + (0.1036 \pm 0.0258).x$.

4.3.3.7 Yield Components

In following the 2001 practice, yield components were adjusted to a percent of total fruit yield to allow a standardized comparison of crop maturity (Fig. 4.19). Irrigation treatments did not significantly affect the percent of fruit that were marketable, rots or culls. Across treatments, marketable yield averaged approximately 87 % of total yield. The predominant rot species was water mold. The contrast comparing only the percent rots between border treatments was significant ($p < 0.06$); rot incidence was approximately 5 % for the 50 d cutoff and 2 % for the 20 d control. Percent culls averaged 5 % of total yield. Although not categorized separately, sunburn-affected fruit accounted for most culls. By comparison, irrigation treatment significantly affected the percent of fruit that were green ($p < 0.02$); at harvest, green fruit comprised approximately 3 % of total yield for the 50 d treatments compared to 7 % for the 20 d or 30 d treatments. Large sampling variability within treatments was observed for the rot, cull and green components (cv = 80, 49 and 44 %, respectively).

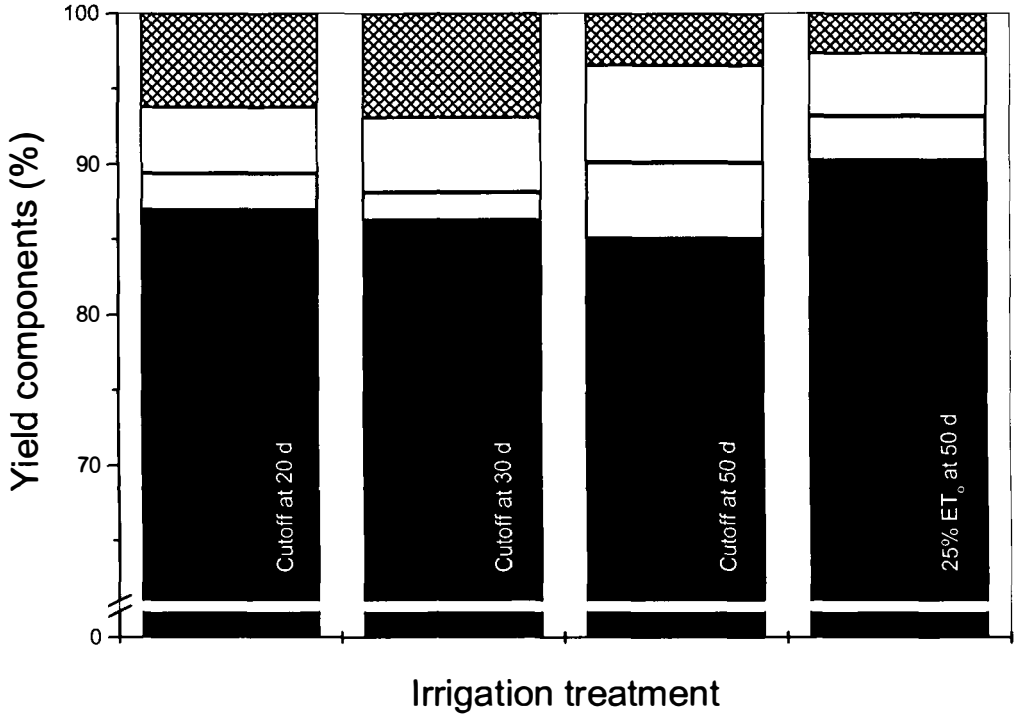


Fig. 4.19. Effect of irrigation treatment on yield components at maturity. Yield Components were marketable (■), rots ( ), culls (□) and greens (⊠).

4.4 Discussion

4.4.1 Effect of Water Application on Plant Canopy Cover

Poorly-timed irrigation deficits can cause severe canopy die-back in processing tomatoes, increasing the likelihood of fruit 'sunburn'. Sunburn is an imperfection on fruit rendering them unsuitable for whole-peeling. Such symptoms appear when fruit are directly exposed to solar radiation and overheating of tissue occurs (Adegoroye and Jolliffe, 1983). Ideally, growers need to establish a full vegetative canopy early in the season to support flowering and fruit set, and retain as much of this cover until close to harvesting. This not only allows fruit to be shaded to some extent (in so doing reducing the risk of sunburn), but also retains leaf assimilate supplies that can be redistributed to fruit as they develop (ensuring high fruit quality). Some degree of canopy decline is unavoidable as plants senesce close to harvest; however, late-season irrigation strategies that cause excessive die-back should be avoided.

In both seasons full plant cover was achieved before irrigation treatments were imposed; accordingly, there was no water-stress impediment to maximum canopy development. In no instance did increasing late-season water stress significantly reduce

measures of percent canopy made in 2001. This suggests a high tolerance to water deficit without canopy decline; even the most severe 60 d irrigation cutoff did not accelerate plant die-back or vine collapse. Typically, ψ_{Leaf} exceeding -0.6 to -0.7 MPa causes stomatal closure in tomato (Cerda *et al.*, 1979; Rudich *et al.*, 1981), which in turn can reduce the ability of the plant to regulate its internal temperature; excessively high temperature can disrupt a number of physiological processes and also cause leaf tissue to die. Although on several sampling occasions severe stress treatments had ψ readings exceeding this threshold, these were generally only observed under peak solar load; plants returned to less negative water potentials overnight. Rudich *et al.* (1981) suggested that even well-watered field tomatoes can experience daily fluxes in ψ that exceed -0.6 MPa. Where ψ consistently exceeds critical thresholds canopy decline may become problematic; on a lighter-textured soil with low moisture retention, severe irrigation cutoffs imposed as early as 60 days preharvest may have in fact increased dieback. Cultivar selection can also have a strong effect on the incidence of canopy decline; cultivars with a large root system may be able to buffer water deficits to a greater extent, thereby moderating water stress in the plant.

4.4.2 Effect of Water Application on Plant Water Status

4.4.2.1 Effect of Sampling Technique

Traditionally, predawn measurements of ψ have been made to quantify plant water status when it is close to equilibrium with available soil water (Meyer and Green, 1980). However, the commercial use of this technique has been limited because measurements on exposed leaves must occur before sunrise (and increasing water demand). In the current studies, bagging leaves overnight for early morning sampling the next day extended the period during which estimates of predawn plant water potential could be reliably made. This would allow growers to monitor a greater number of fields between 0500 HR (sunrise) and 0700 HR. The fact that 0700 HR ψ_{Stem} (measured on bagged leaves) was generally less negative than 0700 HR ψ_{Leaf} (measured on exposed leaves) confirmed the rapid effect of radiation and air temperature on transpiration and plant water potential.

Meyer and Green (1981) suggested that the bagging technique can also reduce short-term environmental variability as compared to actively transpiring leaves. Greatest variability is frequently observed under peak solar radiation, which is also concurrent to maximum photosynthetic rates and water demand. However, sampling ψ under these conditions provides an important measure of plant water stress unaffected by the overnight recovery of water turgor. Bagging leaves for at least two hours before afternoon measurement reduced sampling variability related to transient environmental factors; across seasons, the difference between ψ_{Leaf} and ψ_{Stem} averaged approximately 0.35 MPa. By substantially reducing transpiration, the bagging technique allowed the water potential of leaves to equilibrate with the stem and roots. This provided a more reliable indicator of overall plant water status as related to fruit yield and quality. The overall success of the bagging technique was consistent to findings made in other crops (Fulton *et al.*, 2001; McCutchan and Shackel, 1992). This appeared to be the first work published specifically on processing tomato.

4.4.2.2 Effect of Irrigation Treatment

Plant-based measurements provide the only true measure of actual water stress at any given time; methods such as the bagging technique that reduce variation may then have some practical field application for late-season irrigation management. Early morning and early afternoon measurements of plant water potential on bagged leaves confirmed that irrigation treatments caused varying levels of water stress. This was generally reflective of the percent of ET_o applied; greater irrigation amount resulted in lower plant water stress.

Average ψ_{Stem} during fruit ripening was consistently correlated to fruit yield and SSC at commercial maturity. Measurements made in the early afternoon typically resulted in the strongest relationships with yield and quality. This appeared to reflect the absence of overnight recovery in leaf turgor, as was observed with many early morning measurements; inasmuch, overnight recovery tended to moderate differences between treatments. More negative plant water potential (indicative of greater water stress) was associated with lower yield and higher fruit SSC. Average 1300 HR ψ_{Stem} in the range of -0.5 to -0.7 MPa during the final six weeks preharvest was sufficient to achieve fruit SSC levels > 5.0 °Brix, an acceptable commercial target for many

growers. These results suggest that the use of ψ_{Stem} to help augment late-season irrigation management (particularly when measured under peak solar load) may warrant further research.

4.4.3 Effect of Water Application on Soil Water Status

The rapid sensitivity of soil water status to irrigation application has resulted in a number of soil-based monitoring techniques being investigated to track soil moisture and manage fruit SSC (Cahn *et al.*, 2003, 2004; Calado *et al.*, 1990; Hartz, 1996; Phene, 1999). Soil-based moisture measures are not generally influenced by transient weather factors, a limitation of traditional ψ measurements. Many growers therefore believe soil measures to be a more reliable predictor on which to manipulate irrigation decisions.

Measurements of θ_V confirmed that irrigation practices achieved varying levels of water availability within the soil. This was generally reflective of the percent of ET_o applied; greater irrigation amount resulted in higher availability. In neither year did θ_V in the top 60 cm decline significantly until after each respective treatment was imposed. This strongly suggests that the calculated irrigation amounts were sufficient to replace actual evapotranspiration (as intended). Volumetric water content generally declined at a rapid rate immediately following the implementation of the each treatment, slowing thereafter as soil tension increased; increasing soil tension reduces the availability of water to the plant roots, as the soil matrix holds water more tightly (Brady, 1990). In several treatments, available soil water was substantially depleted by harvest, although θ_V did not generally drop below the permanent wilting point associated with each soil. Although prolonged periods just above the permanent wilting point would likely increase fruit SSC, a disproportionate loss in yield may also result. Such severe water stresses are seldom recommended for commercial practice.

Average θ_V during fruit ripening was not as strongly correlated to yield and fruit SSC as 1300 HR ψ_{Stem}. As previously described, this appeared to be the result of bagging leaves for several hours before measurement, which overcame many of the limitations previously related to sampling exposed leaves. Volumetric water content was further interpreted in terms of available soil moisture and ψ_{Soil}. However, across seasons no reliable ψ_{Soil} target during fruit ripening was found. In the first season, ψ_{Soil}

as modest as approximately -90 kPa was sufficient to achieve fruit SSC > 5.0 °Brix, while in the second season ψ_{Soil} as high as approximately -250 kPa was necessary. By comparison, Cahn *et al.* (2004) reported that a ψ_{Soil} of -150 kPa across the final 6 weeks preharvest was sufficient to achieve fruit SSC > 5.0 °Brix.

Collectively, these observations indicated that monitoring soil water status did not offer the best approach from which to base late-season irrigation to accurately raise fruit SSC with minimal yield loss. Because no irrigation system is entirely uniform and no soil is completely homogenous, representative readings can only be obtained by monitoring moisture at various depths and locations within each field; this type of setup may become impractical to manage. The use of soil-based monitoring systems therefore appears best targeted as a 'backstop' for over- or under-watering based upon modelled crop water balances. For this purpose, electrical resistance blocks and soil tensiometers appear most appropriate, because they are affordable, practical, and can be automated. Despite improvements in the reliability and accuracy of ψ measures through bagging, growers are unlikely to use such techniques as an irrigation back-stop; this is because measuring ψ_{stem} can be time consuming and requires a greater level of user-expertise.

4.4.4 Effect of Water Application on Yield and Quality Measurements

4.4.4.1 Total and Marketable Fruit Yield

Total and marketable fruit yield generally decreased with reduced water application during ripening. These findings were consistent with previous studies under both arid and humid climates (Cahn *et al.*, 2001, 2003; Calado *et al.*, 1990; May and Gonzales, 1994, 1999; May *et al.*, 1990; Mitchell *et al.*, 1991a, b; Murray, 1999; Renquist and Reid, 2001; Wudiri and Henderson, 1985; Zegbe-Domínguez *et al.*, 2003). Most report that increasing water deficit during fruit sizing and ripening reduces yield, although the magnitude of loss has varied considerably depending on the timing and severity of deficit and by soil and environmental factors.

