Fruit water relations, growth, yield, and quality of 'Braeburn' apple in response to deficit irrigation and to crop load

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Bussakorn Sriprasert Mpelasoka

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ABSTRACT

Allocation of water for agriculture has decreased due to increased demand as a result of population growth, industrial development, and water pollution. Irrigation management aiming at efficient use of water has become a high priority. Deficit irrigation (DI), if applied judiciously, saves water, decreases vegetative growth and pruning costs, reduces leaching of agrichemicals into ground water, and may improve fruit quality. In apple, there is less beneficial effect of DI on shoot growth reduction because fruit set and cell division phases occur at the same time as predominant shoot growth and so DI applied during this period will reduce fruit size. However, there appear to be potential of DI in apple fruit quality improvement but research findings on this aspect have been inconclusive. To promote the adoption of DI in apple production, there is need to confirm and expand the effects of DI on fruit quality and to minimise DI effects on fruit size reduction. This study was to confirm DI effects on fruit quality by addressing relationship between fruit size and quality and to investigate DI effects on under-researched aspects of fruit quality such as physiological disorders, maturation and ripening, aroma volatiles, and storage potential. The possibility of integrating light crop load with DI to increase fruit size was also explored by investigating interactions of DI and crop load on tree water use, fruit size regulation, yield, and quality. The study involves three experiments. Irrigation treatments include control irrigation (CI), early deficit irrigation (EDI) applied from 63 to 118 days after full bloom (DAFB), late deficit irrigation (LDI) applied from approximately 118 DAFB until final harvest, and whole-season deficit irrigation (WDI) applied from 12 DAFB until final harvest. Crop load treatments, which were included in two experiments, were commercial crop load (CCL) and light crop load (LCL) equivalent to 60-67% of CCL. 'Braeburn' apple (*Malus domestica* Borkh.) was used in all experiments.

Deficit irrigation applied at any time during the growing season reduced fruit growth and size. Fruit size reduction by DI was counteracted by a lighter crop load. The interactions of DI and crop load on photosynthetic rate, fruit water potential, and fruit turgor potential (which were generally similar between CCL and LCL under CI but were lower in CCL under DI) are possible mechanisms for this counteraction. Tree water use (TWU) was

reduced in DI and in LCL. The difference in TWU between CI and DI were greater at CCL than at LCL and that between CCL and LCL were greater under CI than under DI.

Among the quality attributes studied, only firmness and dry matter concentration (DMC) were affected by fruit size with their values being higher in smaller fruit. The DI fruit were firmer and had higher DMC than CI fruit when comparing fruit of similar size. Total soluble solids (TSS) and total sugar concentration (TSC) were higher in DI fruit than in CI fruit in all experiments. In general, DI did not affect titratable acidity (TA) except for one experiment where TA at harvest was higher in EDI fruit than in CI fruit. Fruit ripened more quickly in LDI and WDI than in EDI which was similar in this respect to CI. The advancement in ripening of DI fruit appeared to be responsible for the enhanced production of aroma volatiles. This enhancement was observed on some occasions during ripening and after cold storage. Deficit irrigation may increase storage potential of the fruit as DI did not affect incidence of physiological disorders but decreased the weight loss during storage. The DI fruit were also firmer than CI fruit for at least 10 weeks of cold storage but this advantage was loss after longer storage due to the advanced ripening of the DI fruit. Apart from the enhancement on individual quality attributes, DI also improved overall fruit quality when many quality attributes were considered collectively using multivariate analysis. This was true both at harvest and after storage.

There was no interaction between irrigation and crop load on any quality attributes under investigation. Light crop load improved fruit quality at harvest in terms of increased firmness, TSS, TSC and fruit density but increased weight loss during storage and incidence of bitter pit after storage.

This research programme showed that deficit irrigation has a great potential as a strategy to save water and to improve fruit quality in apple production. 'Braeburn' is a large-fruited variety. Although fruit size was reduced under DI, DI fruit still met standard export requirements. In situations where price favours large size fruit, light crop load may be integrated with DI to increase fruit size but light crop load may adversely affect fruit quality after storage.

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List of Symbols and Abbreviations

ABA	Abscissic acid
ANOVA	Analysis of variance
^{o}C	Degree celcius
Ca^{2+}	Calcium
CCL	Commercial crop load
CI	Commercially irrigated control
C_i	Intercellular CO_2 concentration ($\mu mol\ mol^{-1}$)
CO_2	Carbon dioxide
D	Drainage volume ($L\ d^{-1}$)
d	Day
DAFB	Day(s) after full bloom
DI	Deficit irrigation
DMC	Dry matter concentration ($mg\ g^{-1}$)
EDI	Early-season deficit irrigation
ENZA	The New Zealand Apple and Pear Marketing Board (ENZA International)
E_{pan}	Pan evaporation (mm)
ET	Evapotranspiration
FID	Flame ionisation detector
FW	Fresh weight (g)
g	Gram(s)
g_s	Stomatal conductance ($mol\ m^{-2}\ s^{-1}$)
H	Hue angle (^{o})
HPLC	High performance liquid chromatography
HPV	Heat-pulse velocity
hr	Hour
I	Irrigation volume ($L\ d^{-1}$)
IEC	Internal ethylene concentration ($\mu L\ L^{-1}$)
K^+	Potassium
k_c	Crop coefficient

kg	Kilogram(s)
L	Litre(s)
LCL	Light crop load
LDI	Late-season deficit irrigation
LSD	Least significant difference
MANOVA	Multivariate analysis of variance
min	Minute(s)
Mg^{2+}	Magnesium
mL	Milli-litre(s)
µL	Micro-litre(s)
mm	Milli-meter(s)
µmol	Micromole(s)
MPa	Mega pascal(s) (1 MPa = 10 bars)
N	Newton(s)
N	Nitrogen
P	Phosphorus
P	Probability
Pn	Photosynthetic rate (µmol m^{-2} s^{-1})
r^2	correlation coefficient
s	Second(s)
SAS	Statistical analysis system software
SPI	Starch pattern index
TA	Titratable acidity (% malic acid)
TDR	Time domain reflectometry
TOU	Total odour units
TSC	Total sugars concentration (mg g^{-1} FW)
TSS	Total soluble solids (%)
TVC	Total volatile concentration (µmol L^{-1})
TWU	Tree water use (L d^{-1})
VPD	Vapour pressure deficit (KPa)
WDI	Whole-season deficit irrigation

θ	Volumetric soil water content ($m^3\ m^{-3}$)
Ψ_l	Leaf water potential (MPa)
Ψ_{fw}	Fruit water potential (MPa)
Ψ_{fs}	Fruit osmotic potential (MPa)
Ψ_{fp}	Fruit turgor potential (MPa)
Ψ_{stem}	Stem water potential (MPa)
ΔW	Changes in soil water content (L)

SECTION ONE

GENERAL INTRODUCTION AND

GENERAL MATERIALS AND METHODS

This section comprises Chapters 1 and 2. In Chapter 1, the importance of deficit irrigation is highlighted, research problems discussed, and the objectives of this research outlined. Chapter 2 describes the materials and methods generally employed in this research. Experimental conditions and treatments are described in Chapters 4, 6, 7, 8, 9, and 11 where research results are presented.

Chapter One

General Introduction

1.1 Water resources and irrigation

Irrigation of agricultural lands accounts for over 85% of water usage world wide (Van Schilfgaarde, 1994). Irrigation practices have been used to supplement the amount of soil water stored in the root zone to ensure its availability throughout the growing season. As a result, many growers tend to over-irrigate which not only wastes water but also contributes to pollution of water resources with agrichemicals making it difficult to sustain recycling and reuse of both surface and ground water resources (Kirda and Kanber, 1999). Almost all liquid fresh water on the planet occurs underground (Bouwer, 2000). Groundwater must therefore be protected against depletion as well as contamination. Pollution of groundwater can also cause pollution of surface water, lakes, and coastal waters. This pollution can be caused from point sources (e.g. sewage and industrial wastewater discharge) and non-point sources. Point source pollution is, at least in principle, relatively simple to control and prevent. Non-point source is of a much greater threat and the major non-point source of groundwater pollution is agriculture through leaching of agrichemicals (Cresswell, 1996; Bouwer, 2000). Hence, irrigation management practices that aim to maximise production with little or no concern for environmental impacts are now considered to be unsustainable. Increased population results in increasing demands for municipal and industrial uses of water. At the same time more irrigation water will be required to meet increasing demands for food for growing populations. More water will also be needed for environmental issues including preservations of aquatic life, riparian habitats, wildlife refuges, scenic reserves, and recreation areas (Bouwer, 2000). Increased competition for water is expected and there is urgent need to enforce irrigation strategies that aim to increase efficient use of water resources as well as to minimise groundwater pollution. Deficit irrigation could be such a strategy.

1.2 Deficit irrigation

Deficit irrigation (DI) is a technique of giving less water to the plant than the prevailing evapotranspiration demand at selected times during the growing season. DI therefore saves water. It was initially developed in peach and pear where DI was applied early in the season to reduce shoot growth and pruning costs (Chalmers et al., 1981; Mitchell and Chalmers, 1982; Mitchell et al., 1984). Control of shoot growth is usually required in most deciduous fruit trees in order to maintain consistent production and to facilitate orchard management. Active growth periods of shoot and fruit are clearly separated in peach and pear and early-season DI reduces shoot growth with minimum effect on fruit growth. In apple, there may be less beneficial effect of DI on shoot growth reduction because fruit set and cell division phases occur at the same time as predominant shoot growth and DI applied during this period will reduce fruit size. However, there appear to be potential of DI in apple fruit quality improvement but research findings on some quality aspects have been inconclusive. Deficit irrigation may have a positive impact on environmental quality. Although well-drained soils are suitable for the establishment of deciduous orchards, they also tend to facilitate the leaching of agrichemicals into ground water. Deficit irrigation has potential to minimise ground water pollution because leaching seldom occurs. Pollution from nitrate-nitrogen has been given the greatest attention as it has high solubility and is easily leached out of the root zone (Loehr, 1984). Less nitrogen fertilisers may also be needed where DI is practiced because DI often reduces vegetative growth which has high nitrogen demand.

1.3 Research problems

To promote the adoption of DI as a sustainable irrigation management tool, the following problems need to be addressed and related information obtained.

1) Timing of the development of water deficit is the key factor determining the success of DI because most events in plant development occur periodically during the season and are sensitive to water deficit only during their active periods. Most studies have focused on an early-season DI, much less information is known on the impacts of DI applied at later stages of crop development. Extensive work has been carried out on the effects of DI on shoot and fruit growth (e.g. Chalmers et al., 1981; Mitchell et al., 1984) and on

plant water relations (e.g. Higgs and Jones, 1991) but there is limited information on its effects on fruit quality. Research at Massey University for the last eight years has focused on the effects of DI applied at different times during the growing season on various aspects of 'Braeburn' apple fruit quality (Mills et al., 1994 and 1996; Kilili et al., 1996a and 1996b; Behboudian et al., 1998). However, results are not conclusive for some aspects. For example, Kilili et al. (1996a and 1996b) reported that late-season DI increased total soluble solids, sugars, and flesh firmness whereas Mills et al. (1996) observed minimal influence on fruit quality from late-season DI. Timing effects of DI on fruit quality need to be clarified and this formed part of my research.

2) Research findings are still contradictory regarding DI effects on some fruit quality attributes such as flesh firmness. Some authors have reported increased flesh firmness under DI (e.g. Kilili et al., 1996b), while the others found no effect (e.g. Irving and Drost, 1987) or decreased flesh firmness under DI (Raese et al., 1982). Flesh firmness may be influenced by fruit size (Ebel et al., 1993). Relationship between fruit size and fruit quality has not been sufficiently considered in most studies and this may be one of the reasons for contradictory results of DI effects on some quality attributes. This thesis addressed relationship between fruit size and fruit quality in order to confirm the effects of DI on fruit quality.

3) Fruit quality and storage potential are highly dependent on maturity at harvest. Effects of DI on fruit physiological maturity are not clearly understood. Some studies indicated that DI fruit were more advanced in maturity than well-watered fruit based on maturity-related quality attributes; such as higher TSS, redder blush or more yellow background colour; rather than physiological maturity of the fruit. This study investigated the effects of DI on fruit physiological maturity and on relationships between physiological maturity and maturity-related quality. This will provide basic information needed in identification of a harvest period that optimises the relationship between increasing eating quality and decreasing storage potential for fruit where DI is practiced.

4) There have been limited studies on some important quality attributes such as aroma volatiles, physiological disorders, and storage potential. The New Zealand apple industry is export-based and production of high quality fruit with long storage potential is of prime

importance. These quality attributes as affected by DI are therefore included in this research.

5) One possible disadvantage of DI is a reduction in fruit size especially if severe water deficit is allowed to develop during rapid fruit growth. This effect of DI could be counteracted by reducing crop load (Naor et al., 1997a and 1999). However, little is known about the mechanisms for this counteraction. In addition, information on interaction of irrigation and crop load on fruit quality other than fruit size is lacking for apple. This thesis explored the possibilities of integrating light crop load with DI to increase fruit size by investigating interactions of DI and crop load on fruit size regulation, yield, and quality.

6) Reduction of water use is a clear advantage of DI. Understanding tree water use in relation to soil water availability and to plant water status is essential in developing an efficient irrigation management. However, there are only a few data on transpiration or tree water use for apple (Wünsche et al., 2000; Green and McNaughton, 1997) and there is no data available on apple tree water use as affected by DI at different levels of crop load. Tree water use in response to DI at different crop levels is therefore examined in this research.

1.4 Thesis objectives

The objectives of this thesis were:

1) To clarify timing effects of DI on fruit quality and to address the relationship between fruit size and fruit quality in order to confirm the DI effects (Chapter 4)

2) To investigate the effects of DI on hitherto under-researched aspects of fruit quality such as production of aroma volatiles (Chapters 4 and 9); physiological disorders (Chapters 4 and 7); and storage potential (Chapters 4, 8, and 11)

3) To investigate the effects of DI applied at different times during the growing season on fruit maturity and on relationship between fruit maturity and maturity-related quality (Chapter 11)

4) To estimate tree water use and its control mechanisms in response to DI and to crop load (Chapter 6)

5) To investigate the interaction between irrigation and crop load on fruit size and the mechanisms behind this interaction (Chapter 7)

6) To investigate the interaction between irrigation and crop load on individual quality attributes as well as on collective quality when many quality attributes were considered together (Chapter 8)

Chapter Two

General Materials and Methods

2.1 Measurements of soil water status

Volumetric soil water content (θ, m^3 m^{-3}) was determined using time domain reflectometry (TDR) (model 1502C, Tektronix Inc., Beaverton, OR, USA). The TDR system involves measurements of propagation velocity of electromagnetic waves in the soil which is dependent on the dielectric constant of the soil. Dielectric constant of the soil depends on volume fractions of soil constituents and their individual dielectric constants but is dominated by volumetric content of soil water because water has, by far, the highest dielectric constant. Hence, the TDR system has been applied for measuring soil water content successfully (Topp and Davis, 1985). More details on the theory of TDR for measuring soil water content can be found in White and Zegelin (1995). Sets of three-wire TDR probes were used in this study and were inserted vertically into the soil to integrate soil water content over the probes' length. Length of probes and depth of probe installation varied in each experiment and details will be given accordingly.

2.2 Measurements of plant water relations

2.2.1 Leaf water potential

Leaf water potential (Ψ_l, MPa) was determined using a Scholander pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, California, USA). Fully expanded leaves were excised from exposed shoots and immediately enclosed in small plastic bags to avoid water loss due to evaporation. The excised leaves were placed, within 30 s from excision, in the pressure chamber humidified with a moist paper towel. Nitrogen gas was used to apply pressure into the chamber until leaf sap appeared at the cut cross-section of the vascular tissue. The pressure applied, which was equal to turgor pressure of the xylem, was taken as an estimate of xylem or leaf water potential because osmotic pressure of the xylem sap is low. More details of Ψ_l measurements using a Scholander pressure chamber can be found in Turner (1988). Measurements were generally made

between 1200 and 1300 HR local time (midday Ψ_l). Diurnal changes in Ψ_l were also evaluated on some occasions.

2.2.2 Fruit water potential

Fruit water potential (Ψ_{fw}, MPa) and its component, osmotic potential (Ψ_{fs}, MPa), were determined using a Wescor Psychrometer-Hygrometer (C-52 sample chambers with a HR-33T microvolt meter, Wescor, Inc., Logan, Utah, USA). Fruit were picked at dawn between 0600 and 0700 HR local time. Disks were taken from the outer equatorial portion of the fruit, excluding the skin, and placed in sample chambers. The Ψ_{fw} was determined after fruit disks were left to equilibrate for one hour. Fruit disks were then wrapped in cellophane sheet and aluminum foil and dipped into liquid air. Cell wall and membrane are disrupted upon thawing and turgor becomes zero. The disks were then returned to sample chambers and Ψ_{fs} was determined after one hour equilibration time. Fruit turgor potential (Ψ_{fp}, MPa) was calculated as the difference between Ψ_{fw} and Ψ_{fs}.

2.3 Measurements of stomatal conductance and photosynthesis

Leaf stomatal conductance (g_s, mol m^{-2} s^{-1}) and photosynthetic rate (Pn, μmol m^{-2} s^{-1}) were measured using a portable photosynthesis system (LI-6200, Li-Cor Inc., Neb., USA). Measurements were made on fully expanded sunlit leaves generally between 1200 and 1300 HR local time. Diurnal changes were also evaluated on some occasions.

2.4 Measurements of growth

2.4.1 Shoot growth

Shoots of similar size were randomly selected at the outer portion of the middle canopy with equal number on each side of the row. Selected shoots were tagged and their lengths were measured at each sampling interval until growth ceased.

2.4.2 Fruit growth

Fruit of similar size were randomly selected at the outer portion of the middle canopy with equal number on each side of the row. Selected fruit were tagged and their

diameters were measured at each sampling interval until commercial harvest. Measurements of fruit diameter were made across the widest part of the fruit using a Cranston Fruit Gauge (Cranston Machinery Co., Oregon, USA) or a digital caliper (model CD-6″, Mitutoyo Corporation, Japan). Fruit volume was calculated from fruit diameter assuming that fruit were spherical. Fruit growth rate was calculated as changes in fruit diameter or fruit volume per time.

2.5 Measurement of fruit yield and size distribution

All fruit picked at commercial harvests were graded using a commercial grading machine and were sorted into six size categories considered to be suitable for the Z-pack counts used by the New Zealand Apple and Pear Marketing Board (ENZA International). The Z-pack counts contain 80, 90, 100, 110, 120, and 135 fruit per standard export carton box, hence higher counts represent smaller fruit. The correspondent approximate ranges of fruit weight are 211-240 g, 191-210 g, 176-190 g, 161-175 g, 146-160 g, and 130-145 g. Two other categories for less than 80 (over-sized) and more than 135 (under-sized) fruit per standard export carton box were also included. Fruit yield per tree was recorded as sum of individual weight of fruit from that tree.

2.6 Determination of fruit maturity

2.6.1 Internal ethylene concentration

Internal gas samples were drawn from the core cavity of each fruit while submerged under water to prevent contamination of the sample from the air. Internal ethylene concentration (IEC, $\mu L\ L^{-1}$) was determined by analysing 1-mL internal gas samples using a Gas Chromatograph (Shimadzu GC-4B PTF; Shimadzu Seisakusho Ltd, Kyoto, Japan) equipped with a flame ionisation detector and a nickel activated alumina column. The peak areas were integrated with an integrator (Hewlett-Packard 3390A; Hewlett-Packard Co., Avondale, PA, USA) calibrated with external ethylene standards (certified as β-standard by B.O.C. gases NZ Ltd). Temperature settings for the column, injector, and detector were 100, 150, and 155°C, respectively. Nitrogen at a flow rate of 30 mL min^{-1} was used as the carrier gas and the flame was maintained with hydrogen at 30 mL min^{-1} and air at 300 mL min^{-1}

2.6.2 Starch pattern index

Starch pattern index (SPI) was determined by dipping cross-sectional fruit halves for 30 s in an iodide solution made up of 8.8 g potassium iodide and 2.2 g iodine in one litre of water. Hydrolysis of starch was rated on a scale of 0 (100% starch) to 6 (no starch).

2.7 Determination of fruit quality

2.7.1 Fruit density

Fruit density (g cm^{-3}) was determined as fruit mass per unit volume. Individual fruit weight was measured using an analytical balance (Mettler PM4800, Greifensee, Switzerland) and fruit volume was measured as detailed in section 2.4.2.

2.7.2 Fruit skin colour

Fruit skin colour was measured as hue angle (H, ^{o}) on two positions of each fruit, red blush and background green colour, using a portable tristimulus chromameter (CR-200, Minolta, Osaka, Japan). Calibration of the instrument was made against a standard green plate (CR-A47 G).

2.7.3 Flesh firmness

Flesh firmness (N) was determined on two positions, red blushed and unblushed background surface areas, at the equator of each fruit after removing the skin using a press-mounted Effegi penetrometer (model FT 327, Alfonsine, Italy) with an 11.1-mm head to a depth of 7.9 mm (Harker *et al.*, 1996). The readings were converted into Newtons (N) by multiplying with a correction factor of 9.807.

2.7.4 Physiological disorders

Incidence of physiological disorders was investigated in all fruit used in quality determination. Water core incidence was rated as none, acceptable, slight, or severe according to the water core chart of the New Zealand Apple and Pear Marketing Board (ENZA, 1998). Incidence of each physiological disorder was expressed as percentage of fruit with that disorder.

2.7.5 Aroma volatiles

Aroma volatile concentrations were determined from 20-mL juice samples, produced by a domestic juicer, extracted in 20 mL solvent mixture of diethyl ether and pentane (2:1 v/v) (Larsen and Poll, 1990) with 0.2 μL octyl acetate added as an internal standard. Samples were kept at –18°C until the aqueous phase was frozen. The unfrozen solvent phase of each sample was concentrated to about 200 μL (approximately 100 fold) using a fast oxygen-free N_2 gas stream (200 mL min^{-1}). A sample of 1 μl was then analysed for aroma volatiles using a gas liquid chromatograph (Hewlett-Packard 5890 Series II Plus, Hewlett-Packard Co., Avondale, PA, USA) equipped with a flame ionisation detector using a 30 m × 0.32 mm (i.d.) fused silica, DBWAX, 0.5 μm film thickness capillary column. Quantification of volatile compounds in the sample was by comparison with authentic compounds, made to a concentration of 200 μL L^{-1} in the solvent mixture. Odour units were calculated for each volatile as the ratio of the concentration of a volatile in the sample and the threshold concentration of that volatile in water (Frijters, 1979). Total odour units for each sample were calculated as the sum of odour units for each volatile compound in that sample. Odour threshold concentration of each volatile compound was listed in Appendix.

2.7.6 Total soluble solids

Total soluble solids (TSS, %) was measured from fruit juice, produced by a domestic juicer, using a hand held refractometer with automatic temperature compensation (ATC-1 Atago, Tokyo, Japan). The instrument was calibrated with distilled water before use.

2.7.7 Titratable acidity

Titratable acidity (TA, % malic acid) was determined by titration of fruit juice, produced by a domestic juicer, against 0.1 N sodium hydroxide, using an automatic titrator (Mettler DL21, Greifensee, Switzerland) equipped with a Mettler DG111 pH electrode, to an endpoint of pH 7.1 (malic acid). A sample of 1 mL fruit juice diluted in 40 mL of distilled water was used in the titration. Sodium hydroxide concentration was checked by titration against 0.1 N hydrochloric acid solution (Convol solution, BDH chemicals) to an endpoint of pH 7. A sample of distilled water used to dilute the fruit juice was titrated to

pH 7.1. The volume of sodium hydroxide used to neutralise the distilled water was subtracted from the subsequent volume of sodium hydroxide used to neutralise the juice sample. Percentage equivalent malic acid was then calculated.

2.7.8 Soluble sugars

Soluble sugar concentration (mg g^{-1} fresh weight) was determined using a Waters high-performance liquid chromatography (HPLC) system (Waters, Milford, MA, USA) equipped with a carbohydrate analysis column (Aminex HPX87C, Life Science Group, Hercules, CA, USA) maintained at 85°C with a de-ashing guard column. The detector (Optilab 5922 RI Chromatography Module, Tekator AB, Högnäs, Sweden) was maintained at 40°C. The flow rate was 0.6 mL min^{-1}. Sample preparation was done according to Pesis *et al.* (1991). A 5-g sample of fresh cortical tissue was placed in 20-mL 95% ethanol to inactivate invertase enzyme which may lead to increase in glucose and fructose (Paull *et al.*, 1984). The samples were stored for at least one month at –18°C before the determination to allow precipitation of cell components. A 1-mL aliquot of clear supernatant was taken from each sample and was completely dried down using a concentrator (model RH 40-11; Savant Instruments, Farmingdale, NY, USA). The residue was redissolved in 3-ml Barnstead nano-pure water and filtered using 0.3-µm nylon membrane filters. Concentrations of sucrose, glucose, fructose, and sorbitol which are the major soluble sugars in apple fruit (Chan *et al.*, 1972), were determined from 15 µL of each sample. The areas under curves were computed by a β-RAM software package and concentration of each sugar for the sample was calibrated with each sugar standard of known concentration. Results were then calculated as mg of sugar per g of fruit fresh weight. Total sugars concentration (TSC) was calculated as the sum of sucrose, glucose, fructose, and sorbitol concentrations.

2.7.9 Dry matter concentration

Fruit dry matter concentration (DMC, mg g^{-1}) was determined from 30-g fresh cortical tissue and placed in an oven at 70°C for 14 days on an aluminum foil tray. The dry tissue was weighed and calculated as mg dry weight per g fresh weight.

2.7.10 Fruit mineral concentration

Fruit mineral concentrations (mg g^{-1} dry weight) were determined using 10 g of fresh cortical tissue. The samples were dried at 70°C for 14 days, ground into powder, and kept in an oven at 70°C for about 12 hours to remove any moisture before analysis. Fruit Ca^{2+}, Mg^{2+}, and K^{+} concentrations were analysed from 0.1 g dry ground tissue using an atomic absorption spectrometer (model GBC 904 AA, GBC Scientific Equipment, Dandenong, Victoria, Australia) following nitric acid digestion. Fruit N and P concentrations were analysed from 0.1 g dry ground tissue using chlorimetric autoanalysis (Technicon Instruments Corp., NY, USA) following Kjeldahl digestion (Twine and Williams, 1971).

2.7.11 Weight loss

Individual fruit weight (g) was measured using an analytical balance (Mettler PM4800, Greifensee, Switzerland) at each sampling interval. Fruit weight loss was calculated as percent reduction from initial weight.

2.8 Statistical analysis

Statistical procedures were performed using statistical analysis systems (SAS) software version 6.12 (SAS Institute, Cary, NC, USA).

SECTION TWO

TIMING EFFECTS OF DEFICIT IRRIGATION ON FRUIT GROWTH, SIZE, AND QUALITY

This section covers Chapters 3 and 4. Chapter 3 presents background information for Chapter 4 as well as literature review for the effects of deficit irrigation on fruit growth, size, and quality attributes for which information is either limited or not conclusive. An experiment using field-grown 'Braeburn' apple in Marlborough region during the growing season 1997/98 is presented in Chapter 4.

In Chapter 4, effects of DI applied during early and late season on fruit size and quality were investigated. Early-season DI commencing after the cessation of fruit cell division was chosen and its effects on shoot and fruit growth were investigated. Fruit for quality assessments were sampled from three different sizes with equal numbers from each size and relationships between fruit size and fruit quality were explored. Quality attributes assessed included those for which literature information is inconclusive such as size, firmness, TA, and mineral concentration; and those with limited data available such as aroma volatiles, physiological disorders particularly water core, and storage potential.

Chapter Three: Literature Review

Seasonal Timing of Deficit Irrigation and Their Effects on Fruit Growth, Size, and Quality

3.1 Introduction

Apple trees, the same as other deciduous fruit trees, are active for approximately nine out of twelve months (Westwood, 1993). Generally, they enter dormancy annually in late summer or in autumn, characterised by lack of visible growth. Dormancy is a mechanism that enables the plants to survive cold temperatures during winter months. After exposure to sufficient chilling, trees will resume growth the following spring. Vegetative growth once commenced may continue until harvest with one or more active growth periods. Fruit growth commences after shoot growth. The degree of overlapping between the active periods of shoot growth and fruit growth varies among species and cultivars. Water deficit has the most influence on crop performance during the active growth phase, hence, impact of DI is strongly dependent on timing of the development of water deficit. Information on timing effects of DI on fruit size and some other quality attributes is still inconclusive. Moreover, there is insufficient information for timing effects of DI on some important quality attributes such as aroma volatiles, physiological disorders, and storage potential.

3.2 Water deficit and fruit growth

The term water deficit implies that water status is less than the optimum value for plant growth and development (Taylor, 1968). Plant water deficit occurs when water absorption lags behind transpiration. Thus excessive transpiration, slow absorption, or their combination can lead to plant water deficit.

Water deficit during rapid fruit cell expansion generally decreases fruit size as cell expansion is sensitive to reduced water status (Li et al., 1989; Boyer, 1985; Hsiao, 1973). Although cell division appears not to be so sensitive to water deficit (Li et al., 1989), water deficit during this period may reduce cell number (Hsiao, 1973). This may in turn

reduce final fruit size which has been found to be closely correlated with cell number in the cortex (Goffinet et al., 1995). Water deficit throughout the season, covering cell division and rapid growth period, often reduces fruit size (Kilili et al., 1996c; Mills et al., 1996). Water deficit developed during slow fruit growth, i.e. later in the season, may not affect fruit size as exemplified by apple (Mills et al., 1997; Mills et al., 1996; Kilili et al., 1996c) and Asian pear (Behboudian et al., 1994). Effects of early-season water deficit on fruit size are inconclusive. Kilili et al. (1996c) observed a reduction in final fruit size for apple when irrigation was withheld early in the season. Whereas others reported that, after an early-season water deficit is relieved, fruit size recovered by the time of harvest in peach (Chalmers et al., 1981), pear (Chalmers et al., 1986; Mitchell et al., 1986), Asian pear (Behboudian et al., 1994), and apple (Mills et al., 1997). The inconsistent effect of early-season water deficit on fruit size could be due to different degrees of water deficit developed and weather conditions. This thesis investigated effects of early-season DI applied after the cessation of cell division and late-season DI on fruit growth and size of 'Braeburn' apple grown in a commercial orchard in Marlborough region which is a relatively dry area of New Zealand.

3.3 Water deficit and fruit quality

There are conflicting reports on effects of water deficit on various fruit quality attributes. Both level and timing of plant water deficit may play important roles in the conflicting responses observed. As some quality attributes may be influenced by fruit size, its variation may account for some of these contradictions.

3.3.1 Flesh firmness

Raese et al. (1982) reported that pear fruit tended to be softer on trees exposed to water deficit whereas Caspari et al. (1996) found no change in firmness of Asian pear grown under water deficit. In apple, fruit from plants grown under water deficit conditions were firmer as observed by Guelfat'Reich et al. (1974), Assaf et al. (1975), and Kilili et al. (1996a). Irving and Drost (1987), however, found no change in firmness of apple fruit under reduced irrigation. Ebel et al. (1993) reported that small fruit were firmer than large fruit. The contradictory results of DI on fruit firmness could have been due to the confounding effects of fruit size on flesh firmness.