In the current studies, means separation or contrasts confirmed that four of the five treatments applying less than 40 % of ET_o in the final 60 days had significantly lower fruit yields than the control treatment; this included cutoff treatments initiated 40

days or more preharvest and cutback treatments initiated 60 days preharvest. By comparison, there was a relatively high tolerance to water deficits imposed within the final 40 days (approximately 6 weeks) of ripening. In no trial did the application strategy itself (cutoff or cutback) appear to have an overall statistical influence on fruit yield (total or marketable). In as much, the percent of ET_o applied appeared to be a useful predictor of yield once fruit had set and begun to ripen.

Lower yield was primarily related to smaller fruit size, although severe irrigation cutoffs imposed more than six weeks preharvest also caused a small reduction in fruit number per plant. Declining fruit mass in response to irrigation deficits imposed after fruit have set has been commonly reported (Cahn *et al.*, 2003, 2004; Colla *et al.*, 1999; May and Gonzales, 1994, 1999; Mitchell *et al.*, 1991b; Murray, 1999). Lower fruit number may have resulted from increased flower abortion under elevated plant water stress (Atherton and Othman, 1983; Colla *et al.*, 1999; Pulupol *et al.*, 1996; Wudiri and Henderson, 1985) or an increasing number of fruit that rotted and were not counted (Nichols *et al.*, 2001; Murray, 1999). Because most fruit are set between 11-6 weeks preharvest (fruit set in the final 6 weeks do not typically mature before harvest), avoiding water stress during this sensitive period appears critical in maximizing fruit yields.

Although the standard grower practice of irrigating late into the season resulted in the greatest yield, such practices in drip-irrigated fields have historically caused highly variable fruit SSC. This variability has been largely related to field-specific factors (soil texture, rooting depth and wetting pattern away from the drip tape), making it impossible to develop a generic cutoff date recommendation. An alternative approach to complete irrigation cutoff is cutback irrigation. Imposing a controlled water deficit early in the fruit ripening phase has shown the potential to increase SSC with only a minimal sacrifice in fruit yield (Cahn *et al.*, 2001; Renquist and Reid, 2001). In the current studies, cutback strategies also appeared to provide this 'middle-ground' between cutoff dates imposed too early and those imposed too late. In both years, the yield of moderate cutback deficits (40 d and 50 d) even to 25 % of ET_o were comparable to the standard 20 d irrigation cutoff.

4.4.4.2 Effect of Water Application on Fruit Soluble Solids

Fruit SSC generally increased with reduced water application during ripening. This observation was consistent with previous studies (Battilani, 1994; Cahn *et al.*, 2001, 2003; Calado *et al.*, 1990; Colla *et al.*, 1999; Lowengart-Aycicegi *et al.*, 1999; May and Gonzales, 1994, 1999). Water stress increases plant water potential (Mitchell *et al.*, 1991a; Renquist and Reid, 2001; Rudich *et al.*, 1981), which reduces the movement of solutes into developing fruit; this decreases fruit expansion and results in higher sugar concentrations (Ehret and Ho, 1986). While early-season irrigation cutoffs (60 d or 50 d) increased fruit SSC, they also disproportionately depressed yields and were therefore uneconomical. Although even the control treatment reached the commercial benchmark of 5.0 °Brix in both trials, this presumably reflected the modest yields (high fruit loads can reduce SSC; Dumas *et al.*, 1994) and careful management afforded to experimental plots. In the commercial setting, a large number of drip-irrigated fields have not met this standard using the standard 20 d cutoff approach, most commonly due to insufficient water stress during fruit ripening. Fruit SSC levels have been as low as 3.9 °Brix in some drip-irrigated fields (Linden, 2004); although this represents the extreme, Hartz (2001) suggested a consistent decline in fruit SSC of between 0.2-0.5 °Brix when compared to the furrow average.

To reliably increase fruit SSC, sufficient water stress needs to be imposed sooner than the standard grower practice achieves; 50-70 % of fruit may have developed colour by the time irrigation is stopped 20 days preharvest, leaving only a small percent of green fruit on which subsequent water stresses are effective (Hartz *et al.*, 2004). As an alternative to full cutoff, irrigation cutbacks imposed at the onset of ripening (approximately 6 weeks preharvest) appeared to provide greater flexibility in managing SSC, as a large percent of fruits were subjected to modest water deficits without a high risk of excessive yield loss. Across seasons, fruit SSC in treatments that were cutback to 25 % of ET_o at 40 d and 50 d was approximately 0.2 °Brix higher when compared to the standard 20 d cutoff; this was achieved with only a small yield loss. Even small improvements in fruit SSC are important to processors because the savings can be substantial (Renquist and Reid, 2001); based on the financial estimations provided by Linden (2004), an improvement in fruit SSC of 0.2 °Brix would reduce processing expenses by approximately US$230 per hectare.

4.4.4.3 Effect of Water Application on Brix Yield

Generally, Brix yields did not decline with reduced water application during fruit ripening. This observation was consistent with the 'dilution' relationship between fruit yield and SSC, which often results in lower SSC with increasing yield and higher SSC with decreasing yield (Cahn *et al.*, 2001, 2003; Colla *et al.*, 1999; Dumas *et al.*, 1994; May and Gonzales, 1994, 1999; Phene, 1999; Renquist and Reid, 2001; Rudich *et al.*, 1977; Stevens and Rudich, 1978). However, this trade-off relationship was not unlimited; across years, Brix yields from the earliest cutoff treatments were lower when compared against only control treatment; average Brix yield loss was approximately 0.5 Mg Brix solids ha^{-1}. This confirmed a disproportionate loss of yield per SSC increase. At current market pricing in California, the financial value per Mg of Brix solids is approximately US$1050; decline of 0.5 Mg ha^{-1} could therefore result in a grower loss of US$525 per hectare. To maximize Brix yields, irrigation cutoff implemented more than six weeks preharvest should therefore be avoided.

As a practical tool, irrigation cutbacks appeared to provide greater control of Brix yield than full irrigation cutoff. Irrigation cutback to 25-50 % of ET_o imposed at the onset of fruit ripening resulted in high SSC outcomes with no overall loss in Brix yield. Although full irrigation cutoff 30 or 40 days preharvest achieved comparable Brix yields to the standard in the current trials, these strategies do not appear to offer the same degree of flexibility as irrigation cutback. On lighter-textured soils, irrigation cutoff at 40 days may have resulted in larger yield loss, while on a heavy-textured soil irrigation cutoff at 30 days may not have greatly affected fruit SSC. By supplying only a reduced amount of water during fruit ripening, growers have the beneficial effect of modest water stress on SSC without the same degree of risk associated with yield loss. Unlike irrigation cutbacks, cutoff decisions are also typically irreversible, in that by the time excessive stress conditions are observed, productivity has invariably been lost.

The use of irrigation cutbacks in drip-irrigated fields warranted further research. In a continuation of these initial trials, irrigation cutback for use in commercial fields was investigated under conditions representative of the California processing tomato industry. This research is summarized by Johnstone *et al.* (2005b, Appendix IV). In addition to irrigation cutback, these trials also advocated monitoring the SSC of early ripening fruit at a breaker-stage maturity (equivalent to 30-60 % of the fruit surface showing a colour other than green). Fruit monitoring provides the flexibility to tailor

irrigation strategies on a field-specific basis; more aggressive water deficit strategies could be considered in fields with low initial SSC, while modest water deficits could be used when SSC levels are already high. Because some degree of marketable yield loss is unavoidable with water stress, predicting the SSC of these early-ripening fruit should minimize unnecessary loss of productivity.

Cutback techniques may also be promising in humid environments such as N.Z., where rainfall can be received during the fruit ripening period. Rainfall can mitigate the effect of late-season cutoffs (20-30 days), reducing the ability of growers to increase SSC. A similar problem was described by Burgmans *et al.* (1998); in four of five seasons, they were unable to impose a substantial water stress on plants because of rainfall and subsurface water supplies. An irrigation cutback started during early ripening may therefore allow some degree of moisture stress to accrue with time, reducing the impact of late rainfall (if received). Such cutback techniques appear to warrant further research in these types of environments.

4.4.4.4 Effect of Water Application on Blended Fruit Colour

The blended colour of marketable fruit generally improved with reduced water application during ripening. These results were consistent with those of others (Cahn *et al.*, 2003, 2004; Colla *et al.*, 1999; May and Gonzales, 1999; Zegbe-Domínguez *et al.*, 2003); all found that increasing water stress during ripening increased the red colour intensity of fruit. The relationship between irrigation management and fruit colour is presumably an indirect result of water stress accelerating fruit ripening (Wolf and Rudich, 1988); ripening includes the degradation of green chlorophyll and synthesis of lycopene.

Importantly, even the colour scores of the control treatments were acceptable for subsequent processing. Larger treatment differences appeared to be moderated by the small effect of irrigation on crop maturity. Because all treatments were harvested when the control treatment was approximately 95 % ripe, most fruit had matured; there was then an inherently low ratio of green to red colour in all fruit. It is therefore unlikely that fruit colour will be limited by irrigation management decisions in fields that are harvested close to commercial maturity.

4.4.4.5 Effect of Water Application on Fruit pH

Fruit pH was unaffected by reduced irrigation application. This confirmed that late-season water management does not offer growers a reliable tool to manipulate fruit pH. Similar observations were made by Cahn *et al.* (2003); across 10 commercial field experiments, variability was greater between sites than between irrigation treatments. May and Gonzales (1994) and Murray (1999) also found no consistent relationships between fruit pH and irrigation. Cultivar selection and harvesting fruit at a correct stage of maturity remain the most effective strategies for pH manipulation.

4.4.4.6 Effect of Water Application on Yield Components

There was little effect of irrigation management on fruit maturity; by design, differences were moderated by selecting a harvest date that reflected the commercial maturity of the control treatment (i.e. the least stressed treatment). Across seasons, the percent of ripe fruit at harvest was high (approximately 95 %). Good 'field-storage' capability in 'Halley' as suggested by May and Guillen (2001) meant that the percent of marketable fruit was similar across most irrigation treatments. Some studies have suggested that severe irrigation deficits can increase fruit culls and rots (Adegoroye and Jolliffe, 1983; Colla *et al.*, 1999; May and Gonzales, 1999; Murray, 1999). With the exception of the earliest irrigation cutoffs in each year (60 d and 50 d), all other treatments resulted in low fruit culls and rots. It is likely that other production conditions (late rainfall, free moisture on bed tops, humidity and air temperature) influence fruit culls and rots more severely than irrigation strategies imposed during the final 6 weeks preharvest. Selecting a harvest date when most fruit are ripe (but before excessive fruit rots prevail) is therefore important in maximizing marketable yield and quality. Such a strategy will also minimize the percentage of fruit that are green.

CHAPTER 5: Summary

The use of drip fertigation has significantly increased the yield of processing tomatoes, while offering increased fertilizer and irrigation efficiency. Reducing production inputs may improve overall environmental stewardship. However, current fertilizer norms may over-estimate plant demand in such systems. Additionally, some processors have remained hesitant of drip because fruit soluble solids have been lower than achieved with conventional irrigation strategies. A series of four experiments were conducted to investigate both fertilizer and irrigation management in drip-irrigated processing tomatoes. Improved stewardship in both areas not only offers a potential grower benefit (reduced costs and greater productivity) but also lowers the potential risk of environmental degradation.

5.1 1998-1999 Aeroponic Nutrition Trial

A glasshouse nutrition experiment was conducted during the summer of 1998-1999. The experiment was designed to evaluate the effect of low or high fertility combinations during vegetative development, fruit development and fruit ripening on plant growth and subsequent fruit yield and quality of processing tomato. Aeroponic technology was selected to enable sharp comparison of fertility regimes in each growth period; supply of nutrients directly at the root surface effectively eliminated any buffering capacity of a soil volume, which has been a limitation of traditional fertilizer trials in the field. The aeroponic experiment was conducted at Massey University, Palmerston North. Twelve destructive plant harvests were made to quantify the effect of time and fertility combinations on plant biomass. Tomato yield and fruit quality were determined at the final harvest. Cumulative uptake of N, P and K was calculated for each period of plant growth, and related to maximum yield and fruit quality.

5.1.1 Effect of Fertility on Plant Growth

Seasonal plant biomass accumulation for all treatments was sigmoidal, consistent with the typical growth habit of processing tomato. Compared to low fertility treatments, high fertility during early growth increased the vegetative framework established by the plants. This difference in early vegetative growth largely determined

subsequent yield outcomes. With high initial fertility, fruit number and total biomass were maximized, which mostly likely reflected greater assimilate supply in plants that had established larger vegetative canopies.