3.3.2 Total soluble solids (TSS)

Numerous authors have reported an increase in TSS under plant water deficit in apple (Ebel et al., 1993; Mills et al., 1994; Kilili et.al., 1996a; Mills et al., 1996), pear (Raese et al., 1982), and peach (Crisosto et al., 1994). However, there is an indication that timing of water deficit may have influence on such increases in TSS. For example, if an early-season water deficit is followed by full irrigation, the increased TSS during the deficit period may disappear by the time of harvest as has been observed in Asian pear (Behboudian and Lawes, 1994; Caspari et al., 1996) and apple (Kilili et al., 1996a; Mills, 1996).

3.3.3 Titratable acidity (TA)

The published data on the effect of water deficit on fruit TA are inconclusive. Irving and Drost (1987) reported no change in fruit TA under water deficit whereas Drake et al. (1981) reported a decrease and Mills et al. (1994) observed an increase in fruit TA under water deficit.

3.3.4 Skin colour

Fruit skin colour depends on the amount of pigments in the skin and the type of radiation (Gorski and Creasy, 1977). Apple has red, green, and red/green skinned cultivars. 'Braeburn' is one of the red/green skinned cultivars. The red blushed skin portion is mainly due to the development of anthocyanins and the green background portion is due to chlorophyll. As fruit mature, chlorophyll is broken down and carotenoids (yellow pigments) are unmasked, hence the ground colour changes from green to yellow (Gorski and Creasy, 1977). Fruit skin colour is determined by several factors such as light interception, temperature, and fruit nutrients especially nitrogen (Daugaard and Grauslund, 1999). High N levels have been reported to encourage large fruit with poor colour development (Richardson, 1986; Bramlage, 1993). High nitrogen levels delay chlorophyll breakdown (Magness et al., 1940) and hence reduces the development of red and yellow colour in apple.

Proebsting et al. (1984) and Ebel et al. (1993) reported that reduced irrigation did not affect red coloration of 'Delicious' apple. Similarly, Caspari et al. (1996) observed no change in colour of Asian pears due to reduced plant water status. However, red coloration was

enhanced under reduced plant water status for 'Braeburn' apple (Mills et al., 1994; Kilili et al., 1996a) and grape (Matthews and Anderson, 1988). There are indications for a reduction in fruit N with reduced irrigation in pear (Raese et al., 1982) and apple (Mills et al., 1994). This lowering of N may contribute to enhanced colour development in fruit from water deficit treatments. In Kilili et al. (1996a), while DI fruit had redder skin colour, there was no difference in N between DI and control fruit. These authors related the redder skin colour of DI fruit to its more advanced maturity. Anthocyanins are composed of anthocyanidin and sugar (Lancaster, 1992). The redder colour of fruit under water deficit could also be due to increased sugar concentration. In a laboratory study, anthocyanins production in apple was stimulated by fructose, glucose, and sucrose (Vestrheim, 1970).

3.3.5 Mineral composition

Some studies have indicated the importance of fruit mineral concentration for texture and storage potential of the fruit (Johnson, 1992; Sharples, 1994). Fruit mineral concentration has been linked to the development of physiological disorders. Low Ca^{2+} concentration has been associated with the occurrence of many physiological disorders including bitter pit, water core, senescent breakdown, internal breakdown, and scald (Shear, 1975). High K^+ and Mg^{2+} generally aggravate problems caused by lack of calcium (Bangerth, 1979). Low P increases the risk of low temperature breakdown (Johnson et al., 1987). High N levels in apple fruit may predispose fruit to the development of corkspot, bitter pit, and internal breakdown (Bramlage, 1993). In larger fruit, Ca^{2+} levels are effectively diluted. Since high N levels encourage large fruit, some of the changes observed as a response to increased N may be linked to a reduction in Ca^{2+} concentration of the fruit (Bramlage, 1993).

If mineral concentration of the fruit is reduced under water deficit, it may be due to the difficulty of nutrient uptake by the plant from the soil solution (Mengel and Kirkby, 1987). Although nutrient uptake may be less under reduced irrigation, decreased fruit size and/or increased DMC under water deficit may reduce the dilution effect of minerals present in the fruit and thus increase mineral concentration. Published data regarding effects of water deficit on fruit mineral concentration are conflicting. In apple fruit, reduced water supply to the trees resulted in a reduction of N (Ericsson, 1993; Mills et

al., 1994), Ca^{2+} (Mills et al., 1994), and K^{+} (Guelfat'Reich et al., 1974; Lötter et al., 1985). However, Failla et al. (1992) found an increase in K^{+}, Ca^{2+} and Mg^{2+} under water deficit whereas Kilili et al. (1996a) and Irving and Drost (1987) reported that water deficit had no effects on the concentration of N, P, K^{+}, Ca^{2+} or Mg^{2+}. A reduction in the levels of N, P, K^{+}, Ca^{2+} and Mg^{2+} were recorded for Asian pear fruit under early-season but not late-season water deficit (Behboudian and Lawes, 1994). In contrast, Caspari et al. (1996) observed no effect on mineral concentration by either early-season or late-season DI for Asian pear.

3.3.6 Aroma volatiles

Flavour of apple fruit and fruit juice appears to be a result of a delicate balance of sweet, sour, and astringent taste; and aroma of a number of volatile compounds (Dürr and Schobinger, 1981; Kingston, 1992; Yahia, 1994). Although taste and texture are crucially important to its perception, it is the presence of trace amount of volatile compounds which is responsible for odour that gives much of the character to the fruit and their processed products (Williams, 1979). Formation of aroma volatiles in fruit may be influenced by both internal factors, e.g. genetic differences and metabolic activity, and external factors such as pre- and post- harvest treatments (Paillard, 1981; Yahia, 1994).

The only published paper available for effects of reduced irrigation on apple fruit aroma volatiles is that of Behboudian et al. (1998) who reported that late-season DI enhanced aroma volatiles both at harvest and after storage. However, their study was based on a lysimeter study with limited numbers of trees and fruit.

3.3.7 Storage potential

Important quality attributes that determine storage potential of the fruit are the occurrence of physiological disorders, decay, water loss, and loss of firmness during and after storage.

Information on the effects of reduced irrigation on development of physiological disorders is not conclusive. Proebsting et al. (1984) and Mills et al. (1994) found no differences in the occurrence of physiological disorders between trees under water deficit and those receiving ample water. Whereas other studies observed less incidence of

physiological disorders in fruit grown under reduced irrigation (Guelfat'Reich et al., 1974; Lötter et al., 1985; Irving and Drost, 1987; Failla et al., 1990). Early-season water deficit has been reported to decrease water core in apple (Lötter et al., 1985) and alfalfa greening and cork spot in pear (Brun et al., 1985), but increase flesh spot decay in 'Nijisseiki' Asian pear (Behboudian and Lawes, 1994). Development of many physiological disorders in apple fruit has been attributed to fruit mineral concentration, especially Ca^{2+} (section 3.3.5). Guelfat'Reich et al. (1974) suggested that the higher incidence of fruit disorders in well-watered trees than in deficit-irrigated trees could be due to a mineral imbalance, i.e. a high K^{+}:Ca^{2+} ratio, in the former.

Water loss is a major cause of deterioration in storage. It leads to loss of marketable weight, changes in texture due to reduction in cell turgor, wilts and shrivels, undesirable changes in colour, early ripening, and increased susceptibility to diseases (Grierson and Wardoski, 1978; Ben-Yehoshua, 1987; Hatfield and Knee, 1988; Woods, 1990). The only published data available regarding effects of reduced irrigation on apple fruit water loss are those of Kilili et al. (1996b) and Mills (1996). While Kilili et al. (1996b) reported a higher weight loss in fruit from well-watered trees than those from non-irrigated trees, Mills (1996) found no effect of reduced irrigation on fruit water loss. In peach, Crisosto et al. (1994) observed less water loss during storage in fruit from trees exposed to water deficit throughout the season.

Softening is one of the most significant quality alterations associated with maturity and ripening (Ferguson, 1984). It affects storage life as well as palatability of the fruit (Kays, 1991). Kilili et al. (1996b) reported that apple fruit from trees not receiving irrigation late or throughout the growing season were firmer, during and after storage, than those from well-watered trees.

Chapter Four

Timing Effects of Deficit Irrigation on Fruit Quality and Storage Potential of 'Braeburn' Apple in Relation to Fruit Size

Abstract

This study explored the potential of deficit irrigation (DI) applied at different times during the growing season for improving fruit quality and storage potential of 'Braeburn' apple growing in a commercial orchard. Because DI often reduces fruit size, effects of fruit size on fruit quality were also examined. The irrigation treatments were: commercially irrigated control (CI), early deficit irrigation (EDI) applied from 63 to 118 days after full bloom (DAFB), and late deficit irrigation (LDI) applied from 118 DAFB to final harvest on 201 DAFB. Both EDI and LDI improved fruit quality in terms of increases in: dry matter concentration (DMC) at harvest, flesh firmness, total soluble solids, and total sugar concentration both at harvest and after storage. The DI fruit had less weight loss during storage than did CI fruit. Deficit irrigation affected the concentrations of a few individual aroma volatiles but not total volatile concentration. Incidence of physiological disorders was not affected by irrigation treatments. Mean fruit weight at harvest was lower in DI than in CI but the difference was not significant. Among the quality attributes studied, only firmness and DMC were affected by fruit size with their values being higher in smaller fruit.

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Improvement of fruit quality and storage potential of 'Braeburn' apple through deficit irrigation

Bussakorn S. Mpelasoka[1], M. H. Behboudian[1], J. Dixon[1], Sue M. Neal[2] and H. W. Caspari[2]

[1]Institute of Natural Resources, College of Sciences, Massey University, Palmerston North, New Zealand

[2] The Horticultural and Food Research Institute of New Zealand Ltd, Marlborough Research Centre, Blenheim, New Zealand

4.1 Introduction

The New Zealand apple industry is export-based and production of high quality fruit that meets stringent specifications of international clients is of prime importance. Quality enhancement should be through methods compatible with sustainability and consumer health. Deficit irrigation (DI), if applied judiciously, saves water, decreases vegetative growth and therefore pruning costs, reduces leaching of agrichemicals into ground water, and may improve fruit quality (Behboudian and Mills, 1997). Research in this laboratory for the last eight years has focussed on the effects of DI on various aspects of apple fruit quality (e.g. Mills et al., 1994 & 1996; Kilili et al., 1996a & 1996b; Behboudian et al., 1998). The research has been carried out in the humid climate of Palmerston North which is not a centre of commercial apple production in New Zealand. Although timing of DI application is expected to affect fruit quality, our previous results are not conclusive. Kilili et al. (1996a) reported that late DI (from 104 days after full bloom (DAFB) to final harvest on 198 DAFB) increased total soluble solids (TSS), sugars and flesh firmness. But Mills et al. (1996) observed minimal influence on fruit quality from DI applied late in the season (from 105 DAFB to final harvest on 183 DAFB). These contradictory results could be due to differences in weather conditions during experimentation. However, in all experiments DI has decreased fruit size when applied during the entire season (Kilili et al., 1996a; Mills et al., 1996). But late-season DI has not affected fruit size (Kilili et al., 1996a; Mills et al., 1996). The objectives of this study were: to further investigate DI's timing effect on 'Braeburn' apple quality but in Marlborough district which is a dry area and a major apple production centre in New Zealand and to investigate effects of DI on hitherto under-researched aspects of fruit quality such as aroma volatiles. So far there is only one published paper on this aspect and that was based on a lysimeter study with limited number of trees and fruit (Behboudian et al., 1998). Although firmness is an important quality attribute especially for shipment to distant markets, published data on the effect of DI on this attribute are inconclusive. Some authors have reported increased flesh firmness under DI (e.g. Kilili et al., 1996a), while the others found no effect (e.g. Irving and Drost, 1987) or decreased flesh firmness under DI (Raese et al., 1982). These contradictory results could have been due to the confounding effects of fruit size on flesh firmness with smaller fruit being

firmer (Ebel et al., 1993). This study therefore addressed the relationship between fruit size and flesh firmness to confirm the DI effects. Storage potential is another important quality aspect especially for fruit destined to distant markets. Another objective was therefore to have a comprehensive evaluation of DI effects on fruit weight loss, firmness loss, and development of physiological disorders including bitter pit in storage. This study also investigated the incidence of water core, a physiological disorder which has been observed in recent years in New Zealand apples (Clark and Richardson, 1999), and there is limited information on the effect of irrigation on its incidence.

4.2 Materials and methods

4.2.1 Experimental conditions and treatments

The experiment was conducted during the 1997-98 growing season using ten-year-old apple trees (cv. 'Braeburn' on MM106 rootstock) growing in a commercial orchard in Marlborough (latitude 41° 30′ S, longitude 173° 55′ E), New Zealand. The area has an evenly distributed average annual rainfall of 640 mm and the orchard soil was a deep well-drained sandy alluvium loam. Thirty-six ten-year-old 'Braeburn' apple trees (4.5 m between rows, 2.4 m within rows) trained as central leader were divided into four blocks of nine trees. Each block had three plots of three trees and was surrounded by six guard trees. Three irrigation treatments were randomly applied to each plot within each block. The treatments were: commercially irrigated control (CI), early deficit irrigation (EDI) applied from 63 to 118 DAFB, and late deficit irrigation (LDI) applied from 118 DAFB until final harvest on 201 DAFB. Full bloom occurred on 4 October 1997. The CI trees were irrigated to maintain soil moisture at or close to field capacity. During deficit periods DI trees were irrigated with the same amount of water but at approximately half of the frequency of the CI trees. They were irrigated the same as CI trees outside the deficit periods.

4.2.2 Measurements of soil water status

Volumetric soil water content (θ) was measured as detailed in Chapter 2 (section 2.1) at depths of 300 mm and 600 mm.

4.2.3 Measurement of fruit growth, yield, and size distribution

Fruit growth rates and changes in fruit volume were determined from forty fruit per treatment using procedures listed in Chapter 2 (section 2.4.2).

Fruit were picked at three commercial harvests on 180, 192 and 201 DAFB. After harvest, fruit were refrigerate-transported to Massey University where yield, size distribution, and quality were assessed. Measurements of fruit yield and size distribution are listed in Chapter 2 (section 2.5).

4.2.4 Fruit sampling and quality assessment protocols

Fruit picked at final commercial harvest from four trees per treatment (one tree per block) were used for quality assessments. The assessments included measurements of: internal ethylene concentration (IEC), starch pattern index (SPI), flesh firmness, total soluble solids (TSS), titratable acidity (TA), aroma volatiles, soluble sugars, dry matter concentration (DMC), and minerals (N, P, Ca^{2+}, Mg^{2+}, and K^{+}). The measurements were made both at harvest and after storage except for DMC and minerals that were determined only at harvest. The quality assessments after storage were done after 7 days shelf life simulating at 20°C following 12 weeks of cold storage at 0°C (±1°C). This storage protocol was to mimic commercial storage followed by presentation of the fruit to retail outlets. Fruit were divided into three weight groups: 131-160 g, 161-190 g, and 191-240 g and referred to as small, medium, and large weight groups, respectively. At harvest the assessments were done on 20 fruit per weight group per tree selected at random and after storage they were done on 10 fruit per weight group per tree selected at random.

Fruit density was determined from a sample of 48 fruit per tree strip-picked on 172 DAFB from four trees per treatment (one tree per block). All fruit used in quality assessments both at harvest and after storage were assessed for incidence of physiological disorders. Water core incidence at harvest was assessed in 300 more fruit per tree strip-picked on 172 DAFB from four trees per treatment. Water core incidence was rated as none, acceptable, slight, or severe according to the water core chart of the New Zealand Apple and Pear Marketing Board.

Procedures for the assessments of each quality attribute are described in Chapter 2 (sections 2.6 and 2.7).

4.2.5 Statistical analysis

Data on fruit quality attributes at harvest were averaged for each weight group from individual trees and were subjected to analysis of variance (ANOVA) as a split plot design with irrigation treatments as main plots and weight groups as sub plots. Data of quality attributes that were affected by fruit size were further analysed by ANOVA separately for each weight group as a randomised complete block design with four blocks and three treatments. Data on soil volumetric water content, fruit weight loss, and fruit quality after storage were averaged for each tree and were subjected to ANOVA as a randomised complete block design with four blocks and three treatments. Mean comparisons were performed using t-tests.