Greater accumulation of vegetative biomass with high initial fertility was attributable to an increased RGR in plants, which itself was related to a higher LAR early in the season. These observations were consistent with the larger leaf area developed with high initial fertility; by comparison, low early fertility caused a mild N deficiency, which reduced leaf area. The P and K status of plants appeared unrelated to any biomass measure.

5.1.2 Effect of Fertility on Leaf Nutrient Concentrations

The N, P and K status of youngest-mature leaves were monitored seasonally and compared against established nutrient sufficiency norms for processing tomatoes.

5.1.2.1 Nitrogen Concentration

Seasonally, leaf N concentrations declined as assimilates were redistributed to developing fruit. In plants receiving low fertility during vegetative development, the concentration of N in leaf tissue fell increasingly below established sufficiency norms; tissue values appeared to be mildly deficient. These observations were consistent with reduced vegetative growth. Early N deficiency appeared to primarily reflect high demand for this nutrient during the intensive period of vegetative growth. During fruit development and ripening, tissue N concentrations were above established sufficiency norms for all treatments.

5.1.2.2 Phosphorus Concentration

Seasonally, the concentration of P in leaf tissue remained very high for all treatments; values were well above established sufficiency norms. Leaf P concentration did not decline as fruit developed. Both observations suggested that P availability in solution was sufficient for optimal growth, even under low fertility; irrespective of concentration in solution P was continuously available in highly-soluble plant forms. There was no evidence to suggest that such high concentrations in the plant reflected an

actual critical growth requirement. Differences in plant growth and fruit yield therefore appeared unrelated to P status in the plant.

5.1.2.3 Potassium Concentration

Seasonally, the concentration of K in leaf tissue remained very high for all treatments, well above established sufficiency norms. Given the high early-season K concentrations in the leaf, there was no evidence to suggest that differences in vegetative biomass and subsequent fruit yields were related to tissue K status. This suggested that K availability in solution was sufficient for optimal growth, even under low fertility. There was no seasonal decline in leaf K concentrations for most treatments, and in some (particularly those receiving high late fertility), tissue K concentrations actually increased as fruit developed and ripened. This increase most likely reflected luxury absorption of K due to availability in solution rather than an actual plant demand; fruit yields were determined well in advance of such increases.

5.1.3 Effect of Fertility on Fruit Yield and Quality

Maximum total fruit yield was achieved with high initial fertility. Higher yield was due to greater fruit number rather than mean individual fruit mass, which varied little between treatments. Marketable yields were low for all treatments because the final harvest occurred before full maturity. High initial fertility did not increase fruit culls, nor did it cause a significant delay in crop maturity. Maximizing total yield would therefore also maximize marketable yield. BER incidence was high across treatments; there was no evidence to suggest that high fertility regimes increased BER.

Across treatments, fruit SSC was low. Most likely this reflected an earlier than ideal harvest before full maturity and also a lack of significant osmotic stress during ripening. There was a small improvement in SSC with high fertility, particularly when supplied during fruit ripening. It was unclear whether elevated solution conductivity or higher K availability caused this response. However, the efficacy of high late-season fertility as fruit ripened appeared poor, because plant nutrient demand after most growth had ceased was comparatively low. Given the positive effect of high initial fertility particularly on total yield (and to a lesser extent fruit SSC), Brix yield was also maximized with high initial fertility. High late-season fertility increased titratable

acidity of fruit, although this improvement was small. There was no effect of fertility on lycopene content of ripe fruit.

5.1.4 Effect of Fertility on Nutrient Uptake

Plant uptake for N, P and K followed closely the pattern of biomass accumulation. Greatest nutrient uptake was during the period of rapid fruit biomass accumulation. The fact that nutrient uptake was sigmoidal emphasized that crop demand for nutrients changes seasonally. Seasonal plant nutrient uptake for high fruit yield (> 90 Mg ha^{-1}) was equal to 12.1, 3.0 and 20.8 g $plant^{-1}$ for N, P and K, respectively; at 22,222 plants ha^{-1}, this was equivalent to approximately 270, 67 and 460 kg ha^{-1}, respectively. Plant N uptake was similar to that in high-yielding commercial fields, while both P and K were well above typical field levels. Although aeroponic culture provided the ideal root environment for plant growth and allowed manipulation of fertility directly at the root surface, the interpretation of nutrient uptake results obtained from this method appeared confounded by its own unique limitations. All nutrients were supplied in highly absorbable forms, so although nutrients varied in concentration, they were readily available. In this system there was luxury uptake of both P and K.

5.2 1999-2000 Field Nutrition Trial

A field experiment was conducted during the summer growing season of 1999-2000, to validate the results found in the aeroponic experiment. Based on the aeroponic study under controlled conditions, 'optimum' nutrient uptake was quantified for maximum tomato yield and fruit quality. Closely matching nutrient supply with this plant demand was tested as a means of maintaining high yield in processing tomato while improving fertilizer efficiency with small but regular nutrient fertigation. The experiment was conducted at Massey University, Palmerston North. Soil texture for this study was a sandy loam. Field treatments compared optimum fertility to rates below (0 or 0.5x optimum) and above (1.5 and 2.0x optimum) this estimation. Only N and K treatments were evaluated in the field, because the experimental site had a very high initial soil test P value. Treatments were supplied by drip fertigation, three times per week. The nutrient status of the crop was monitored at early bloom, full bloom and

early fruit ripening. An early destructive plant harvest was made to quantify the effect of fertility on plant biomass. Tomato yield and fruit quality were determined later in the season but before commercial maturity.

5.2.1 Effect of Fertility on Leaf Nutrient Concentrations

The N, P and K status of youngest-mature leaves were monitored seasonally and compared against established nutrient sufficiency norms for processing tomatoes.

5.2.1.1 Nitrogen Concentration

As in the aeroponic experiment, leaf N concentration declined seasonally as assimilates were redistributed to fruit. Optimal fertility and above resulted in tissue N values interpreted as sufficient for high yield. In plants receiving above optimal fertility tissue N concentrations were not supra-optimal despite very large N applications (as much as double typical commercial applications); this suggested plant demand was not as high as these rates supplied. Tissue N concentration appeared to be mildly deficient during early bloom in treatments receiving less than optimal fertility; a similar observation was made for the low fertility treatment under aeroponics. Late-season tissue N concentration in these treatments was not below established sufficiency values, suggesting that N application after most active fruit growth has stopped was unnecessary.

5.2.1.2 Phosphorus Concentration

All treatments resulted in adequate tissue P status compared to established sufficiency norms. This reflected the high soil test P value at the experimental site. Leaf P concentration declined seasonally in the field. Tissue P concentrations were considerably lower than found under aeroponics, even at what was considered to be a high soil test P level. This confirmed that there was luxury uptake of P in the aeroponics experiment.

5.2.1.3 Potassium Concentration

All treatments resulted in adequate to high tissue K status compared to established sufficiency norms. Seasonal decline was observed in all treatments, even those supplying large amounts of fertilizer K; this reflected redistribution of K to the fruit. Although K application during fruit ripening resulted in greater leaf K concentrations, such applications were unnecessary for maximum yield and fruit quality. Field results confirmed that the high late-season tissue K concentrations under aeroponics represented luxury levels; K uptake under glasshouse conditions therefore over-estimated actual plant demand.

5.2.2 Effect of Fertility on Plant Growth

Plants receiving optimal fertility and above established the greatest total biomass and leaf area by flowering. The N status of plants was most important in accounting for these differences; plants with low biomass and small leaf area had leaf tissue N concentration below sufficiency norms at early bloom. The P and K status of plants were adequate for all treatments. These findings were consistent to those made under aeroponics.

5.2.3 Effect of Fertility on Fruit Yield and Quality

High total fruit yield was achieved with treatments that supplied optimal fertility and above. Higher yield was due primarily to greater fruit number rather than mean fruit mass. Improved fruit number appeared associated with the larger vegetative frameworks established early in the season. These findings were consistent to those made under aeroponics, and were also related to early-season N status in plants rather than to P or K. Marketable yields were not maximized for any treatment; this reflected an early harvest date due to an increasing incidence of plant disease and fruit rots. Above-optimal fertility resulted in the lowest percent of total yield that was marketable. This was linked to high tissue N status which delayed maturity. However, there was no effect of fertility on fruit culls. If all treatments had been grown to commercial maturity, marketable yields would have been greatest in plants receiving optimal

fertility and above. The incidence of BER was almost non-existent in the field compared to levels found under glasshouse aeroponic culture.

Applying above optimal fertilizer did not increase fruit yields compared to the optimal treatment. The likelihood of N (and possibly K) leaching out of the active root zone was high due to heavy summer rainfall and a light-textured soil. It appeared that the optimal fertility treatment itself would most likely have been sufficient to maximize growth and subsequent yields under normal field conditions (i.e. a drier season). Fertilizer applications made during fruit ripening were not useful, as mean fruit mass was not improved. Maximum yields therefore appeared attainable at rates equivalent to plant uptake determined for only the initial two periods of growth under aeroponics (vegetative development and fruit development); at a density of 22,222 plants ha^{-1} this was equal to approximately 210 and 310 kg ha^{-1} of N and K, respectively. These rates were comparable with current supply in commercial processing tomato fields.

Across treatments, low fruit SSC reflected high soil moisture availability during ripening and also a final harvest before full maturity. Higher fertility resulted in greater fruit SSC. This improvement may have been associated with the larger plant canopies established with higher fertilizer rates; larger canopies often have improved assimilate capacity. There was no correlation between fruit tissue K concentration and fruit SSC. Application of K fertilizer during fruit ripening was therefore neither a reliable nor cost effective means to favourably influence SSC, and did not appear to offer any further benefit beyond appropriate late-season water management; considerably higher fruit SSC levels were achieved without excessive K application but where late-season soil moisture stress was imposed by rain-shelter. Given the positive effect of at least optimal fertility on total yield and fruit SSC, Brix yield was also maximized for these treatments.

The concentration of N, P and K in fruit reflected the overall availability of each nutrient in the plant, but otherwise appeared unimportant. Nutrient removal in the harvested marketable product was closely associated with fruit yields; higher yields resulted in greater removal of N, P and K. However, the majority of applied N and K were not removed in the harvested fruit, and therefore either remained in the soil, was leached or returned to the soil as crop residue. Fertilizer efficiency was poor, less than 25 % of applied N and K for all fertilizer treatments. The very low efficiency at above optimal fertility confirmed that such applications were not only unjustified, but extremely wasteful; these applications exceeded plant demand under normal field

conditions. Despite poor efficiency, fertigation technology still offered the potential to closely match plant demand with supply compared to conventional pre-plant and side-dressing fertilization techniques.

5.3 2001 and 2002 UCD Irrigation Management Trials

Management for high fruit SSC levels was not reliably achieved by heavy late-season fertilization. Subsequently, irrigation experiments were conducted during the summer of 2001 and again in 2002. The aim was to evaluate the effects of irrigation management during fruit ripening on yield and SSC of drip-irrigated processing tomatoes. Late-season irrigation cutoff and cutback treatments were investigated, from no water during the final 60 days preharvest (late fruit growth) to no water during the final 20 days preharvest (the current commercial standard). These experiments were conducted at the University of California, Davis. California has an arid environment, ideal for irrigation trials. Soil texture in both years was a loam. Plant canopy cover, plant water potential, and soil water status were documented during fruit ripening in response to the irrigation deficits imposed. At commercial maturity, fruit yield and quality were assessed.

5.3.1 Effect of Water Application on Plant Canopy Cover

Plant canopy cover decreased seasonally with natural plant senescence. A high tolerance to water stress without canopy decline was observed; even the most severe 60 d irrigation cutoff did not accelerate plant die-back or vine collapse. This degree of restriction to the water supply may have caused canopy dieback in fields with a lighter-textured soil type and low moisture retention. Cultivar selection may also affect canopy dieback.

5.3.2 Effect of Water Application on Plant Water Status

5.3.2.1 Effect of Sampling Technique

Bagging leaves overnight for early morning sampling the next day extended the period during which estimates of predawn plant water potential could be made. This

would allow growers to monitor a greater number of fields between 0500 HR (sunrise) and 0700 HR; previously all measurements had to be completed before sunrise, which limited commercial application of the technique. Bagging leaves for at least two hours before afternoon measurement reduced sampling variability related to transient environmental factors. By substantially reducing transpiration, the bagging technique allowed the water potential of leaves to equilibrate with the stem and roots. This provided a more reliable indicator of overall plant water status as related to fruit yield and quality.

5.3.2.2 Effect of Irrigation Treatment

Early morning and early afternoon measurements of plant water potential on bagged leaves confirmed that irrigation treatments caused varying levels of water stress. Generally, the values measured reflected the percent of ET_o applied; greater irrigation amounts resulted in lower plant water stress. Average plant water potential during fruit ripening was consistently correlated to fruit yield and SSC at maturity; measurements made in the early afternoon typically resulted in the strongest relationships with yield and quality. More negative plant water potential (indicative of greater water stress) was associated with lower yield and higher fruit SSC. Average 1300 HR ψ_{Stem} in the range of -0.5 to -0.7 MPa during the final six weeks preharvest was sufficient to achieve fruit SSC levels > 5.0 °Brix.

5.3.3 Effect of Water Application on Soil Water Status

Measurements of θ_V confirmed that irrigation practices achieved varying levels of water availability within the soil. Generally, increasing the percent of ET_o applied increased soil water availability. Average θ_V during fruit ripening was not as strongly correlated to yield and fruit SSC as 1300 HR ψ_{Stem}. No reliable ψ_{Soil} target during fruit ripening was found to achieve acceptable SSC.

5.3.4 Effect of Water Application on Yield and Quality

5.3.4.1 Total and Marketable Yield

Total and marketable yield generally declined with decreasing water application during fruit ripening. Lower yield was primarily related to smaller fruit size, although severe irrigation cutoffs imposed more than six weeks preharvest also caused a small reduction in fruit number per plant. Lower fruit number may have resulted from increased flower abortion under elevated plant water stress or an increasing number of fruit that rotted and were not counted. Irrigation strategies should prevent water stresses that impede fruit set or that cause a substantial increase in rots; this precluded early-season cutoffs implemented more than six weeks preharvest. Although the standard grower practice of irrigating late into the season resulted in the greatest yield, this strategy did not maximize fruit SSC. Irrigation cutback strategies implemented during early ripening provided an intermediate degree of water stress, and balanced yield decline with a proportional SSC increase.

5.3.4.2 Fruit Soluble Solids

Fruit SSC generally increased with reduced water application during ripening. To reliably increase fruit SSC, sufficient water stress needs to be imposed sooner than the standard grower practice achieves; 50-70 % of fruit may have developed colour by the time irrigation is stopped 20 days preharvest, leaving only a small percent of green fruit on which subsequent water stresses are effective. While early-season cutoffs increased SSC they disproportionately depressed yields. As an alternative to cutoffs, irrigation cutbacks imposed at the onset of ripening provide considerable flexibility in managing SSC, as a large percent of fruits can be subjected to modest water deficits.

5.3.4.3 Brix Yield

Generally, Brix yields did not decline with reduced water application during fruit ripening. This was consistent with the inverse relationship observed between fruit yield and SSC. However, this trade-off relationship was not unlimited; applying less than 20 % of ET_o during the final 60 days resulted in a significantly lower Brix yield.

To maximize Brix yields, irrigation cutoff implemented more than six weeks preharvest should be avoided. As a practical tool, irrigation cutbacks provide greater control of Brix yield than full irrigation cutoff; an irrigation cutback to 25-50 % of ET_o imposed at the onset of fruit ripening resulted in high SSC outcomes with no overall loss in Brix yield. In a series of later commercial trials, monitoring the SSC of early ripening fruit at a breaker-stage maturity (equivalent to 30-60 % of the fruit surface showing a colour other than green) was a useful tool to guide irrigation cutback. Fruit monitoring provided the flexibility to tailor irrigation strategies on a field-specific basis; more aggressive water deficit strategies could be considered in fields with poor initial SSC, while modest water deficits could be used when SSC levels are already high.

5.3.4.4 Blended Fruit Colour

The blended colour of marketable fruit generally improved with reduced water application during ripening. However, the colour scores of even the control treatments were acceptable for subsequent processing. It is unlikely that fruit colour will be limited by irrigation management decisions in fields that are harvested close to commercial maturity.

5.3.4.5 Fruit pH

Fruit pH was unaffected by reduced irrigation application. This confirmed that late-season water management does not offer growers a reliable tool to manipulate fruit pH. Cultivar selection and harvesting fruit at a correct stage of maturity remain the most effective strategies for pH manipulation.

5.3.4.6 Yield Components

There was little effect of irrigation management on fruit maturity; by design, differences were moderated by selecting a harvest date that reflected the commercial maturity of the standard grower cutoff. Good 'field-storage' capability meant that the percent of marketable fruit was similar across most irrigation treatments; culled or rotten fruit accounted for only a small percent of total yield. Selecting a harvest date

when most fruit are ripe but before excessive fruit rots prevail is important in maximizing yield and quality.

CHAPTER 6: Conclusions

6.1 Plant Nutrition Studies

- Nutrition studies confirmed that growers should maximize vegetative growth during the 6-8 weeks after transplanting. Nutrient supply should not limit vegetative growth during this period of development; adequate N supply is particularly important in establishing a large and healthy canopy. Maximizing vegetative growth was necessary to maximize fruit set. Reinstating adequate fertility after vegetative growth had stopped and fruit number had been determined did not improve yield. High fruit quality was not strongly related to K nutrition. In particular, large late-season K applications to improve fruit SSC did not offer any further benefit beyond appropriate late-season water management. Collectively, these findings were largely consistent with existing literature.

- Aeroponic and field studies confirmed that plant nutrient demand changes seasonally. Although adequate fertility is required for vegetative growth, nutrient uptake was greatest during fruit development; where practical, fertilizer application should be concentrated during this period of growth. Applying fertilizers during fruit ripening was not justified for maximum fruit yield and quality. Closely matching nutrient supply with plant demand may improve fertilizer efficiency compared to traditional pre-plant and side-dressed applications. Limiting fertilizer application during periods when demand is low will minimize nutrient loss potential. Drip fertigation offers an effective means in which to match supply more closely with crop uptake. Seasonal plant uptake equal to 9.4 and 13.8 g $plant^{-1}$ of N and K, respectively, was sufficient to maximize vegetative growth and achieve high fruit yield (> 90 Mg ha^{-1}); at a medium density of 22,222 plants ha^{-1} this was equivalent to approximately 210 and 310 kg ha^{-1} of N and K, respectively. These numbers were consistent with current commercial N and K applications; higher rates would only be justified where field-specific factors dictated.

- ❖ Closely matching supply with periods of most intensive nutrient uptake by plants and accurately predicting the availability of nutrients already in the soil offer good potential for growers to reduce fertilizer applications and improve environmental stewardship. Fertility status can vary greatly from site-to-site, and so management tools that allow fertilizer decisions to be based on robust estimates of nutrient availability in the soil (as related to fruit yield and quality) appear particularly promising.

6.1 Irrigation Management Studies

- ❖ Irrigation cutoff prior to fruit ripening can reduce fruit set, decrease fruit size, and substantially increase the incidence of fruit rots; growers should therefore minimize plant water stress prior to the final six weeks preharvest. However, late-season irrigation deficits applied during fruit ripening can increase fruit SSC without excessive yield loss. Irrigation cutbacks provide greater grower control of Brix yield outcomes than full irrigation cutoff; an irrigation cutback to 25-50 % of ET_o imposed at the onset of fruit ripening appears sufficient to improve fruit SSC and maintain Brix yields as compared to the current industry practice (late irrigation cutoff).

- ❖ Brix monitoring of the earliest ripening fruit (when 30-60 % of the fruit surface shows a colour other than green) can help classify fields as to the severity of irrigation cutback required to reach desirable fruit SSC at harvest. More aggressive water deficit strategies could be considered in fields with poor initial SSC, while modest water deficits could be used when SSC levels are already high. Other important quality determinants such as fruit colour and pH are unlikely to be adversely affected by such irrigation practices. Similarly, irrigation cutbacks initiated during fruit ripening are unlikely to cause extreme canopy dieback, so there is not a greatly increased risk of increased fruit culls due to excessive exposure of fruit to direct sun and heat.

- ❖ Compared to traditional exposed-leaf measures, bagging healthy leaves to determine plant water status extended potential sampling windows and reduced sampling variability. Even with this technique, measuring plant water status

remains an unappealing option to many commercial growers because of the considerable effort and user-expertise required. Soil-based measures of water content continue to be a useful management tool to avoid over- or under-watering, and the equipment can be automated or permanently set in fields.

LITERATURE CITED:

Adams, P. 1986. Mineral nutrition, p.281-334. In: J.G. Atherton and J. Rudich (eds.). The tomato crop: a scientific basis for improvement. Chapman and Hall, New York, N.Y.

Adams, P., J.N. Davies and G.W. Winsor. 1978. Effects of nitrogen, potassium and magnesium on the quality and chemical composition of tomatoes grown in peat. J. Hort. Sci. 53:115-122.

Adams, P and L.C. Ho. 1992. The susceptibility of modern tomato cultivars to blossom-end rot in relation to salinity. J. Hort. Sci. 67:827-839.

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 Soil 154:127-132.

Adegoroye, A.S. and P.A. Jolliffe. 1983. Initiation and control of sunscald injury of tomato fruit. J. Amer. Soc. Hort. Sci., 108:23-28.

Amable, R.A. and S. Sinnadurai. 1977. The influence of potassium, calcium and irrigation treatments on tomato fruit quality. Acta Hort. 53:165-170.

Andrews, W.F. 1972. Soil survey of Yolo County, California. U.S. Dept. Agr. Soil Conserv. Serv., Washington, D.C.

Atherton, J.G. and G.P. Harris. 1986. Flowering, p.167-200. In: J.G. Atherton and J. Rudich (eds.). The tomato crop: a scientific basis for improvement. Chapman and Hall, New York, N.Y.

Atherton, J.G. and S. Othman. 1983. Effects of irradiance and water stress on flower abortion in the glasshouse tomato. Acta Hort. 134:133-138.

Baldet, P., C. Devaux, C. Chevalier, R. Brouquisse, D. Just and P. Raymond. 2002. Contrasted responses to carbohydrate limitation in tomato fruit at two stages of development. Plant Cell Environ. 25:1639-1649.

Barak, J., J.D. Smith, A.R. Krueger and L.A. Peterson. 1996. Measurement of short-term nutrient uptake rates in cranberry by aeroponics. Plant Cell Environ. 19:237-242.

Barrett, D.M. and G. Anthon. 2001. Lycopene content of California-grown tomato varieties. Acta Hort. 542:165-173.

Bartholomew, R.P. and G. Janssen. 1929. Luxury consumption of potassium by plants and its significance. J. Amer. Soc. Agron. 21:751-765.

Battilani, A. 1994. Effects of irrigation, ethrel and harvest date on yield and quality of processing tomato. Acta Hort. 376:299-302.

Besford, R.T. and G.A. Maw. 1975. Effect of potassium nutrition on tomato plant growth and fruit development. Plant and Soil 42:395-412.

Biddinger, E.J., C. Liu, R.J. Joly and K.G. Raghothama. 1998. Physiological and molecular responses of aeroponically grown tomato plants to phosphorus deficiency. J. Amer. Soc. Hort. Sci. 123:330-333.

Blackmer, A.M. 1987. Losses and transport of nitrogen from soils, p. 85-103. In: F.M. D'Itri and L.G. Wolfson (eds.). Rural groundwater contamination. Lewis Publ. Inc. Chelsea, MI.

Blakemore, L.C., P.L. Searle and B.K. Daly. 1987. Methods for chemical analysis of soils. N.Z. Soil Bur. Scientific Rpt. 80. N.Z. DSIR, Wellington, N.Z.

Brady, N.C. 1990. The nature and properties of soils. 10th ed. Macmillan, New York, N.Y.

Bruggink, G.T. and E. Heuvelink. 1987. Influence of light on the growth of young tomato, cucumber and sweet pepper plants in the greenhouse: effects on relative growth rate, net assimilation rate and leaf area ratio. Scientia Hort. 31:161-174.

Burgess, S.M. 1988. The climate and weather of Manawatu. N.Z. Meteorological Service Pub. 115(18). Wellington, N.Z.