4.3 Results and discussion

4.3.1 Volumetric soil water content (θ)

Deficit irrigation decreased θ during most of the deficit periods (Figure 4.1B&C). The θ value was lower in EDI than in CI and LDI from the first measurement on 75 DAFB and was maintained until the end of the early deficit period on 118 DAFB. The difference of θ on 107 DAFB was, however, not significant for the 300-mm depth. After irrigation was resumed (on 118 DAFB), the θ values of EDI gradually increased although remained lower than those of CI in most measurements the differences were not significant. After the start of LDI on 118 DAFB, the θ values of LDI gradually decreased. The lower θ values in LDI than in CI were not significant until 157 DAFB at 600-mm depth and until 177 DAFB at 300-mm depth. The less impact of LDI than EDI on reducing soil θ was due to higher amount of rainfall during the late deficit period (Figure 4.1A).

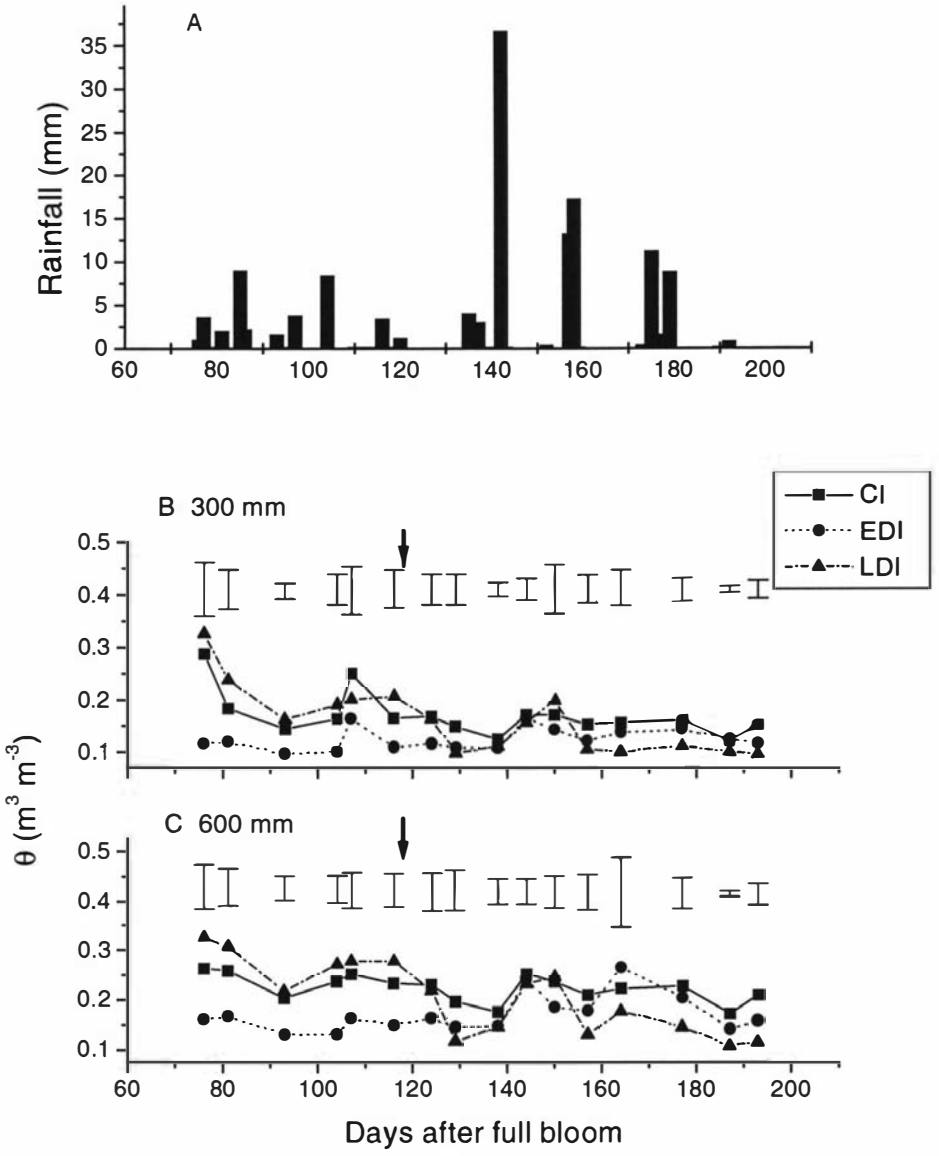

Figure 4.1 Rainfall data (A) and changes in volumetric soil water content (θ) at depths of 300 mm (B) and 600 mm (C) during the growing season for 'Braeburn' apple trees under three irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Arrows indicate the end of EDI and the start of LDI. Vertical bars represent LSD.

4.3.2 Fruit growth

During early deficit period, cumulative growth (Figure 4.2A) and growth rate (Figure 4.2B) of EDI fruit were lower than those of CI and LDI fruit. After resumption of irrigation, growth rate increased in EDI fruit. Before the commencement of late deficit period, cumulative growth (Figure 4.2A) and growth rate (Figure 4.2B) of LDI fruit were similar to those of CI fruit. After the start of LDI treatment (118 DAFB), fruit growth rate decreased in LDI and became lower than that in CI from 143 DAFB. The increase in fruit growth rates in all treatments at 150 DAFB was possibly due to rain.

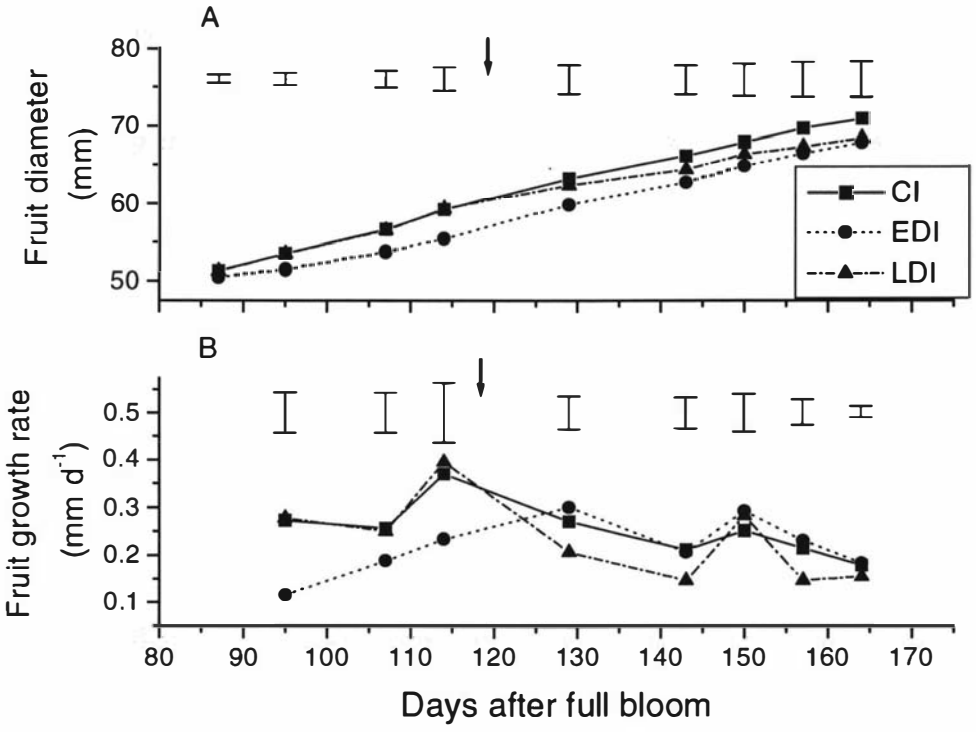

Figure 4.2 Fruit diameter (A) and fruit growth rate (B) during the growing season of 'Braeburn' apple under three irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Arrows indicate the end of EDI and the start of LDI. Vertical bars represent LSD.

4.3.3 Yield, mean fruit weight and fruit size distribution

Gross yield per tree (kg, $LSD_{0.05}$ = 24.1) was 77.9, 67.0 and 58.3 for, respectively, CI, EDI, and LDI treatments. The corresponding mean fruit weights (g, $LSD_{0.05}$ = 19.8) were 199.0, 167.3, and 167.9. The lower gross yield per tree and the lower mean fruit weight for the DI treatments were not significant because of large variation in yield from tree to tree possibly due to biennial bearing habit of the trees. Although EDI and LDI fruit were not significantly smaller than the CI fruit, the significant decreases in rates of fruit growth for the DI treatments during the deficit periods were indicative of DI impact on fruit growth suppression (Figure 4.2).

Irrigation treatments affected fruit size distribution (Figure 4.3). Control trees yielded more oversized fruit than DI trees. Less proportion of very large fruit in DI trees may prove to be beneficial in terms of packing especially for large fruit size cultivar like 'Braeburn'.

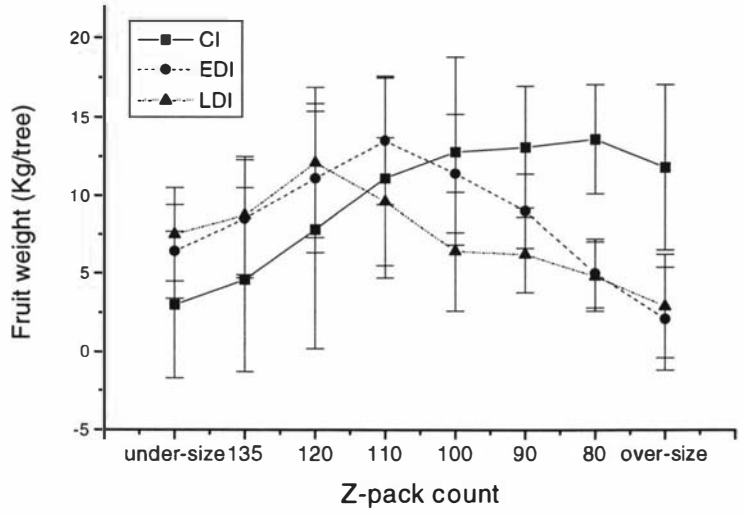

Figure 4.3 Fruit size distribution for 'Braeburn' apple grown under different irrigation treatments: CI = commercially irrigated control; EDI = early deficit irrigation; and LDI = late deficit irrigation. The higher Z-pack counts represent smaller fruit. Vertical bars represent LSD.

4.3.4 Fruit quality and storage potential

4.3.4.1 Firmness, dry matter concentration, and density

At harvest, DI fruit were firmer than control fruit in all weight groups except the small weight group in which the higher firmness values of LDI fruit was not significant (Table 4.1). After storage, although more flesh firmness was lost in DI fruit than in CI fruit, DI fruit were still firmer than CI fruit (Table 4.1). The small weight group was firmer than medium and large groups and the medium group was firmer than large group. Flesh firmness (N, $LSD_{0.05}$ = 1.2) at harvest was 88.3, 86.3, and 83.9 for, respectively, fruit from small, medium, and large weight groups. Increased flesh firmness of DI fruit was reported to be due to increased cellular density with a reduction in fruit size (Ebel et al., 1993). In our study DI fruit were firmer than CI fruit even when comparing fruit of similar sizes (Table 4.1) suggesting that there are other factors besides fruit size involved in flesh firmness. Both EDI and LDI fruit had higher density than CI fruit, suggesting that cells could be more densely packed in DI fruit compared to CI fruit. Fruit density (g cm^{-3}, $LSD_{0.05}$ = 0.03) was 0.81, 0.86, and 0.87 for, respectively, CI, EDI, and LDI fruit. Fruit from small and medium weight groups had higher DMC than fruit from large weight group. Fruit DMC (mg g^{-1}, $LSD_{0.05}$ = 2.25) was150.24, 149.80, and 146.18 for, respectively, small, medium, and large weight groups. Increased DMC was observed in DI fruit in all weight groups except the medium group in which the increased DMC of EDI fruit was not significant (Table 4.2). Decreased cellular hydration as a result of reduced irrigation may also have contributed to increased flesh firmness.

Table 4.1 Flesh firmness (N) at harvest and after storage (12 weeks at 0 °C followed by 7 days at 20 °C) of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

	At harvest for different weight group				**After storage**
Treatment	131-160 g	161-190 g	191-240 g	Average	
CI	84.5b	82.9b	80.0b	82.5b	66.6b
EDI	91.1a	88.4a	87.2a	88.9a	70.8a
LDI	89.2ab	87.6a	84.4a	87.1a	70.1a

Table 4.2 Fruit dry matter concentration (mg g^{-1}) at harvest of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

	Weight group			
Treatment	131-160 g	161-190 g	191-240 g	Average
CI	142.3b	143.5b	138.8b	141.5b
EDI	156.1a	151.4ab	151.6a	154.1a
LDI	152.4a	154.5a	148.1a	150.6a

4.3.4.2 Total soluble solids (TSS), soluble sugars, and titratable acidity (TA)

Both EDI and LDI fruit had higher TSS (Table 4.3) and total sugar concentration (TSC) (Table 4.4) than CI fruit at harvest. Concentration of fructose was higher than any other sugars in all treatments. Increased TSC in DI fruit at harvest was due mainly to an increase in fructose concentration (Table 4.4). Because DI fruit had higher DMC than CI fruit, dilution effects could have led to decreased TSC and TSS concentration in the CI fruit. Fruit TA was higher at harvest in EDI but was not affected by LDI (Table 4.3), confirming the results of Mills et al. (1996). Fruit TA decreased after storage to the same levels in all treatments (Table 4.3) due to consumption of malic acid as a metabolic substrate in fruit respiration (Ackermann et al., 1992). In contrast, both TSS (Table 4.3) and TSC (Table 4.4) increased after storage in all fruit because of increased conversion of starch to sugars during ripening (Brady, 1987). These concentrations were still higher in DI fruit than in CI fruit. Increased TSC after storage in DI fruit was due mainly to increases in fructose and glucose concentrations. However, the higher glucose concentration in LDI fruit than CI fruit was not significant (Table 4.4). There was no effect of fruit size on fruit TSS, TSC, and TA (data not shown).

Table 4.3 Total soluble solids (TSS, %) and titratable acidity (TA, % malic acid) at harvest and after storage (12 weeks at 0°C followed by 7 days at 20°C) of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

	At harvest		**After storage**	
Treatment	TSS	TA	TSS	TA
CI	13.3b	0.69b	14.3b	0.59a
EDI	14.3a	0.79a	14.9a	0.60a
LDI	14.2a	0.72ab	14.9a	0.60a

Table 4.4 Fruit soluble sugars (mg g^{-1} fresh weight) at harvest and after storage (12 weeks at 0°C followed by 7 days at 20°C) of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Comparison was made within each category: 'At harvest' and 'After storage'. Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

Treatment	Sucrose	Glucose	Fructose	Sorbitol	Total
At harvest					
CI	25.6a	10.6a	44.2b	2.1a	82.5b
EDI	28.3a	13.8a	52.8a	2.6a	97.5a
LDI	26.8a	14.0a	52.5a	2.3a	95.6a
After storage					
CI	27.3a	17.9b	58.0b	2.0a	105.2b
EDI	23.4a	22.5a	62.9a	2.2a	111.0a
LDI	26.5a	21.5ab	63.1a	2.5a	113.7a

4.3.4.3 Aroma volatiles

While TSS, TA, DMC, and TSC are important factors determining fruit taste, flavour is determined by volatile substances produced in the fruit. Volatile compounds considered important for apple aroma were classified into four groups: alcohols, aldehydes, ethyl esters, and non-ethyl esters (Table 4.5). There were differences in concentrations of some individual aroma volatiles among fruit from different irrigation treatments (Table 4.5). At harvest the concentrations of propan-1-ol, propyl acetate, butyl acetate, and propyl butanoate were lower in EDI fruit than LDI fruit. The LDI fruit also had higher propan-1-ol and propyl acetate than CI fruit. There was no difference in concentrations of individual aroma volatiles at harvest between CI and EDI fruit. After storage, total volatile concentrations decreased compared to those at harvest and ethyl butanoate and ethyl-2-methyl butanoate were higher in EDI fruit than LDI fruit. The concentration of ethyl butanoate was also higher in CI fruit than in LDI fruit but both LDI and EDI fruit had higher propan-1-ol than CI fruit. Several volatile compounds have been observed to increase with a rise in ethylene production (Song and Bangerth, 1996), reach a maximum at the fruit climacteric and then decrease as fruit senesce (Dirinck et al., 1989). The decrease in volatile concentrations in fruit from all treatments after storage could have been because the maximum production period of most volatile compounds had passed. There was no effect of irrigation treatment (Table 4.5) or fruit size (data not shown) on total volatile concentration either at harvest or after storage. Behboudian et al. (1998) reported that concentrations of volatiles for CI and EDI fruit were similar and were lower than that for LDI fruit both at harvest and after storage. Early deficit irrigation did not affect volatile concentration because formation of most volatiles is initiated at or after the climacteric rise (Yahia, 1994). The differing effect of LDI on volatile concentration between this study and that of Behboudian et al. (1998) could be due to their trees having developed higher degree of water deficit as they were growing in lysimeters where roots were more limited in exploring large volumes of soil. However, plant water status was not measured in this study for a definite comparison. Total volatile concentrations at harvest were higher in this study compared to theirs. This could be because our fruit were more mature as the assessment of volatiles was done five days after fruit harvest.