Burgmans, J.L., J.P. C. Watt and W.T. Bussell. 1998. Lcssons from processing tomato irrigation trials in Hawkes Bay, New Zealand. N.Z. J. Crop Hort. Sci. 26:307-312.

Cahn, M., B. Hanson and R. Snyder. 2000. Weather stations for irrigation management, p.11-18. California Tomato Research Institute Annual Project Reports. CTRI Inc., Escalon, CA.

Cahn, M.D., E.V. Herrero, B.R. Hanson, T.K. Hartz and E.M. Miyao. 2001. Water management strategies for improving fruit quality of drip-irrigated processing tomatoes. Acta Hort. 542:111-116.

Cahn, M.D., E.V. Herrero, B.R. Hanson, T.K. Hartz and E.M. Miyao. 2004. Late-season water management effects on quality and yield of processing tomatoes. Acta Hort. 664:111-118.

Cahn, M.D., E.V. Herrero, B.R. Hanson, R.L. Snyder, T.K. Hartz and E.M. Miyao. 2003. Effects of irrigation cutoff on processing tomato fruit quality. Acta Hort. 613:75-80.

Calado, A.M., A. Monzon, D.A.Clark, C.J. Phene, C. Ma and Y. Wang. 1990. Monitoring and control of plant water stress in processing tomato. Acta Hort. 277:129-136.

Carangal, A.R., E.K. Alban, J.E. Varner and R.C. Burrell. 1954. The influence of mineral nutrition on the organic acids of the tomato, *Lycospersicon esculentum.* Plant Phys. 29:355-360.

Cassman, K.G., D.C. Bryant, and B.A. Roberts. 1990. Comparison of soil test methods for predicting cotton response to soil and fertilizer potassium on potassium-fixing soils. Comm. Soil Sci. Plant Anal. 21:1727-1743.

Cavero, J., R.E. Plant, C. Shennan, and D.B. Friedman. 1997. The effect of nitrogen source and crop rotation on the growth and yield of processing tomatoes. Nutr. Cycl. Agroecosyst. 47:271-282.

Cavero, J., R.E. Plant, C. Shennan, and D.B. Friedman, J.R. Williams, J.R. Kiniry and V.W. Benson. 1999. Modelling nitrogen cycling in tomato-saftflower and tomato-wheat rotations. Agr. Syst. 60:123-135.

Cavero, J., R.E. Plant, C. Shennan, J.R. Williams, J.R. Kiniry and V.W. Benson. 1998. Application of EPIC model to nitrogen cycling in irrigated processing tomatoes under different management systems. Agr. Syst. 56:391-414.

Cerda, A., F.T. Bingham, G.J. Hoffman and C.K. Kuszar. 1979. Leaf water potential and gaseous exchange of wheat and tomato as affected by NaCl and P levels in the root medium. Agron. J. 71:27-31.

Cerne, M. 1990. Different kinds and levels of nitrogen nutrition in tomatoes. Acta Hort. 277:179-182.

Clark, M.S., W.R. Horwath, C. Shennan, K.M. Scow, W.T. Lanini and H. Ferris. 1999. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. Agric. Ecol. Environ. 73:257-270.

Colla, G., R. Casa, B. Lo Cascio, F. Saccardo, O. Temperini and C. Leoni. 1999. Responses of processing tomato to water regime and fertilization in central Italy. Acta Hort. 487:531-535.

Colla, G., A. Battistelli, S. Moscatello, S. Proietti, R. Casa, B. Lo Cascio and C. Leoni. 2001. Effects of reduced irrigation and nitrogen fertigation rate on yield, carbohydrate accumulation, and quality of processing tomato. Acta Hort. 542:187-196.

Cuartero, J. and R. Fernández-Munoz. 1999. Tomato and salinity. Scientia Hort. 78:83-125.

Dadomo, M., A.M. Gainza, Y. Dumas, P. Bussières, J.I. Macua, M. Christou and X. Branthôme. 1994a. Influence of water and nitrogen availability on yield components of processing tomato in the European union countries. Acta Hort. 376:271-274.

Dadomo, M., S. Leoni, A. Rodriguez, T. Koutsos, J.I. Macua, M.L. Taborda, C.M. Portas and G. Gandolfi. 1994b. 1992 Main results of the EEC research programme – action C. variability in relation to cultivar and country. Acta Hort. 376:43-50.

Davies, J.N. 1964. Effect of nitrogen, phosphorus and potassium fertilizers on the non-volatile organic acids of tomato fruit. J. Sci. Food Agric. 15:665-673.

Davies, J.N. and G.E. Hobson. 1981. The constituents of tomato fruit – the influence of environment, nutrition and genotype. CRC Critical Rev. Food Sci. Nutr. 15:205-280.

Davies, J.N. and G.W. Winsor. 1967. Effect of nitrogen, phosphorus, potassium, magnesium and liming on the composition of tomato fruit. J. Sci. Food Agric. 18:459-466.

Davies, J.N. and G.W. Winsor. 1969. Some effects of variety on the composition and quality of tomato fruit. J. Hort. Sci. 44:331-342.

Dumas, Y. 1990. Tomatoes for processing in 90's: nutrition and crop fertilization. Acta Hort. 277:155-166.

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

Ehret, D.L. and L. Ho. 1986. The effects of salinity on dry matter partitioning and fruit growth in tomatoes grown in nutrient film culture. J. Hort. Sci. 61:361-367.

Eymar, E., C. Cadahía and A. Sánchez. 2001. Foliar nutrient reference levels obtained in hydroponic cultures as preliminary norms for DRIS to fertigate conifers. Commun. Soil Sci. Plant Anal. 32:267-282.

Fereres, E., D.A. Goldhamer and L.R. Parsons. 2003. Irrigation water management for horticultural crops. HortScience 38:1036-1042.

Fisher, K.J., P.R. Johnstone and M.A. Nichols. 2002. Nutrition of processing tomato. Acta Hort. 571:45-49.

Flores, P., J.M. Navarro, C. Garrido, J.S. Rubio and V. Martinez. 2004. Influence of Ca^{2+}, K^{+} and NO_3^{-} fertilization on nutritional quality of pepper. J. Sci. Food Agric. 84:569-574.

Fontes, P.C.R. and G.E. Wilcox. 1984. Growth and phosphorus uptake by tomato cultivars as influence by phosphorus concentrations in soil and nutrient solution. J. Amer. Soc. Hort. Sci. 109:633-636.

Fulton, A., R. Buchner, B. Olson, L. Schwankl, C. Gilles, N. Bertagna, J. Walton and K. Shackel. 2001. Rapid equilibration of leaf and stem water potential under field conditions in almonds, walnuts, and prunes. HortTechnology 11:609-615.

Geisenberg, C. and K. Stewart. 1986. Field crop management, p. 511-557. In: J.G. Atherton and J. Rudich (eds.). The tomato crop: a scientific basis for improvement. Chapman and Hall, New York, N.Y.

Gillaspy, G., H. Ben-David and W. Gruissem. 1993. Fruit: a developmental perspective. Plant Cell 5:1439-1451.

Goldhamer, D.A. and R.L. Snyder. 1989. Irrigation scheduling: a guide for efficient on-farm water management. Univ. of Calif. Coop. Ext. Bul. 21454.

Greenwood, D.J., F. Gastal, G. Lemaire, A. Draycott, P. Millard and J.J. Neeteson. 1991. Growth rates and %N of field grown crops: theory and experiments. Ann. Bot. 67:181-190.

Greenwood, D.J. 2001. Modeling N-response of field vegetable crops grown under diverse conditions with N_ABLE: a review. J. Plant Nutr. 24:1799-1815.

Grierson, D. and A.A. Kader. 1986. Fruit ripening and quality, p.241-280. In: J.G. Atherton and J. Rudich (eds.). The tomato crop: a scientific basis for improvement. Chapman and Hall, New York, N.Y.

Güler, S., H. Ibrikci, A. Apaydin and H. Kar. 2002. Response of field-grown tomatoes to nitrogen and potassium applied with drip or furrow irrigation. Acta Hort. 571:187-193.

Halbrooks, M.C. and G.E. Wilcox. 1980. Tomato plant development and elemental accumulation. J. Amer. Soc. Hort. Sci. 105:826-828.

Hanson, B.R. 1995. Practical potential irrigation efficiencies. Proc. 1st Int. Conf. Water Resources Engineering Div., Amer. Soc. Civil Engineering, San Antonio, Tex. 14-18 Aug., 1995.

Hanson, B.R., D.M. May and L.J. Schwankl. 2003. Effect of irrigation frequency on subsurface drip irrigated vegetables. HortTech. 13:115-120.

Hanson, B.R., S. Orloff and D. Peters. 2000a. Monitoring soil moisture helps refine irrigation management. Calif. Agr. 54(3):38-42.

Hanson, B.R. and D. Peters. 2000. Soil type affects accuracy of dielectric moisture sensors. Calif. Agr. 54(3):43-47.

Hanson, B.R., D. Peters and S. Orloff. 2000b. Effectiveness of tensiometers and electrical resistance sensors varies with soil conditions. Calif. Agr. 54(3):47-50.

Hartz, T. 1996. Water management in drip-irrigated vegetable production. HortTechnology 6:165-167.

Hartz, T.K. 2001. Status of drip irrigation for processing tomato production in California. Acta Hort. 542:101-102.

Hartz, T.K. 2002a. Sustainable vegetable production in California: current status, future prospects. HortScience 37:1015-1022.

Hartz, T.K. 2002b. Early season irrigation of processing tomato. Vege. Notes, Tulare and Kings Counties, April 2002. Univ. Calif. Cooperative Ext., Tulare, CA.

Hartz, T.K. 2005. Vegetable production best management practices to minimize nutrient loss. HortScience (In press.).

Hartz, T.K. and G.J. Hochmuth. 1996. Fertility management of drip-irrigated vegetable. HortTechnology 6(3):168-172.

Hartz, T.K. and P.R. Johnstone. 2005. Relationship between soil P availability and P loss potential in runoff and leaching. Comm. Soil Sci. Plant Anal. (In press.).

Hartz, T.K., P.R. Johnstone, D.M. Francis and E.M. Miyao. 2005. Processing tomato yield and fruit quality improved with potassium fertigation. HortScience 40:1862-1867.

Hartz, T.K., P.R. Johnstone and M. LeStrange. 2004. Late-season deficit irrigation is a reliable tool for soluble solids improvement in drip-irrigated processing tomato production. Acta Hort. (In press.).

Hartz, T.K. and G. Miyao, 1997. Processing tomato production in California. Division of Ag. and Nat. Res. Publ. 7228. Univ. Calif., Oakland, CA.

Hartz, T.K., E.M. Miyao, R.J. Mullen and M.D. Cahn. 2001. Potassium fertilization effects on processing tomato yield and fruit quality. Acta Hort. 542:127-134.

Hartz, T.K., G. Miyao, R.J. Mullen, M.D. Cahn, J. Valenica and K.L. Brittan. 1999. Potassium requirements for maximum yield and fruit quality of processing tomato. J. Amer. Soc. Hort. Sci. 124:199-204.

Hartz, T.K., E.M. Miyao and J.G. Valencia. 1998. DRIS evaluation of the nutritional status of processing tomato. HortScience 33:830-832

Hills, F.J., F.E. Broadbent and O.A. Lorenz. 1983. Fertilizer nitrogen utilization by corn, tomato and sugarbeet. Agron. J. 75:423-426.

Hinds, A.A. and L.E. Lowe. 1980. Application of the Berthelot reaction to the determination of ammonium-N in soil extracts and soil digests. Comm. Soil Sci. Plant Anal. 11:469-475.

Ho, L.C. 1984. Partitioning of assimilates in fruiting tomato plants. Plant Growth Regulation 2:277-285 (Abstr.).

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

Ho, L.C. and J.D. Hewitt, 1986. Fruit development, p.201-239. In: J.G. Atherton and J. Rudich (eds.). The tomato crop: a scientific basis for improvement. Chapman and Hall, New York, N.Y.

Hochmuth, G., D. Maynard, C. Vavrina and E. Hanlon. 1991. Plant tissue analysis and interpretation for vegetable crops in Florida. Florida Coop. Ext. Spec. Ser. SS-VEC-42.

Hochmuth, G.J., O. Carrijo and K. Shuler. 1999. Tomato yield and fruit size did not respond to P fertilization of a sandy soil testing very high in Melich-1 P. HortScience 34:653-656.

Johnstone, P.R., T.K. Hartz, M.D. Cahn and M.R. Johnstone. 2005a. Lettuce response to phosphorus fertilization in high P soils. HortScience 40:1499-1503.

Johnstone, P.R., T.K. Hartz, M. LeStrange, J.J. Nunez and E.M. Miyao. 2005b. Managing fruit soluble solids with late-season deficit irrigation in drip-irrigated processing tomato production. HortScience 40:1857-1861.

Julian, A.P. 1990. Flower and fruit development in processing tomato. A thesis presented in partial fulfillment of the requirements for the degree of Master of Horticultural Science in Vegetable Production at Massey University. Palmerston North, N.Z.

Keeney, D.R. and R.F. Follett. 1991. Managing nitrogen for groundwater quality and farm profitability: overview and introduction, p.1-7. In: R.F. Follett *et al.* (eds.). Managing nitrogen for groundwater quality and farm profitability. SSSA, Inc. Madison, WI.

Klute, A. 1986. Water retention: laboratory methods, p.635-662. In: A. Klute (ed.). Methods of soil analysis: part 1. physical and mineralogical methods. ASA, Madison, WI.

Krusekopf, H.H., J.P. Mitchell, T.K. Hartz, D.M. May, E.M. Miyao and M.D. Cahn. 2002. Pre-sidedress soil nitrate testing identifies processing tomato fields not requiring sidedress N fertilizer. HortScience 37:520-524.

Lachover, D. 1972. The effect of potassium on "Roma" variety of processing tomato, with special reference to potassium uptake, yield and quality. Qual. Plant Mater. Veg. XXI 3:165-177.

Leathwick, J.R., G. Wilson and R.T.T. Stevens. 2002. Climate surfaces for New Zealand. Landcare Research Contract Report #LC9798/126. Manaaki Whenua – Landcare Research, Hamilton, New Zealand.

Linden, T. 2003. Drip irrigation: getting another look at processing tomato fields. Calif. Tomato Grower 46(3):8-13.

Linden, T. 2004. The brix discussion. Calif. Tomato Grower 47(2):5-8.

Lingle, J.C, and O.A. Lorenz. 1969. Potassium nutrition of tomatoes. J. Amer. Soc. Hort. Sci. 94:679--683.

López, J., R.M. Ruiz, R. Ballesteros, A. Ciruelos and R. Ortiz. 2001. Color and lycopene content of several commercial tomato varieties at different harvesting dates. Acta Hort. 542:243-247.

Lorenz, O.A. and K.B. Tyler. 1983. Plant tissue analysis of vegetable crops (pp. 24-29). In H.M. Reisenauer (ed.) Soil and plant tissue testing. California Coop. Ext. Bul. 1879.

Lowengart-Aycicegi, A., H. Manor, R. Krieger and G. Gera. 1999. Effects of irrigation scheduling on drip-irrigated processing tomatoes. Acta Hort. 487:513-518.

Maas, E.V. 1986. Salt tolerance of plants. Appl. Agric. Res. 1:12-26.

Massey, D.M., Hayward, A.C. and G.W. Winsor. 1984. Some responses of tomato to calcium concentration. Ann. Rep. Glasshouse Crops Res. Inst. 1983:54-56.

May, D.M. and J. Gonzales. 1994. Irrigation and nitrogen management as they affect fruit quality and yield of processing tomatoes. Acta Hort. 376:227-234.

May, D.M. and J. Gonzales. 1999. Major California processing tomato cultivars respond differentially in yield and fruit quality to various levels of moisture stress. Acta Hort. 487:525-529.

May, D.M. and S. Guillen. 2001. Processing varieties that field store to increase grower and processor profit. Acta Hort. 542:365-372.

May, D.M., D. Peters, T. Wolcott and D.W. Grimes. 1990. Moisture stress as it affects yields, 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.

McDonald, A.J.S., T. Ericsson and C.M. Larsson. 1996. Plant nutrition, dry matter gain and partitioning at the whole-plant level. J. Exp. Bot. 47:1245-1253.

McDowell, R.W. and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508-520.

Mencarelli, F. and M.E. Saltveit. 1988. Ripening of mature-green tomato fruit slices. J. Amer. Soc. Hort. Sci. 113:742-745.

Mengel, K. and E.A. Kirkby. 1987. Principles of plant nutrition. 4th ed. Int. Potash Inst., Bern, Switzerland.

Meyer, W.S. and G.C. Green. 1980. Water use by wheat and plant indicators of average soil water. Agron. J. 72:253.

Meyer, W.S. and G.C. Green. 1981. Plant indicators of wheat and soybean crop water stress. Irr. Sci. 2:167-176.

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

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

Murray, M. 1999. Lower Sacramento valley processing tomato irrigation field test results. Acta Hort. 487:510-523.

Nichols, M.A., K.J. Fisher and P. Johnstone. 2001. The effect of harvest date on the yield of processing tomato. Acta Hort. 542:359-363.

Nicklow, C.W. and J.D. Downes. 1971. Influence of nitrogen, potassium and plant population on the maturity of field seeded tomatoes for once-over harvest. J. Amer. Soc. Hort. Sci. 96:46-49.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus, p.403-430. In: A.L. Page *et al.* (eds.). Methods of soil analysis: part 2. chemical and microbiological properties. ASA, Madison, WI.

Ozbun, J.L., C.E. Boutonnet, S. Sadik, and P.A. Minges. 1967. Tomato fruit ripening. I. Effects of potassium nutrition on occurrence of white tissue. Proc. Amer. Soc. Hort. Sci. 91:566–572

Paiva, E.A.S., H.P. Martinez, V.W.D. Casali and L. Padilha. 1998. Occurrence of blossom-end rot in tomato as a function of calcium dose in the nutrient solution and air relative humidity. J. Plant Nutr. 21:2663-2670.

Pan, H.Y., K.J. Fisher and M.A. Nichols. 1999. Fruit yield and maturity characteristics of processing tomatoes in response to drip irrigation. J. Veg. Crop Prod. 5(1):13-29.

Phene, C.J. 1999. Efficient irrigation systems and irrigation scheduling for processing tomato: the challenge. Acta Hort. 487:479-485.

Phene, C.J., J.M. Miyamoto, K.R. Davis, R.L. McCormick and R.C. Liu. 1986. Automated feedback irrigation scheduling and control with a weighing lysimeter. Proc. Agri-Mation 2:135-147.

Picha, D.H. and C.B. Hall. 1981. Influences of potassium, cultivar, and season on tomato graywall and blotchy ripening. J. Amer. Soc. Hort. Sci. 106:704–708.

Picken, A.J., K. Stewart and D. Klapwijk. 1986. Fruit development, p.111-166. In: J.G. Atherton and J. Rudich (eds.). The tomato crop: a scientific basis for improvement. Chapman and Hall, New York, N.Y.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, D.R. Edwards and D.J. Nichols. 1996. Relating extractable soil phosphorus to phosphorus losses in runoff. Soil Sci. Soc. Amer. J. 60:855-859.

Pujos, A. and P. Morard. 1997. Effects of potassium deficiency on tomato growth and mineral nutrition at the early production stage. Plant and Soil 189:189-196.

Pulupol, L.U., M.H. Behboudian and K.J. Fisher. 1996. Growth, yield and postharvest attributes of glasshouse tomatoes produced under water deficit. HortScience 31:926-929.

Rahn, C.R. 2002. Management strategies to reduce nutrient losses from vegetable crops. Acta Hort. 571:19-29.

Reid, J.B. and A.R. Renquist. 1997. Enhanced root production as a feed-forward response to soil water deficit in field-grown tomatoes. Austral. J. Plant Physiol. 24:685-692.

Rendon-Poblete, E. 1980. Effect of soil water status on yield, quality and root development of several tomato genotypes. Univ. of Calif., Davis, PhD Diss.

Renquist, A.R. and J.B. Reid. 1998. Quality of processing tomato (*Lycospersicon esculentum*) fruit from four bloom dates in relation to optimal harvest timing. N.Z. J. Crop Hort. Sci. 26:161-168.

Renquist, A.R. and J.B. Reid. 2001. Processing tomato fruit quality: influence of soil water deficits at flowering and ripening. Austral. J. Agr. Res. 52:793-799.

Rudich, J., D. Kalmar, C. Geizenberg and S. Harel. 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. Ambri. 1981. Use of leaf water potential to determine water stress in field-grown tomato plants. J. Amer. Soc. Hort. Sci. 106:732-736.

Sakamoto, Y., S. Watanabe, T. Nakashima and K. Okano. 1999. Effects of salinity at two ripening stages on the fruit quality of single-truss tomato grown in hydroponics. J. Hort. Sci. Biotech. 74:690-693.

Saure, M.C. 2001. Blossom-end rot of tomato (*Lycospersicon esculentum* Mill.) – a calcium- or a stress-related disorder? Scientia Hortic. 90:193-208.

Schaffer, A.A., M. Petreikov, D. Miron, M. Fogelman, M. Spiegelman, Z. Bnei-Moshe, S. Shen, D. Granot, R. Hadas, N. Dai, H. Levin, M. Bar, M. Friedman, M. Pilowsky, N. Bilboa and L. Chen. 1999. Modification of carbohydrate content in developing tomato fruit. HortScience 34:1024-1027.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920-926.

Sharpley, A.N. 1997. Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. J. Environ. Qual. 26:1127-1132.

Sims, J.T. 1998. Phosphorus soil testing: innovations for water quality protection. Comm. Soil Sci. Plant Anal. 29:1471-1489.

Sims, J.T., A.C. Edwards, O.F. Schoumans and R.R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agricultural management practices. J. Environ. Qual. 29:60-71.

Sinclair, T.R. and T. Horie. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. Crop Sci. 29:90-98.

Stark, J.C., W.M. Jarrell, J. Letey and N. Valoras. 1983. Nitrogen use efficiency of trickle-irrigated tomatoes receiving continuous injection of N. Agron. J. 75:672-676.

Stevens, M.A. 1972. Relationships between components contributing to quality variation among tomato lines. J. Amer. Soc. Hort. Sci. 97:70-73.

Stevens, M.A. 1976. Inheritance of viscosity potential in tomato. J. Amer. Soc. Hort. Sci. 101:152-155.

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

Strand, L.L. 1998. Integrated pest management for tomatoes. 4th ed. Univ. of Calif., Div. Agr. Natural Resources Publ. 3274, Oakland, CA.

Technicon. 1973. Potassium, calcium and magnesium are determined by atomic emission (K) absorption (Ca and Mg) spectroscopy following digestion in nitric acid. Industrial method 98/70w. Technicon, New York, N.Y.

Tei, F., P. Benincasa and M. Guiducci. 2002. Critical nitrogen concentration in processing tomato. Europ. J. Agron. 18:45-55.

Thomas, G.W. 1982. Exchangeable cations, p.159-165. In: A.L. Page *et al.* (eds.). Methods of soil analysis: part 2. chemical and microbiological properties. ASA, Madison, WI.

Tregidga G., M. Tregidga and R. Lewthwaite. 1986. Hydroponics: nutrient film technique for commercial vegetable growing. AgLink HPP322. Ministry Agr. Fisheries, Wellington, N.Z.

Trudel, M.J. and J.L. Ozbun. 1970. Relationship between chlorophylls and carotenoids of ripening tomato fruit as influenced by potassium nutrition. J Exp. Bot. 21:881-886.

Trudel, M.J. and J.L. Ozbun. 1971. Influence of potassium on carotenoid content of tomato fruit. J. Amer. Soc. Hort. Sci. 96:763-765.

Twine, J.R. and C.H. Williams. 1971. The determination of phosphorus in Kjeldahl digests of plant material by automatic analysis. Commun. Soil Sci. Plant Anal. 2:485-489.

Usherwood, N.R. 1985. The role of potassium in crop quality, p.489-513. In: R.S. Munson (ed.). Potassium in agriculture. ASA-CSSA-SSSA, Madison, WI.

Waisel, Y. 1996. Aeroponics: a tool for root research, p.239-245. In: Y. Waisel *et al.* (eds.). Plant roots: the hidden half. Marcel Dekker, New York, N.Y.

Ward, G.M. 1964. Greenhouse tomato nutrition – a growth analysis study. Plant Soil 21:125-133.

Wardlaw, I.F. 1990. The control of carbon partitioning in plants. New Phytol. 116:341-381.