Table 4.5 Concentrations of aroma volatiles (μmol L^{-1}) in juice of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Comparison was made within each category: 'At harvest' and 'After storage'. Values across the row followed by the same letter were not significantly different at $P < 0.05$.

Volatile	**At harvest**			**After storage**		
	CI	EDI	LDI	CI	EDI	LDI
Alcohols						
Propan-1-ol	363.0b	290.0b	494.0a	351.7b	401.3a	405.7a
Butan-1-ol	4541.7a	3632.4a	4236.6a	2592.8a	2505.2a	2584.0a
Pentan-1-ol	125.6a	113.9a	112.8a	34.1a	32.4a	31.9a
Hexanol-1-ol	264.8a	186.1a	262.2a	138.9a	112.5a	131.2a
2&3 Methyl butan-1-ol	810.2a	579.6a	802.7a	203.2a	162.4a	159.0a
Aldehydes						
Hexanal	304.8a	311.4a	413.5a	150.1a	98.1a	134.5a
trans-2-hexenal	1617.2a	1736.5a	2139.8a	524.3a	363.8a	463.7a
Ethyl esters						
Ethyl propionate	265.4a	256.8a	252.4a	174.7a	171.7a	173.5a
Ethyl butanoate	1072.6a	894.6a	928.0a	49.3a	54.6a	39.5b
Ethyl-2-methyl butanoate	3.9a	17.8a	2.8a	8.6ab	14.1a	3.6b
Ethyl pentanoate	333.7a	291.0a	299.5a	40.0a	38.1a	38.4a
Ethyl hexanoate	16.5a	23.4a	17.4a	12.5a	13.6a	8.4a
Non-ethyl esters						
Propyl acetate	96.1b	66.7b	209.3a	95.5a	99.8a	96.8a
Butyl acetate	511.9ab	378.2b	643.2a	461.9a	459.1a	457.5a
Pentyl acetate	86.2a	87.8a	85.8a	22.3a	28.7a	21.8a
Hexyl acetate	95.3a	81.9a	132.9a	83.3a	87.7a	83.5a
Propyl butanoate	1277.4ab	926.4b	1529.3a	312.0a	301.5a	256.8a
2 Methyl butyl acetate	14.8a	14.8a	12.5a	7.6a	3.8a	4.1a
Methyl hexanoate	222.8a	207.1a	206.3a	87.9a	86.7a	85.1a
Total of volatiles	12024.0 a	10096.0a	12781.0a	5350.7 a	5035.1 a	5179.1 a

Each volatile compound varies in contribution to fruit aroma due to its odour threshold, sensory characteristics, and concentration (Dixon, 1999). For example, esters are important compounds for aroma intensity and quality (Brackmann and Streif, 1994) being responsible for the fruity, sweet, scented and floral aroma of apples (Dirinck and Hoskin, 1983). Among esters, ethyl esters have the most potent aroma with low odour threshold values (Teranishi et al., 1987). Alcohols and aldehydes, although contributing to apple aroma, are of minor importance compared with esters (Cunningham et al., 1986). Whether or not the differences in concentrations of individual aroma volatiles among fruit from different treatments had any impact on fruit flavour requires sensory evaluation.

4.3.4.4 Physiological disorders and mineral concentrations

Water core and bitter pit were observed in a few fruit but neither irrigation treatment nor fruit size affected the incidence of these physiological disorders (data not shown). Many physiological disorders have been attributed to low Ca^{2+} concentration in the fruit (Shear, 1975) or to low concentration ratios of Ca^{2+} to other minerals such as K^+ and Mg^{2+} (Volz et al., 1993). Fruit mineral concentrations were not affected by either irrigation treatment (Table 4.6) or fruit size (data not shown). Commercial apple orchards in New Zealand undergo $CaCl_2$ sprays several times during the growing season and it was done 12 times in this orchard.

Table 4.6 Fruit mineral concentrations (mg g^{-1} dry weight) at harvest of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

Treatment	N	P	Ca^{2+}	K^+	Mg^{2+}
CI	2.6 a	0.8 a	0.2 a	7.8 a	0.2 a
EDI	3.0 a	0.8 a	0.2 a	7.5 a	0.2 a
LDI	3.0 a	0.8 a	0.2 a	7.5 a	0.2 a

4.3.4.5 Weight loss

One serious cause of fruit deterioration during storage is fruit water loss (Woods, 1990). After harvest fruit continue to transpire and respire resulting in weight loss. In this study weight loss was lower in DI fruit compared to CI fruit (Figure 4.4). Water loss accounts for 95-98% of the weight loss in storage (Ben-Yehoshua, 1987). The differences in fruit weight loss could be due to the differences in structure, composition, and thickness of the skin or in the cuticle that covers the skin because they generally act as barrier to water vapour movement (Horrocks, 1964). These properties could be modified through DI and this hypothesis deserves investigation. A 6% loss in fruit weight after harvest results in shrivel and loss of marketability (Hatfield and Knee, 1988). Thus reduction of water loss in DI fruit has a distinct benefit especially for fruit destined for long storage.

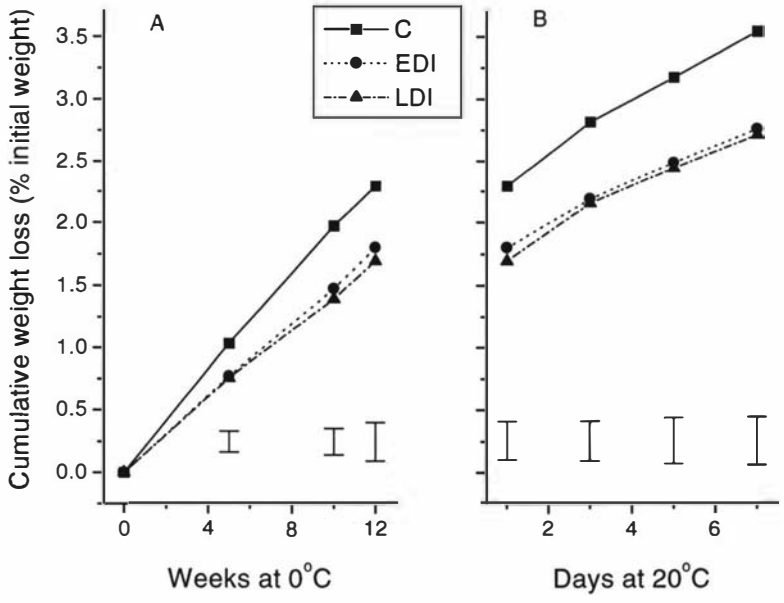

Figure 4.4 Cumulative weight loss during storage: 12 weeks at 0°C (A), followed by 7 days at 20°C (B) for 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Vertical bars represent LSD.

4.3.4.6 Internal ethylene concentration (IEC) and starch pattern index (SPI)

Both IEC and SPI increase as fruit matures and they are useful indicators of apple fruit maturity (Kingston, 1992). At harvest SPI and IEC for CI and EDI fruit were similar and were lower than that for LDI fruit (Table 4.7) suggesting that CI and EDI fruit had similar maturity which was less than LDI fruit. After storage, most starch had been converted to sugars and all fruit had the same SPI but EDI and LDI fruit had higher IEC than CI fruit. Fruit quality and storability are largely determined by maturity at harvest (Beaudry et al., 1993). Although EDI and LDI fruit differed in maturity at harvest, they had similar fruit quality which was generally enhanced (except for aroma volatiles) compared to CI fruit. This suggests that the quality enhancement in DI may not be through alteration in fruit maturity.

Table 4.7 Starch pattern index (SPI) and internal ethylene concentration (IEC, $\mu L\ L^{-1}$) at harvest and after storage (12 weeks at 0°C followed by 7 days at 20°C) of 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Values in the same column followed by the same letter are not significantly different at $P < 0.05$.

Treatment	**At harvest**		**After storage**	
	SPI	IEC	SPI	IEC
CI	3.2b	1.1b	6.0a	303.5b
EDI	3.0b	0.5b	6.0a	418.4a
LDI	3.9a	4.2a	6.0a	422.2a

4.4 Summary

This study showed that deficit irrigation applied either early or late in the growing season could be used as a pre-harvest tool to improve apple fruit quality in commercial orchards. Improvement in fruit quality was similar between the EDI and LDI treatments in terms of increased firmness, total soluble solids, and total sugar concentration both at harvest and after storage. The effect of DI on increasing flesh firmness was through reduction in fruit size, decreased cellular hydration, and increased flesh compactness. The impact of DI on concentrations of individual aroma volatiles needs further investigation in terms of sensory evaluation and their relationships with fruit maturity. The decrease in weight loss during storage for the DI fruit is of great benefit in terms of fruit storage potential. Fruit firmness and dry matter concentration were higher in smaller fruit but fruit size had no influence on other fruit quality attributes. Although the lower mean fruit weight for EDI and LDI compared to CI was not significant, significant decreases in fruit growth rates during deficit periods for both EDI and LDI indicated the negative impact of DI on fruit growth.

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SECTION THREE

TREE WATER USE, TREE PHYSIOLOGY, YIELD AND QUALITY IN RESPONSE TO DEFICIT IRRIGATION AND TO CROP LOAD

This section includes Chapters 5 to 9. Chapter 5 presents background information for the following chapters. Tree water use, tree physiology, growth, yield, and fruit quality for which literature information on the effects of DI and crop load is either limited or inconclusive are discussed.

The section involves two experiments: one on lysimeter-grown trees in Manawatu region during 1997/98 growing season (Chapter 6) and the other on field-grown trees in Manawatu region during 1998/99 growing season (Chapters 7, 8, and 9).

In Chapter 6, water use of 'Braeburn' apple trees grown in lysimeters in response to late-season DI and to crop load was estimated using lysimetry and heat-pulse technique. Relationship between tree transpiration and stomatal conductance was investigated. Responses of plant in terms of fruit growth, yield, fruit size distribution, and some fruit quality attributes were explored.

The main objective of Chapter 7 is to understand plant mechanisms behind the interaction between DI and crop load on fruit size. The study focuses on fruit water relations because turgor is required for cell growth and DI may reduce fruit water potential which may therefore reduce fruit turgor. Photosynthetic rate was measured because fruit size is also determined by translocation of assimilates into the fruit.

Chapter 8 addresses interaction of DI and crop load on individual fruit quality attributes and on collective fruit quality when many quality attributes are considered together both at harvest and after storage.

In Chapter 9, production of aroma volatiles as affected by DI, crop load, and their interaction was investigated. Multivariate relationships between aroma volatiles together with other "maturity-related quality" attributes and the "maturity" attributes were also explored. Maturity attributes included internal ethylene concentration, "percent ripening fruit", and starch pattern index. Maturity-related quality attributes include flesh firmness, total soluble solids, titratable acidity, and aroma volatiles.

Chapter Five: Literature Review

Tree Water Use, Tree Physiology, Yield, and Fruit Quality in Response to Deficit Irrigation and to Crop Load

5.1 Introduction

Deficit irrigation saves water, reduces groundwater pollution, decreases vegetative growth, and improves fruit quality. However, one possible disadvantage of DI is a reduction in fruit size especially if severe water deficit is allowed to develop during rapid fruit growth. Results shown in Chapter 4 indicate about 30g reduction in mean fruit weight at harvest for DI. Although this reduction was not significant statistically, it may be of major concern for growers as fruit size influences economic yield, price per unit weight, and financial return. This effect of DI could be counteracted by reducing crop load (Naor et al., 1997b and 1999). However, little is known about the mechanisms for this counteraction. Reducing crop load by itself results in some similar effects to DI such as decreased stomatal conductance and therefore tree transpiration (Wünsche et al., 2000), increased dry matter concentration (Atkinson, 1995; Wünsche et al., 2000), and increased flesh firmness (Johnson, 1994; Wünsche et al., 2000). However, it also results in some opposite effects to DI such as increased plant water potential (Erf and Proctor, 1987) and increased vegetative growth. Information on interaction of irrigation and crop load on tree transpiration, tree physiology, and fruit quality other than fruit size is lacking for apple. This information is required to determine whether reduced crop load can be integrated with DI in order to maximise the beneficial effects of DI in apple production.

5.2 Tree water use (TWU)

5.2.1 Water loss through transpiration

At most 5% of the water absorbed from the soil remains in the plant with the rest lost in the form of vapour to the atmosphere through transpiration. Generally this water vapour movement is proportional to the difference in vapour pressure between the air inside the leaf and the ambient air outside. Although all aerial plant parts transpire, leaves are, by

far, the major sites of transpiration. Water vapour potential of the air inside the leaf is much higher than that of the ambient air, thus leaves always lose water to the ambient air. Two major components required for the occurrence of transpiration process are the availability of water at the leaf surface and the availability of sufficient energy to vapourise the water. Continuation of the process, however, requires transportation of the humidified air away from the leaf surface (Sharma, 1985). Transpiration rate is therefore determined by supply of water at the leaf surface, supply of energy to vapourise water, magnitude of driving force (water potential gradient), and resistance existing in the pathway. Factors determining transpiration of deciduous fruit trees have been reviewed by Mpelasoka et al. (1997).

5.2.2 Deficit irrigation and tree water use

At the same level of evaporative demand of the atmosphere, transpiration of fruit trees depends strongly on stomatal conductance (g_s) of individual leaves and on total leaf area. Although stomatal opening/closure may be affected by several factors, stomatal closure is often observed with the onset of plant water deficit (e.g. Mills et al., 1996; Caspari et al., 1994) or as the soil dries (Gucci et al., 1996). Effects of water deficit on g_s are discussed in section 5.4.1. Leaf area may also be reduced under water deficit conditions and this is discussed in section 5.6.1.1. Reduced transpiration is therefore expected in plants receiving DI. Decreased TWU was observed in Asian pear when irrigation was withheld (Caspari et al., 1993). These authors observed lower correlation coefficients between TWU and pan evaporation as soil moisture levels decreased and suggested that the influence of weather on TWU decreased as soil water availability declined.

5.2.4 Crop load and tree water use

Most studies have focused on comparing transpiration between fruiting trees and defruited trees rather than between trees with different levels of crop load. Higher transpiration in fruiting trees than in defruited trees was observed in peach (Chalmers et al., 1983) and apples (Lenz, 1986). This could be due to higher g_s in the former, which has been observed in various studies (Monselise and Lenz, 1980a; Chalmers et al., 1983; Jones and Cummings, 1984; DeJong, 1986; Erf and Proctor, 1989). In grapevines, Naor

et al. (1997a) observed higher g_s and higher transpiration rates in two-cluster than in one-cluster treatments. Effects of crop load on g_s are discussed in section 5.4.2.

There are no data on apple tree water use as affected by DI at different crop levels and this has therefore been investigated in this research.

5.3 Plant water status (Ψ)

5.3.1 Roles, influencing factors, and assessment

Plant water status plays a major role in various physiological and developmental processes. Severe water deficits can have detrimental effects on growth, yield, and quality. Whereas mild water deficits sometimes are beneficial, for example, they may shift the balance from excessive vegetative growth toward reproductive growth (Chalmers et al., 1981).

Plant water status changes in response to numerous external factors. It fluctuates rapidly with prevailing environmental conditions both diurnally and seasonally (Jones et al., 1985). The daily Ψ_l is strongly dependent on transpiration of the plant which is dictated to a large extent by the evaporative demand of the atmosphere (Lakso, 1985). Generally, a plant routinely experiences water deficit throughout its life both diurnally and seasonally. During the day, absorption often lags behind transpiration due to the existence of resistance to water flow in the system. The resistance to movement of water out of parenchyma cells, the major site of water storage in the plants, is usually lower than the resistance to water movement from the soil to the roots (Kramer and Boyer, 1995). As transpiration begins, storage water is withdrawn from the tissues resulting in a decrease in tissue water potential. Hence, when evaporative demand is high during daytime, temporary water deficit occurs in the plant. This water deficit is usually reduced or eliminated (when soil water is adequate) during the night when transpiration and absorption are both low but absorption exceeds transpiration (Kozlowski, 1968). The rate of replenishment is dependent upon water availability in the soil and efficiency of water absorption and water conducting system of the plant. In dry soils, the deficit persists and increases in magnitude with time as water deficit is not recovered at night. To be able to optimize plant water status it is necessary to assess it.

The most frequently-used assessment of plant water status is that of leaf water potential (Ψ_l) or stem water potential (Ψ_{stem}) and/or their components. Leaf and stem water potential are expressed in units of negative pressure or tension (-MPa) as the chemical potential of pure water is assumed to be zero. Total Ψ can be separated into its two major components of osmotic potential (Ψ_s) and pressure (or turgor) potential (Ψ_p).

5.3.2 Water deficit and plant water status

Decreased Ψ during water deficit conditions has been observed in various fruit crops including apple (Kilili et al., 1996c; Mills, et al., 1996), Asian pear (Caspari et al., 1993), peach (Garnier and Berger, 1987), prune (McCutchan and Shackel, 1992), and lychee (Stern et al., 1998). As mentioned in section 5.3.1, in situations where soil water is adequate, temporary water deficit which occurs during daytime (when evaporative demand is high) is usually reduced or eliminated during the night when water absorption exceeds transpiration. As rates of replenishment depend on soil water availability, increased water deficit with time is therefore expected under reduced irrigation. However, relationship between Ψ and soil water content may not always be linear because Ψ is not only a function of soil water availability but also of hydraulic resistance along the pathway, plant water capacitance, and evaporative demand. Generally, plants are able to develop mechanisms of adaptation to water deficit which include drought escape, drought tolerance with low Ψ, and drought tolerance with high Ψ. Drought escape requires that plants complete their life cycle before significant water deficit can develop which is not applicable to deciduous trees. Osmotic adjustment is an example of drought tolerance with low Ψ. Osmotic adjustment is the lowering of osmotic potential by the net increase in intracellular solutes in response to a decrease Ψ in order to maintain cell turgor. Drought tolerance with high Ψ can be realised through stomatal control of transpiration and/or increased root water uptake efficiency.

5.3.3 Crop load and plant water status

Lower Ψ in fruiting trees compared with de-fruited trees or in heavy crop load compared with light crop load has been observed in apple (Erf and Proctor, 1987) and peach (Blanco et al., 1995; McFadyen et al., 1996; Marsal and Girona, 1997). The effects of fruit and crop level on Ψ may be due to an increase in water use in trees with fruit or with higher crop

load. Increased transpiration and/or g_s with the presence of fruit have been observed in peach (Chalmers et al., 1983), apple (Hansen, 1971; Monselise and Lenz, 1980a; Lenz, 1986), and grape (Downton et al., 1987). Trees with heavy crop load tend to allocate less assimilates into vegetative growth including root growth (Atkinson, 1980; Lenz, 1986). The effect of crop load on Ψ may also be due to decreased root growth in a heavily cropping tree leading to a reduction in plant water uptake capacity. Fruit are also a sink for water and are more competitive than leaves late in the season (Mills et al., 1997).

In this research leaf water potential (Ψ_l) was measured as an indicator of treatment effects on plant water status. Fruit water potential and its components were measured only in one experiment in order to investigate relationships between fruit water relations and fruit growth in response to DI and to crop load.

5.4 Stomatal conductance (g_s)

Stomatal opening/closure may be affected by several factors such as light, vapour pressure deficit (VPD), CO_2 concentration, the presence or absence of fruit, soil moisture, mineral nutrition, and Ψ (Landsberg and Jones, 1981). Regulation of stomatal opening is important in controlling the balance between carbon gain for photosynthesis and water loss through transpiration (Hinkley and Braatne, 1994).

5.4.1 Water deficit and stomatal conductance

With the onset of plant water deficit, decreased g_s due to stomatal closure is often observed (e.g. Caspari et al., 1994; Mills et al., 1996). Initially it was believed that the decrease in Ψ_l caused a loss of guard cell turgor and resulted in stomatal closure. However it now appears that the mechanism behind stomatal closure maybe somewhat more complex. The involvement of hormones such as ABA (Tallman, 1992; Tardieu and Davies, 1993) and cytokinins (Gollan et al., 1986), which are modified under water deficit, may play a role. Roots, which sense that the soil is drying, send a hormonal message, probably ABA, to the leaves which induces stomatal closure despite the leaves being maintained at full turgor (Gollan et al., 1986). Jones et al. (1985) found that under conditions of lower g_s, the Ψ_l of water stressed apple trees was higher than that of well watered ones, suggesting that g_s may

control Ψ_l. Midday closure of stomata on hot days may be a response to high VPD, so that the development of critically low Ψ_l is prevented (Lakso, 1985).

5.4.2 Crop load and stomatal conductance

Higher g_s in fruiting than in defruited trees have been observed in peach (Chalmers et al., 1983), apple (Hansen, 1971; Monselise and Lenz, 1980a; Lenz, 1986; Erf and Proctor, 1989), nectarine (DeJong, 1986) and grape (Downton et al., 1987). Increased g_s in fruiting trees may be a mechanism to enhance photosynthesis in order to meet the demand for carbohydrates by fruit. The effect of different crop levels on g_s, however, is not consistent. While increased g_s was observed at higher cluster number in grapevine (Naor et al., 1997a), no difference in g_s between different crop levels was observed in apple (Erf and Proctor, 1989) or peach (McFadyen et al., 1996). These data suggest that although fruiting increase g_s compared to defruited trees, relationship between different levels of crop load and g_s is not linear.

In this research, g_s was measured with the main purpose to investigate stomatal regulation as a control mechanism in tree transpiration in response to DI and to crop load.

5.5 Photosynthesis (Pn) and gas exchange

The importance of Pn is self-evident because 90-95% of dry weight of plants is derived from photosynthically fixed carbon (Flore and Lakso, 1989). Environmental factors affecting Pn include water, light, ambient CO_2 and O_2 concentrations, mineral nutrients, and leaf temperature (Lawlor, 1987). Among these, water is often the most limiting factor (Salisbury and Ross, 1992).

5.5.1 Water deficit, photosynthesis, and gas exchange

The process of Pn requires an exchange of gases and this takes place through stomata. Stomatal conductance is therefore an important plant factor in Pn. It has been observed that Pn is reduced under water deficit due to reduced g_s and thus reduced CO_2 uptake (Hsiao, 1973; Farquhar and Sharkey, 1982). However, in some cases, decreased g_s does not closely correlate to decreased Pn. Mills et al. (1994), for example, found a significant decrease in g_s in apple under water deficit, yet Pn was not affected. Hsiao (1993) also reported that stomatal closure appears to have a limited influence on Pn as a reduction in g_s under water

deficit conditions does not necessarily result in a reduction in leaf internal CO_2 concentration. In kiwifruit, large reduction in g_s under water deficit had little effect on intercellular CO_2 concentration (Chartzoulakis et al., 1993). Therefore, a reduction in g_s does not always fully account for changes in Pn under water deficit conditions (Flore and Lakso, 1989) but there may also be non-stomatal inhibition involved (Janoudi et al., 1993) which are not completely understood. However, suggestions have been made including increased mesophyll resistance (Brakke and Allen, 1995), feedback inhibition of Pn due to photoassimilate accumulation (Janoudi et al., 1993), and decreased leaf cell metabolic activity (Hsiao, 1993) under water deficit conditions.

5.5.2 Crop load, photosynthesis, and gas exchange

The presence of fruit has been reported to have positive effect on Pn in various crops such as citrus (Lenz, 1979), peach (DeJong, 1986), grape (Downton et al., 1987), sour cherry (Sams and Flore, 1983), pecan (Marquard, 1987), strawberry (Schaffer et al., 1986), and apple (Monselise and Lenz, 1980b; Fujii and Kennedy, 1985; Palmer, 1992). However, some authors have reported little or no effect of fruit presence on Pn in apple (Ferree and Palmer, 1982) and sweet cherry (Roper et al., 1988). The reason for this discrepancy is not fully known. Nevertheless, in grapevines, Downton et al. (1987) observed that Pn in fruiting and non-fruiting vines were similar early in the day but Pn decreased earlier during the day in non-fruiting vines. In apple, Pn was not affected during the first eight hours after fruit removal but decreased thereafter and Pn was more inhibited in the afternoon than in the morning (Gucci et al., 1996). These data suggest that assimilate production is partly controlled by sink consumption and time of measurement may have influenced the significance of fruit presence. Recent studies in apple showed that differences in Pn among trees with different levels of crop load were small earlier in the season when shoot growth was active but Pn increased at high crop load from midseason until harvest when fruit weight accumulation was high (Palmer et al., 1997; Wünsche et al., 2000). Increased Pn with the presence of fruit or at high crop loads may be due partly to the influence of fruit on increased g_s as discussed above (section 5.4.2). Feedback response may also contribute to the different Pn in trees with different crop loads. Increased demand for carbohydrates in trees with high crop loads may result in increased Pn whereas accumulation of carbohydrates in non-fruiting trees or

in trees with light crop loads may result in decreased Pn (Azcon-Bieto, 1983; Palmer et al., 1997; Wünsche et al., 2000).

This study investigated interaction between DI and crop load on Pn, and relationships between Pn and g_s and between Pn and fruit growth.

5.6 Growth and yield

5.6.1 Water deficit, growth, and yield

Turgor is required for cell growth (Kramer, 1988; Corsgrove, 1993). Turgor may be decreased under reduced Ψ and therefore growth reduction can be expected if water deficit occurs during active growth period.

5.6.1.1 Vegetative growth

A reduction in Ψ during active shoot growth will result in shoot growth reduction in most trees and this concept has been used successfully through DI to control vegetative vigour in peach and pear trees (Chalmers, 1989). Reduced shoot growth due to water deficit has also been reported for apple (Lötter et al., 1985; Ebel et al., 1995; Mills et al., 1996) and Asian pear (Caspari et al., 1994). Boland et al. (1993) observed a reduction in the leaf area index of peach under reduced plant water status. A reduction in total leaf area was observed in potted apple trees exposed to water deficit throughout the season (Mills et al., 1996) but not in field-grown trees under milder water deficit (Mills et al., 1994).

5.6.1.2 Fruit growth, yield, and size

Both fruit number and fruit size are important components of total yield. Fruit number is affected by the number of initiated flowers and final fruit set. In apple, floral initiation of the current crop occurs during early summer of the previous year (Westwood, 1993). Therefore, water deficit has no effect on flower initiation of the current crop but may affect that of the following crop (return bloom). Water deficit during flowering is likely to inhibit fertilisation (Hsiao, 1993) and has been reported to reduce fruit set and increase fruit abscission (Powell, 1974). Fruit growth is sensitive to plant water status and is often decreased if severe water deficit occurs during cell division and rapid growth. As a result, fruit size may be reduced and this may in turn affect yield and quality. The influence of

reduced Ψ on fruit growth and size appears to be dependent on timing of water deficit developed as discussed in Chapter 3 (section 3.2).

5.6.2 Crop load, growth, and yield

5.6.2.1 Vegetative growth

Generally, vegetative growth is found to decrease with increasing crop load. This could be because fruit are stronger sinks for assimilates than vegetative parts. In apple, growth of shoot, root (Palmer, 1992), and trunk (Volz et al., 1993) decrease at high crop load. Heavy cropping not only reduces shoot growth in the current season but also in the following season (Forshey, 1982).

5.6.2.2 Fruit growth, yield, and size

With light crop load, while fruit number is lower, fruit growth rates and final fruit size is usually higher than at heavy crop load. The immediate objective of fruit thinning is often an improvement of fruit size. Increased fruit size with light crop load is well documented (Forshey and Elfving, 1989; Palmer, 1992; Volz et al., 1993; McFadyen et al., 1996). However, Johnson (1995) did not observe any effect of late fruit thinning (at 27 or 39 DAFB) on fruit size but early fruit thinning (at full bloom or at 5 DAFB) increased mean fruit weight at harvest. Goffinet et al. (1995) reported the effect of timing of fruit thinning on final fruit size. Final fruit size was closely correlated with cell number in the cortex (Goffinet et al., 1995). Lakso et al. (1995) suggested that the impact of fruit thinning on increased total cell number could occur during 2-4 weeks after bloom. Flower and fruit thinning may increase fruit size by enhancing cell division and cell expansion (Johnson, 1995). Turgor is required for cell growth (Cosgrove, 1993). McFadyen et al. (1996) observed a lower fruit turgor potential (Ψ_{fp}) at high crop load than at low crop load and a linear relationship between daily average Ψ_{fp} and fruit growth for data points corresponding to Ψ_{fp} greater than 0.4 MPa. They therefore suggested that decreased fruit growth at high crop load was partly due to reduced Ψ_{fp}.

Shoot and fruit growth, yield, and fruit size in response to DI, crop load, and their interaction were measured in this thesis. Possible involvement of fruit water relations and Pn in such responses were explored.

5.7 Fruit quality

5.7.1 Water deficit and fruit quality

Details of this have been discussed in Chapter 3 (section 3.3). In brief, reduced Ψ generally increases fruit TSS but effects of water deficit on firmness, skin colour, and mineral concentration are inconclusive. Both level and timing of plant water deficit may play important roles in the differences in fruit responses observed. Variation in the size of fruit samples used in the assessments may also account for some of these differences. Limited information is available for the effects of reduced irrigation on fruit aroma volatiles, some physiological disorders such as water core, and storage potential.

5.7.2 Crop load and fruit quality

Literature information is conflicting regarding the effects of crop load on some fruit quality attributes. The contradictory reports may be due to both level of crop load and time of thinning.

5.7.2.1 Flesh firmness

Increased fruit firmness at light crop load has been reported from some studies (Johnson, 1994; Elgar et al., 1999; Link, 2000; Opara and Tadesse, 2000; Wünsche et al., 2000). The underlying principles for increased fruit firmness with decreasing crop load is not well understood but may be related to the increase in fruit TSS and DMC at light crop load (Wünsche et al., 2000).

5.7.2.2 Total soluble solids (TSS) and titratable acidity (TA)

While Tough et al. (1998) and Link (2000) reported higher TSS in 'Braeburn' apple from light crop trees, Opara and Tadesse (2000) found no consistent effect of crop load on TSS for 'Pacific Rose' apple. Link (2000) reported increased acid content in fruit from thinned trees compared to fruit from unthinned trees.