Widders, I.E. and O.A. Lorenz. 1979. Tomato root development as related to potassium nutrition. J. Amer. Soc. Hort. Sci. 104:216–220.

Widders, I.E. and O.A. Lorenz. 1982. Potassium nutrition during tomato plant development. J. Amer. Soc. Hort. Sci. 107:960-964.

Wilcox, G.E. 1993. Tomato, p.137-141. In: W.E. Bennett (ed.). Nutrient deficiencies and toxicities in crop plants. APA, St. Paul, MN.

Wolf, S. and J. Rudich. 1988. The growth rate of fruits on different parts of the tomato plant and the effect of water stress on dry weight accumulation. Scientia Hort. 34:1-11.

Wudiri, B.B. and D.W. Henderson. 1985. Effects of water stress on flowering and fruit set in processing tomatoes. Scientia Hort. 27:189-198.

Zalom, F.G. and L.T. Wilson. 1999. Predicting phenological events of California processing tomatoes. Acta Hort. 487:41-47

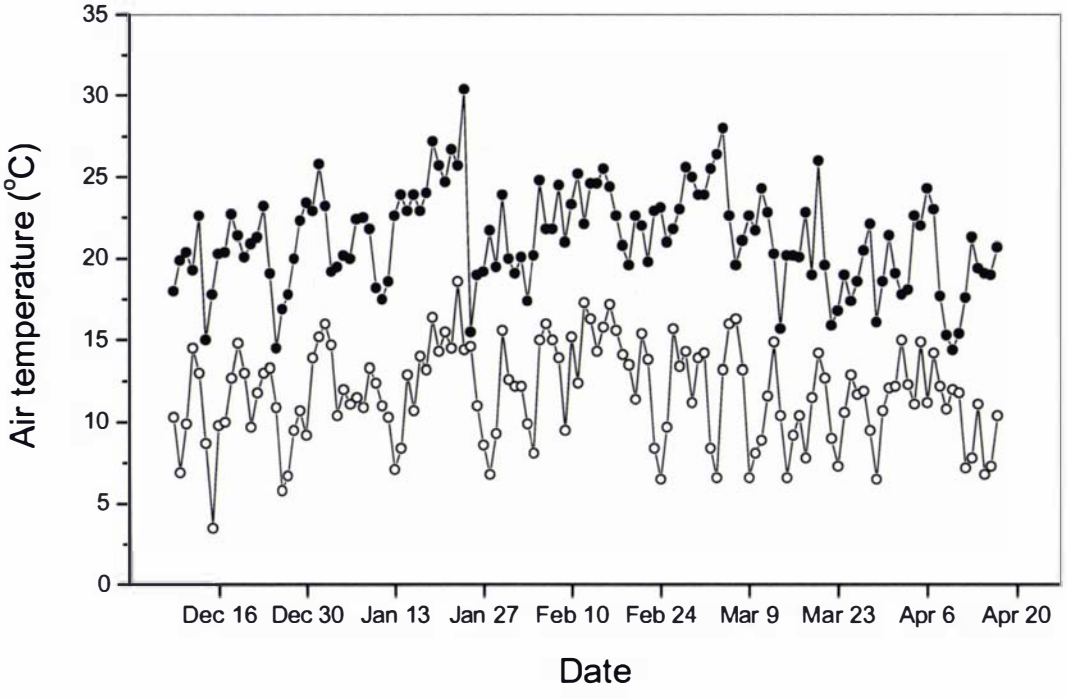
Zegbe-Domínguez, J.A., M.H. Behboudian, A. Lang and B.E. Clothier. 2003. Deficit irrigation and partial rootzone drying maintain fruit dry mass and enhance fruit quality in 'Petopride' processing tomato (*Lycopersicon esculentum*, Mill.). Scientia Hort. 98:505-510.

APPENDICES:

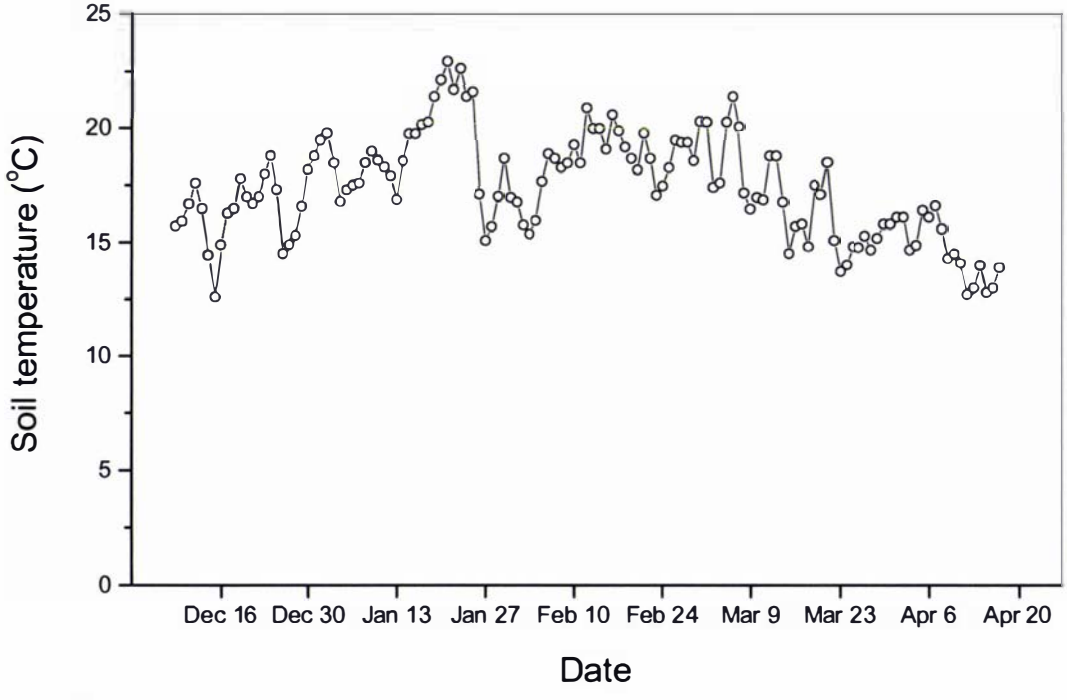
Appendix I. Summary of low (0.7 dS m^{-1}) and high (2.0 dS m^{-1}) fertility treatments, 1998-1999 aeroponic trial.

Nutrient	Treatment regime [z]	
	Low fertility (mg L^{-1})	High fertility (mg L^{-1})
Nitrogen	73	208
Phosphorus	22	62
Potassium	116	332
Caclium	59	168
Magnesium	17	49
Iron	4	12
Manganese	0.7	2.0
Boron	0.11	0.30
Copper	0.02	0.07
Zinc	0.02	0.07
Molybdenum	0.02	0.05

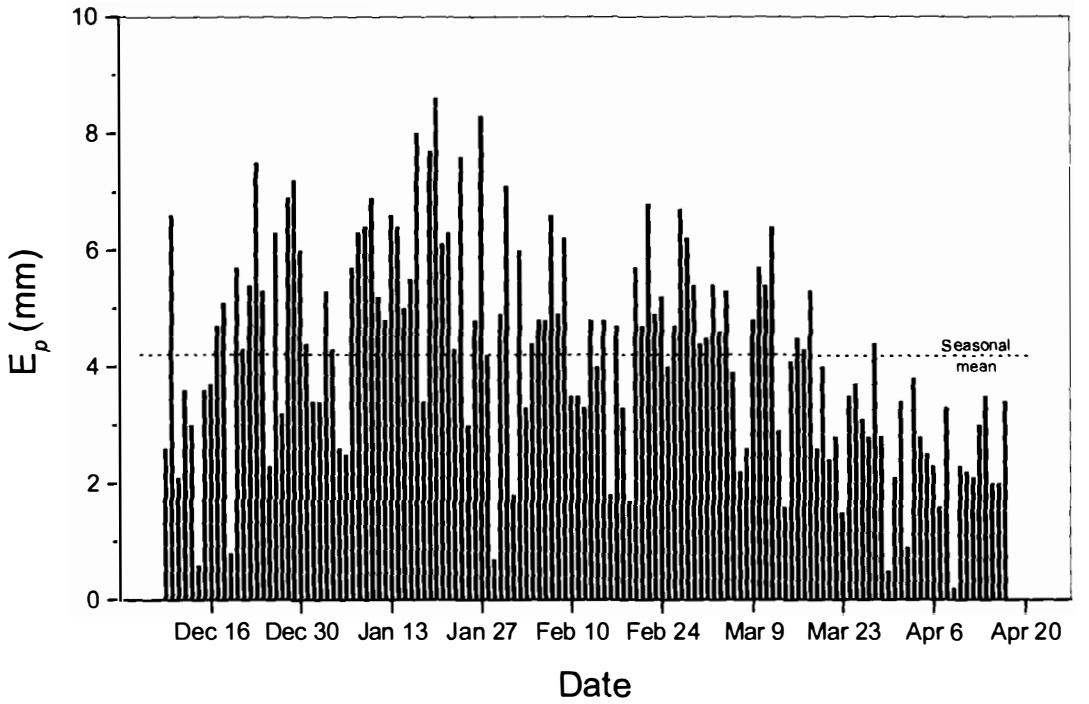
[z] high fertility was based on recommendations by Tregidga *et al.* (1986) for greenhouse tomato production



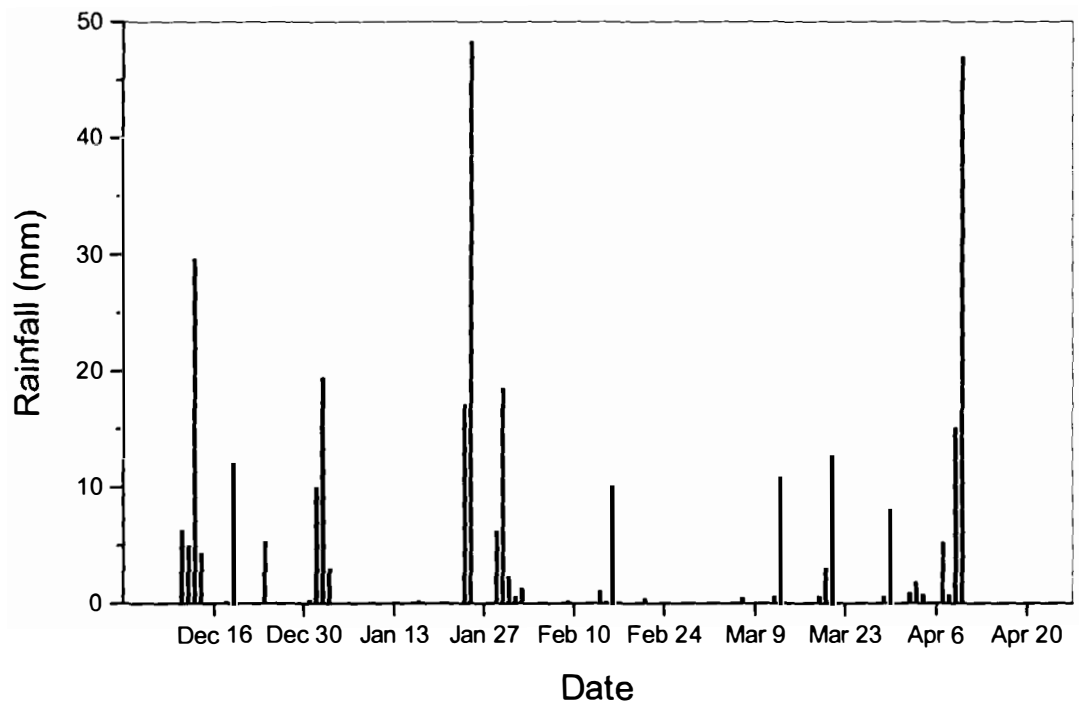
Appendix II-a. Minimum (○) and maximum (●) daily air temperature during summer trial, 1999-2000. Measurements taken at AgResearch Grasslands Centre, Tennent Road (less than 1 km from the experimental site).