5.7.2.3 Skin colour

Apple fruit from thinned trees had redder blush colour (Link, 2000) and more yellow background colour (Johnson, 1995; Link, 2000) than those from unthinned trees.

5.7.2.4 Mineral concentration

Apple fruit from light crop trees had lower Ca^{2+} (Ferguson and Watkins, 1992; Volz et al., 1993; Link, 2000), lower Mg^{2+} (Volz et al., 1993), but higher K^{+} (Ferguson and Watkins, 1992; Volz et al., 1993; Link, 2000) concentrations than fruit from heavy crop trees. In plant, Ca^{2+} travels with water along transpiration stream (Mengel and Kirkby, 1987). Fruit transpiration is small compared to that of leaves. While Ca^{2+} absorption remains the same, increased fruit growth in light crop trees results in decreased Ca^{2+} concentration in the fruit. In contrast, the main transport direction of K^{+} is toward the growing tissue (Mengel and Kirkby, 1987). Increased fruit growth in light crop trees may result in increased K^{+} accumulation in the fruit. A high K^{+}/Ca^{2+} ratio of fruit from light crop load may lead to increased calcium-related disorders such as bitter pit.

5.7.2.5 Storage potential

Apple fruit from light crop trees are more susceptible to physiological disorders including bitter pit, internal breakdown, lenticel blotch, and core flush (Ferguson and Watkins, 1992; Johnson, 1994; Tough et al., 1998; Elgar et al., 1999). There is no published data for crop load effect on fruit water loss during storage.

Although apple fruit from light crop trees are generally firmer than fruit from heavy crop trees (Johnson, 1994; Elgar et al., 1999; Opara and Tadesse, 2000), they decrease their firmness at a faster rate (Johnson, 1994). Johnson (1994) reported that fruit from light crop trees were still firmer after storage while Tough et al. (1998) found no difference in firmness between fruit from light and heavy crop trees after storage.

There is limited information for apple on interaction of DI and crop load on fruit quality attributes other than fruit size. This research investigated various quality attributes of 'Braeburn' apple in response to DI, crop load, and their interaction.

Chapter Six

Water use, yield, and fruit quality of lysimeter-grown apple trees: responses to deficit irrigation and to crop load

Abstract

Effective irrigation scheduling for maximum crop yield and quality in a sustainable environment requires a good understanding of crop water use in relation to its crop load and soil water availability. This study determined tree water use (TWU), fruit growth, yield, and quality of 'Braeburn' apple grown in lysimeters in response to different irrigation and crop load treatments. Irrigation treatments were control level of irrigation (CI) and deficit irrigation (DI). Crop load treatments were commercial crop load (CCL) and a lighter crop load (LCL) equivalent to 60% of the CCL. Tree water use was measured using two methods, lysimetry and heat-pulse technique. Results from both methods showed a similar trend in that DI and LCL both reduced TWU. The difference in TWU between CI and DI were greater at CCL than at LCL and that between CCL and LCL was greater under CI than under DI. Higher stomatal conductance was responsible for the higher TWU in CI but not in CCL. Increased mean fruit weight at harvest but

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B. S. Mpelasoka[1], M. H. Behboudian[1] and S. R. Green[2]

[1]Institute of Natural Resources, College of Sciences, Massey University, Palmerston North, New Zealand

[2]Environmental Group, HortResearch, Palmerston North, New Zealand

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Effects of irrigation regimes and crop load on water use, yield and fruit size distribution of 'Braeburn' apple grown in lysimeters

decreased gross yield was observed in LCL. Deficit irrigation reduced mean fruit weight at harvest but had no significant effect on gross yield. Fruit quality was improved in DI both at harvest and after 12 weeks of cold storage but was, generally, not affected by crop load treatments.

6.1 Introduction

Apples are grown in a wide range of soil and climatic conditions with a large variation in soil water availability (Westwood 1993). Although apple water relations are well studied, data on tree water use are few and have not been related to soil water availability (Green and McNaughton 1997; Wünsche et al. 2000). Green and Clothier (1995) studied apple water uptake in response to soil water availability with a focus on root water uptake in response to soil moisture. Information on tree water use especially in relation to soil water availability is needed for effective application of deficit irrigation (DI).

Reducing crop load may counteract the DI disadvantage in fruit size reduction (Naor et al. 1997a and 1999). Decreasing crop load reduces tree transpiration (Wünsche et al. 2000) and may also have both positive (Johnson 1995; Elgar et al. 1999) and negative (Ferguson and Watkins, 1992; Tough et al., 1998; Elgar et al. 1999) impact on fruit quality. For apple, information seems to be lacking on the interaction of irrigation and crop load on fruit quality other than fruit size.

The main aims of this study were to measure water use of 'Braeburn' apple tree in response to DI and to crop load and to investigate the relationship between tree transpiration and g_s. The interaction of DI and crop load on changes in water relations parameters, fruit size, and other quality attributes were also explored. Late-season DI was chosen because irrigation in New Zealand orchards is predominantly applied during the late summer when rainfall is low, especially in the humid climate of Manawatu region where this experiment was carried out. Therefore late-season DI would minimise water use during this period.

6.2 Materials and methods

6.2.1 Experimental conditions and treatments

The study was carried out during the 1997-98 growing season using the lysimeter facility located in the orchard at Fruit Crops Unit, Massey University, Palmerston North, New Zealand (latitude 40° 2' S, longitude 175° 4' E). The facility comprises 12 drainage lysimeters. Each lysimeter was constructed of a steel cylinder, 1.2 m deep and 1 m diameter, surrounded by a concrete sleeve. The lysimeters were filled with Manawatu

fine sandy loam excavated from the surrounding orchard soil. One four-year-old 'Braeburn' apple tree grown on MM106 rootstock was planted in each lysimeter in 1994. The trees were in a single row at a spacing of 1.2 m between adjacent trees and were trained as central leaders with central support wires installed to give additional support. Fertigation using a modified Hoagland's solution was supplied to each tree via four pressure-compensated trickle emitters, rated at 2 L hr^{-1}. Irrigation was controlled by a solenoid (model M886N24D, Bermad, Israel) and measured using a flow meter (Andrae Leonberg, Germany). Any surplus nutrient solution drained through a polyethylene pipe at the base of the lysimeters was measured using a tipping-bucket gauge (Rain-O-Matic, Pronamic, Them, Denmark). Irrigation and drainage volumes were recorded using a Wormald controller-datalogger (Wormald 1830, Christchurch, New Zealand). The soil surface of each lysimeter was covered with white reflective plastic covers to keep the rain water out and to minimise soil evaporation. More details of lysimeter facility can be found in Chalmers et al. (1992).

Two irrigation treatments and two levels of crop load were studied. The irrigation treatments were control irrigation (CI) and deficit irrigation (DI). The crop load treatments were commercial crop load (CCL) and a lighter crop load (LCL). Each treatment combination was randomly applied to three trees. Trees were hand-thinned at 60 days after full bloom (DAFB) to leave either 5 or 3 fruit per cm of trunk circumference representing, respectively, CCL or LCL. Number of fruit for the CCL was similar to the commercial orchards in the area. Irrigation treatments commenced on 115 DAFB and ended after final harvest on 187 DAFB. The CI trees were irrigated to maintain soil moisture at or close to pot capacity. Pot capacity was observed to be 0.14-0.17 m^3 of water per m^3 of soil (Mills et al. 1997). The DI trees were irrigated at about 40% of the CI trees.

6.2.2 Measurements of volumetric soil water content

Volumetric soil water content (θ) ($m^3\ m^{-3}$) was measured as detailed in Chapter 2 (section 2.1). Six sets of three-wire TDR probes, 180 mm long, were inserted vertically into each lysimeter at a distance of about 0.25 m from the tree trunk. The probes were placed at

depths of approximately 200, 300, 400, 500, 600, and 700 mm to provide a depthwise profile of soil water content in each lysimeter.

6.2.3 Determination of tree water use

One tree from each treatment combination was selected for the determination of tree water use using lysimetry (during 116-187 DAFB) and heat-pulse technique (during 116-162 DAFB). In the lysimetry, tree water use was calculated from a simple soil-water balance equation:

$$TWU=\Delta W+I-D \qquad (1)$$

Where: TWU = tree water use (L d^{-1}), ΔW = changes in soil-water storage (L d^{-1}), I = irrigation volume (L d^{-1}), and D = drainage volume (L d^{-1}). Soil water storage was determined by multiplying the mean θ (average from all depths) by the volume of each lysimeter.

The heat-pulse technique was used to monitor tree transpiration based on the rate of sap movement up the tree stem. The heat-pulse velocity (HPV) system comprises sets of probes and associated electronics connected to a data logger (Campbell CR 10, Campbell Scientific Inc., Logan, Utah, USA). Each set of probes, which consisted of a linear heater and two temperature sensors, was installed radially into the stem of each tree. The heater was activated every 1-2 s to introduce a heat-pulse tracer into the moving sap stream. The data logger interpreted the temperature signals and calculated total sap flow in the tree stem using a purpose-built computer programme. More details of the HPV system can be found in Green (1998). For the purpose of comparison, TWU values are presented per unit leaf area because the experimental trees were different in canopy size. Pan evaporation (E_{pan}) data were obtained from a Class A evaporation pan located about 1 km from the lysimeter facility. Crop coefficients (k_c) were calculated as the ratio of TWU (L m^{-2} leaf area) to E_{pan}. The calculation was made on a weekly basis.

6.2.4 Measurements of plant water status

Midday leaf water potential (Ψ_l) was measured as detailed in Chapter 2 (section 2.2.1) on four fully expanded, sunlit leaves per tree.

6.2.5 Measurements of stomatal conductance

Diurnal changes in stomatal conductance (g_s) were measured as detailed in Chapter 2 (section 2.3) on four fully expanded, sunlit leaves per tree. The measurements were made on 132 and 139 DAFB.

6.2.6 Determination of fruit growth, yield, size distribution, and leaf area

Fruit growth rates and changes in fruit volume were determined from eight fruit per tree using procedures listed in Chapter 2 (section 2.4.2).

Fruit were harvested at two picking dates on 176 and 187 DAFB. Measurement of fruit yield and size distribution were listed in Chapter 2 (section 2.5).

Following the final harvest, all leaves were removed and total leaf area of each tree was measured using a leaf area meter (model LI 3100; Li-Cor, Lincoln, Neb., USA).

6.2.7 Fruit sampling and quality assessment protocols

Fruit for quality assessments were randomly selected from three weight groups, 161-175 g, 176-190 g, and 191-210 g, of each tree with equal numbers of fruit from each group. The assessments included skin colour, flesh firmness, total soluble solids (TSS), total sugar concentration (TSC), titratable acidity (TA), dry matter concentration (DMC), and starch pattern index (SPI). Determination of fruit quality was done both at harvest and after storage for 12 weeks at 0°C except for the DMC and soluble sugars which were assessed only at harvest. Fifteen fruit per tree (45 fruit per treatment combination) were used at each determination. Procedures for the assessments of each quality attribute were stated in Chapter 2 (sections 2.6 and 2.7).

6.2.8 Statistical analysis

For θ and TWU, data from trees carrying different crop loads were combined for the determination of irrigation effects. Likewise, data from trees receiving different irrigation regimes were combined for the determination of crop load effects. The rest of the data were analysed as a factorial design with two irrigation regimes and two crop loads replicated three times in a completely randomised design. Means comparisons were performed using t-tests.

6.3 Results and discussions

6.3.1 Volumetric soil water content (θ)

After the imposition of irrigation treatments (on 115 DAFB), θ in the DI lysimeters decreased and became significantly lower than in the CI lysimeters ($P < 0.05$) from 119 DAFB until final harvest on 187 DAFB (Figure 6.1A). There was no significant difference in θ between the two crop load treatments when data from both irrigation regimes were combined (Figure 6.1B).

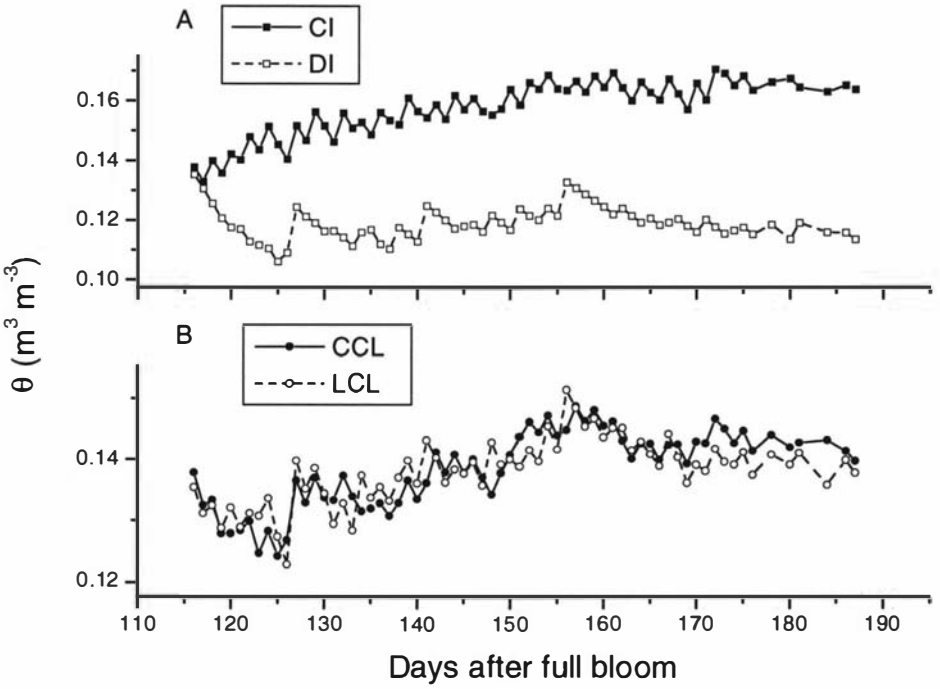

Figure 6.1 Volumetric soil water content (θ) for 'Braeburn' apple grown in lysimeters under different irrigation (A) and crop load (B) treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load. The θ values were lower ($P < 0.05$) in DI than in CI (Figure 1A) from 119 days after full bloom.

6.3.2 Leaf water potential (Ψ_l) and stomatal conductance (g_s)

The decrease in soil moisture of the DI lysimeters was large enough to create soil water deficit that resulted in reduced Ψ_l ($P < 0.05$) in DI trees from 130 DAFB (Figure 6.2A). The lower Ψ_l of DI trees on 145 DAFB was, however, significant at $0.05 < P < 0.1$. The levels of crop load used in this study had little effect on Ψ_l. There was a tendency for the CCL trees to have lower values of Ψ_l than LCL trees and these differences were significant only on 140, 152, and 175 DAFB at $0.05 < P < 0.1$ (Figure 6.2B).