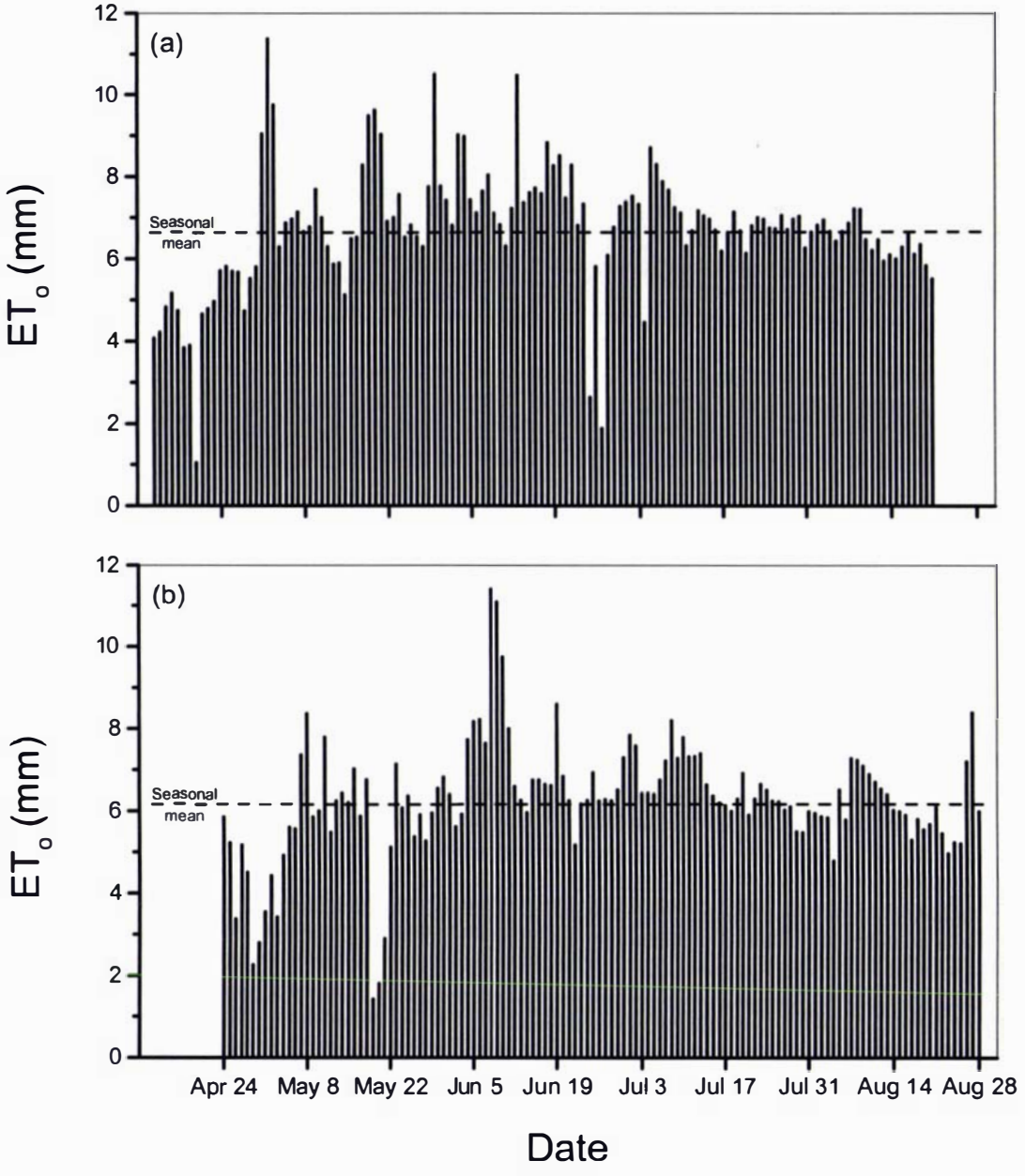
Appendix II-b. Mean daily soil temperature at 15 cm during summer trial, 1999-2000. Measurements taken at AgResearch Grasslands Centre, Tennent Road (less than 1 km from the experimental site).



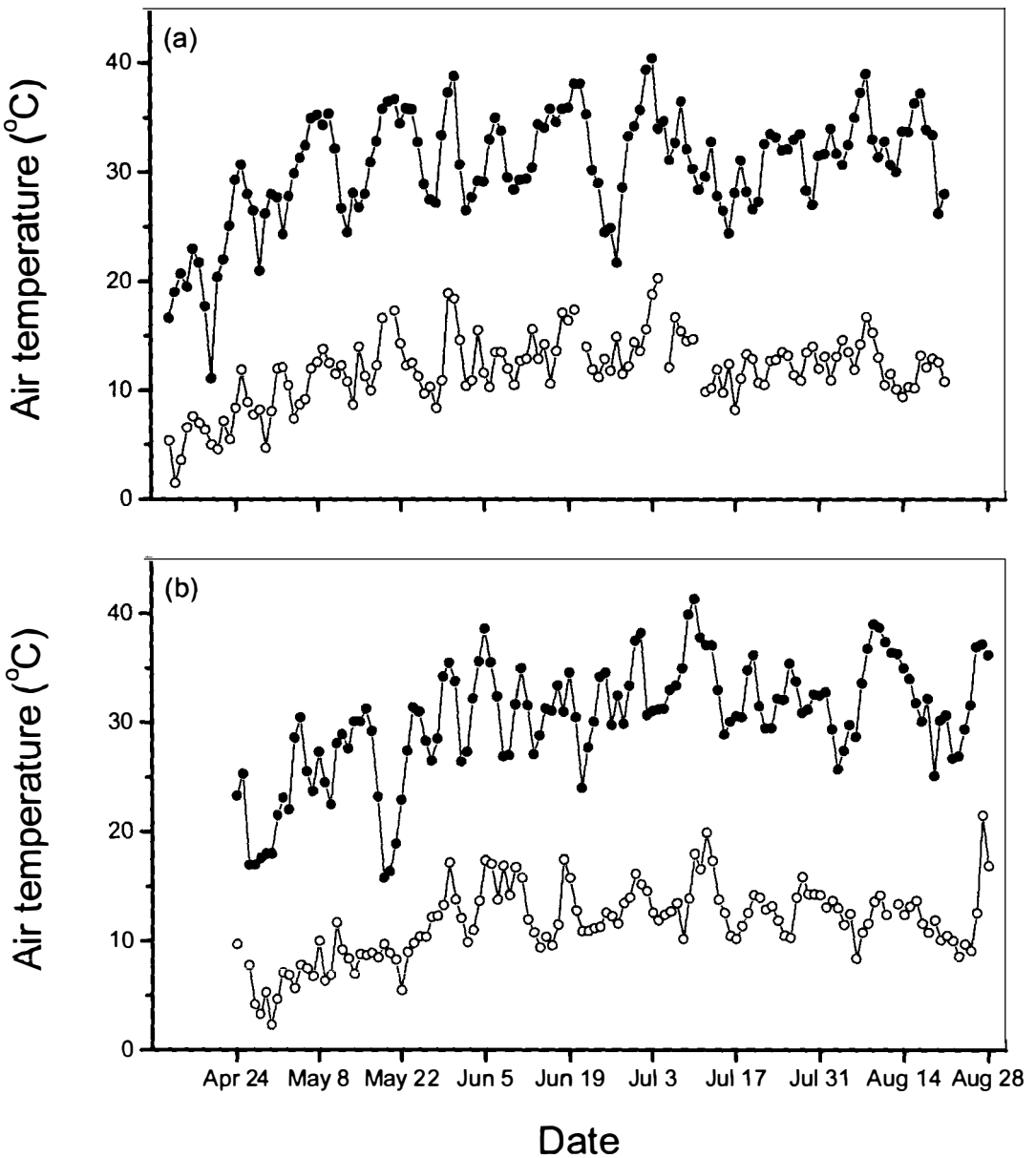
Appendix II-c. Daily pan evaporation (E_p) during summer trial, 1999-2000. Measurements taken at AgResearch Grasslands Centre, Tennent Road (less than 1 km from the experimental site).



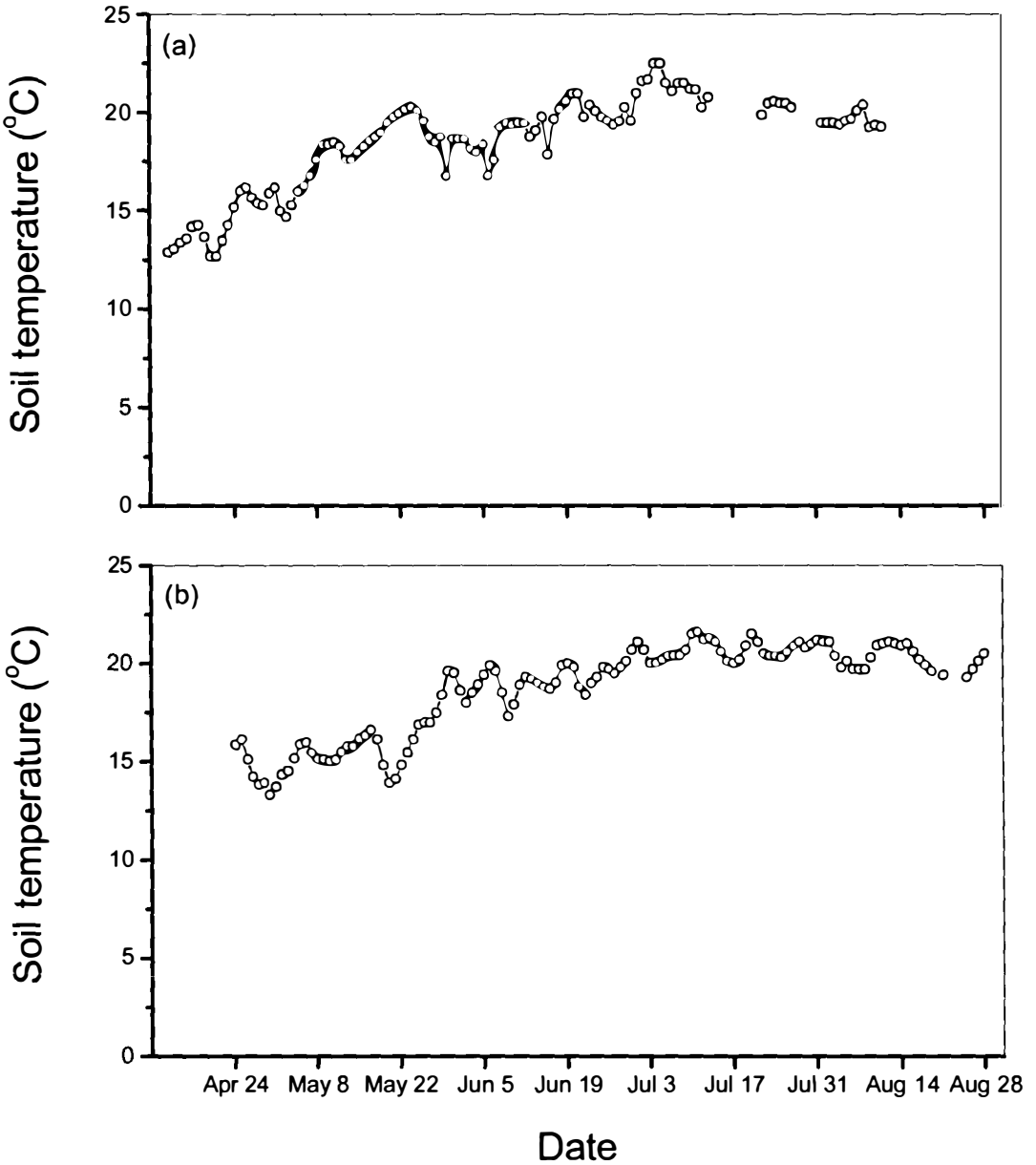
Appendix II-d. Daily rainfall during summer trial, 1999-2000. Measurements taken at AgResearch Grasslands Centre, Tennent Road (less than 1 km from the experimental site).



Appendix III-a. Daily reference evapotranspiration (ET_o) during summer trials, 2001 (a) and 2002 (b). Measurements taken at CIMIS Station #6 (less than 1 km from the experimental sites).



Appendix III-b. Minimum (○) and maximum (●) daily air temperature during summer trials, 2001 (a) and 2002 (b). CIMIS Station #6 (less than 1 km from the experimental site). Gaps indicate missing sensor data.



Appendix III-c. Mean daily soil temperature at 15 cm during summer trials, 2001 (a) and 2002 (b). Measurements taken at CIMIS Station #6 (less than 1 km from the experimental sites). Gaps indicate missing sensor data.

Appendix IV. Managing fruit soluble solids with late-season deficit irrigation in drip-irrigated processing tomato production (HortScience 40:1857-1861).