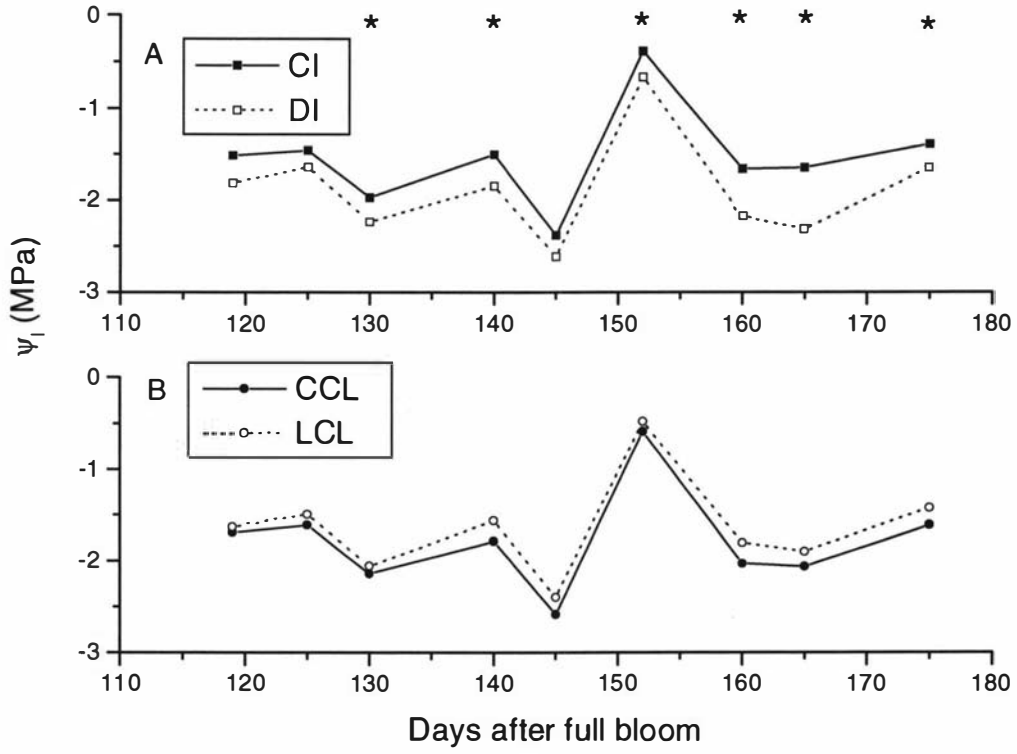

Figure 6.2 Midday leaf water potential (Ψ_l) for 'Braeburn' apple trees grown in lysimeters under different irrigation (A) and crop load (B) treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop loads treatment were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

Stomatal conductances of DI and CI trees were similar at mid morning (Figure 6.3 A and B). However during the middle parts of the day when evaporative demand was higher, g_s of DI trees decreased and became lower than that of the CI trees. On 132 DAFB, g_s of DI trees recovered during late afternoon (Figure 6.3A). Crop load had no significant effect on the g_s during early and late parts of the day but LCL had higher g_s values during the middle parts of the day (Figure 6.4 A and B). Although these differences in g_s between CCL and LCL trees were significant, magnitude of the differences was much less than that between CI and DI trees. Decreased g_s in DI trees often occurred as a result of soil water deficit in parallel with decreased Ψ_l. The effects of crop load on g_s and Ψ_l from other studies are not conclusive. For example, Naor et al. (1997a) reported that g_s and Ψ_l of grapevines increased with cluster number. In contrast, Erf and Proctor (1987) found no significant effects of two crop levels on g_s and Ψ_l of apple although weak positive correlation existed between crop load and g_s and weak negative correlation existed between crop load and Ψ_l. In peach, no difference in g_s between different crop levels was observed (McFadyen et al., 1996). Mills et al. (1997) found decreased fruit water potential in early-season DI but not in late-season DI compared with control. This could be due to the relative strength of the near-mature fruit as a sink for water (Mills et al. 1997). More fruit on CCL trees means more competition for water which may result in decreased Ψ_l. Generally, plants adjust stomatal opening to control the balance between water loss and carbon gain (Hinkley and Braatne, 1994). The lower g_s in CCL in some measurements could be a mechanism to reduce water loss in response to lower Ψ_l. In the measurements where g_s were lower in CCL than in LCL, their leaf photosynthesis was the same. Leaf photosynthesis was higher in CCL than LCL in few measurements where their g_s were the same (data not shown).

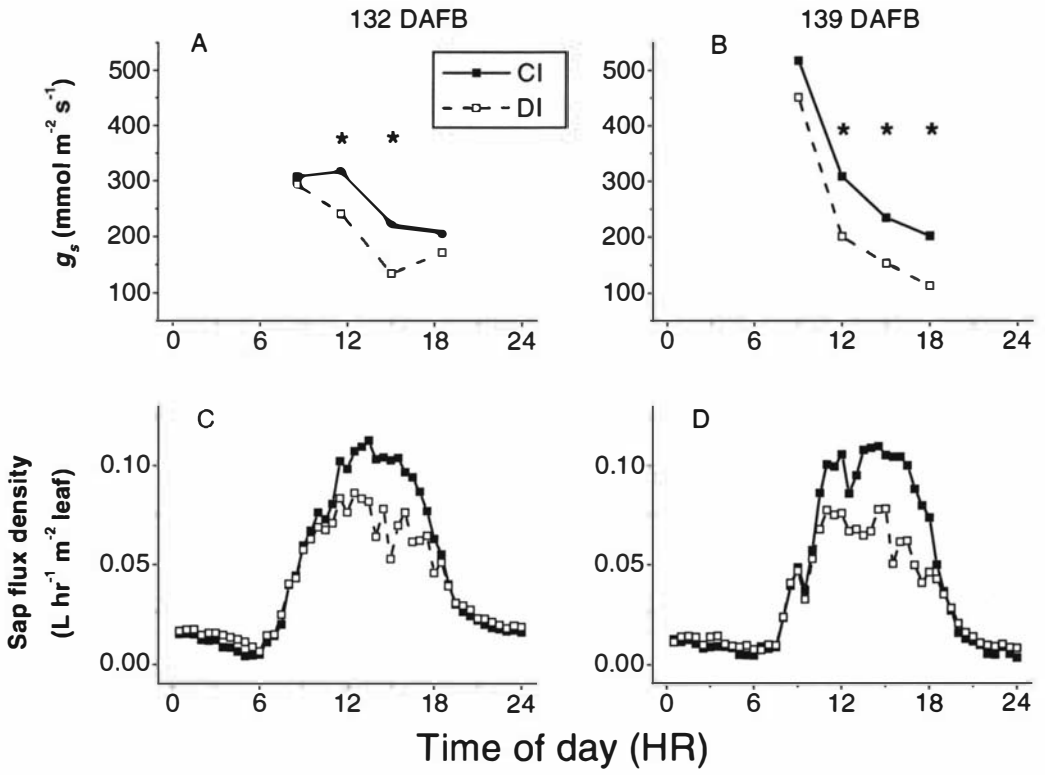

Figure 6.3 Diurnal pattern of stomatal conductance (g_s) (A and B) and sap flux density from heat-pulse measurements (C and D) on 132 and 139 DAFB for 'Braeburn' apple grown in lysimeters under different irrigation treatments: CI = control irrigation and DI = deficit irrigation. Asterisks represent significant differences ($P < 0.05$) and they were applicable only in A and B.

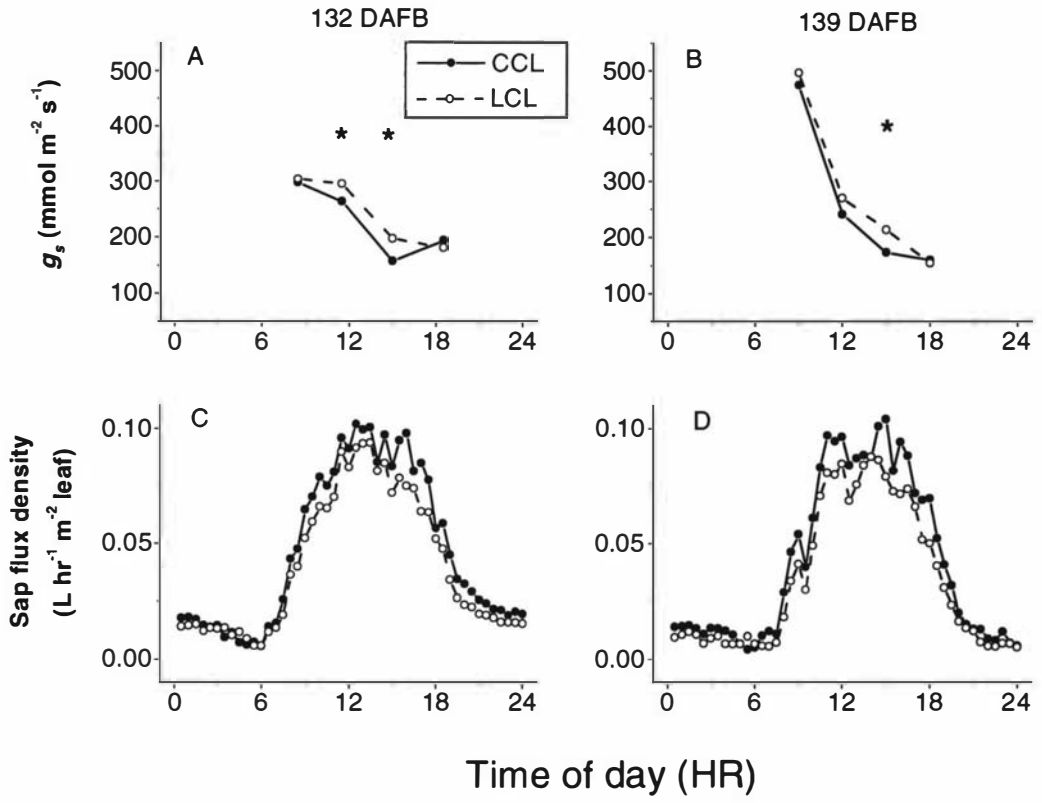

Figure 6.4 Diurnal pattern of stomatal conductance (g_s) (A and B) and sap flux density from heat-pulse measurements (C and D) on 132 and 139 DAFB for 'Braeburn' apple grown in lysimeters with different crop load treatments: CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$) and they were applicable only in A and B.

6.3.3 Tree water use (TWU) and crop coefficient (k_c)

Daily TWU, expressed on a leaf area basis, estimated from the heat-pulse measurements of sap flow is shown in Figure 6.5 B and C. Apart from the first few days (116-124 DAFB), there was a tendency for TWU to be higher in CI than in DI (Figure 6.5B). However, the differences were significant only on 130, 133, 135, 149, 150, and 155 DAFB and at $0.05 < P < 0.1$. There was also a tendency for TWU to be higher in CCL than LCL trees (Figure 6.5C). The differences were significant at $P < 0.05$ on 116, 122, 125, 128, 131, and 152 DAFB; and at $0.05 < P < 0.1$ on 118, 126-127, 136, and 141 DAFB. There was a good correlation between daily TWU and E_{pan}. Respective r^2 values for CI and DI were 0.73 and 0.70 (n=52) when data from 116-162 DAFB were used. Some scatter between TWU and E_{pan} is expected because E_{pan} does not reflect either changes in soil water availability or stomatal control over transpiration.

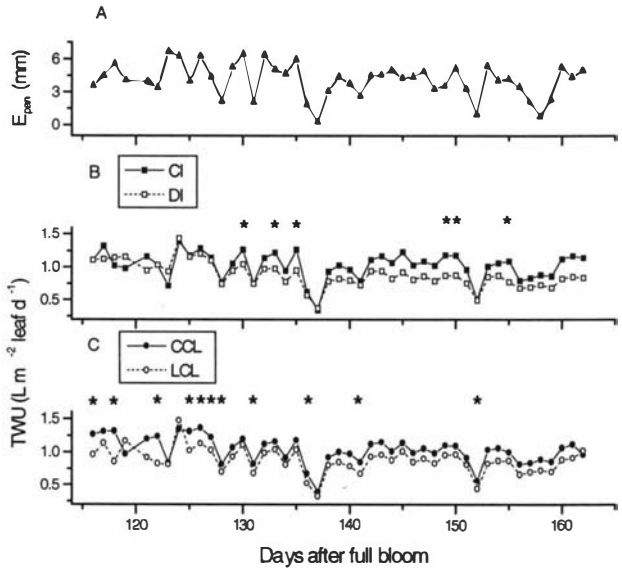

Figure 6.5 Pan evaporation (E_{pan}) (A) and daily tree water use (TWU) per unit leaf area, estimated from trunk sap flow using heat-pulse technique, for 'Braeburn' apple under different irrigation (B) and crop load (C) treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.1$).

Tree water use determined from lysimetry followed a similar trend to that estimated from the heat-pulse technique for weekly intervals (Table 6.1).

Table 6.1 Comparison of tree water use (L m^{-2} leaf) determined from heat-pulse technique and lysimetry for 'Braeburn' apple grown in lysimeters under different irrigation and crop load treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load.

DAFB	**Heat-pulse**				**Lysimetry**			
	Irrigation		Crop load		Irrigation		Crop load	
	CI	DI	CCL	LCL	CI	DI	CCL	LCL
116-124	9.18	9.81	10.07	8.92	10.83	8.45	11.05	8.23
125-131	7.45	6.94	7.80	6.59	8.06	7.30	8.50	6.86
132-138	6.45	5.39	6.34	5.51	7.03	5.81	6.96	5.88
139-145	7.34	5.95	7.24	6.05	7.90	5.80	7.58	6.12
146-152	6.96	5.44	6.68	5.71	6.73	5.43	6.43	5.74
153-159	6.51	5.26	6.46	5.30	6.55	5.47	6.34	5.67
160-166	-	-	-	-	6.97	5.92	6.84	6.05
167-173	-	-	-	-	6.60	5.16	6.25	5.51
174-180	-	-	-	-	6.70	5.23	6.32	5.61
180-187	-	-	-	-	6.54	5.11	6.20	5.45

A linear regression between TWU determined from the two methods gave an r^2 value of 0.79 (n=24) when data from 116-159 DAFB were compared. Total water use (L m^{-2} leaf) during 116-187 DAFB calculated from the lysimetry was 73.92 and 59.68 for, respectively, CI and DI trees and was 72.47 and 61.13 for, respectively, CCL and LCL trees. During this period, total TWU per unit leaf area was approximately 20% lower in DI compared with CI. In peach, DI trees used 30-50% less water than control (Boland et al. 1993). A smaller reduction in TWU of DI trees in our research could be due to the

shorter study period and lower evaporative demand. Diurnal pattern of g_s and sap flux density (Figure 6.3) suggested that lower water use in DI trees could be attributed to lower g_s as the stomata closed in response to decreasing soil water availability. Water use and leaf area were determined after vegetative growth had ceased and before the first sign of leaf senescence. Therefore, changes in leaf area over the experiment were likely to be small. Trees with the commercial crop load used approximately 16% more water than trees with a light crop load. Higher water use in CCL trees appeared not to relate well with their lower g_s compared to the LCL trees (Figure 6.4). Total fruit weight at harvest was 5.6 kg per tree higher in CCL than LCL. Although fruit transpiration is usually very small compared to that of the leaves, water in fruit is a major component contributing 84-87% of the weight. More sink (fruit) demand for water could contribute to a higher water use in this case. Whether or not fruit transpiration is modified by crop load deserves investigation.

The above comparisons were based on the assumption that there was no interaction between irrigation and crop load on TWU. Data of two crop loads were combined when TWU of CI and DI trees were compared, similarly, data of two irrigation regimes were combined when TWU of CCL and LCL trees were compared (Figure 6.5 and Table 6.1). When data were not combined, the differences in TWU between CI and DI trees were more clear at the commercial crop load and the differences in TWU between CCL and LCL trees were more clear under control irrigation (Figure 6.6).

Decreased TWU in DI resulted in reduced k_c compared to CI, similarly, the lower TWU in LCL resulted in lower k_c compared to CCL. During 116-187 DAFB, k_c values for, respectively, CI and DI trees ranged from 0.25 to 0.45 and 0.20 to 0.35 and their corresponding averages over the period were 0.31 and 0.25. The k_c values for, respectively, CCL and LCL trees ranged from 0.23 to 0.43 and 0.19 to 0.38 and their corresponding averages over the period were 0.30 and 0.25. Decreased k_c was observed during the drying cycle periods in Asian pears (Caspari et al. 1993). The k_c values obtained in this study are lower than that reported by Doorenbos and Pruitt (1977) which could be due to differences in methods used to calculate k_c. Different k_c values can be obtained depending on whether evapotranspiration is based on a reference crop (ET_o) or on E_{pan}. Differences in cultivars, tree size, soil water status, and growing conditions

(such as trees growing in lysimeter or in the field) may also contribute to the differences in k_c. Various methods have been used for determining k_c and, as a consequence, differences in k_c values can be seen in the literature.

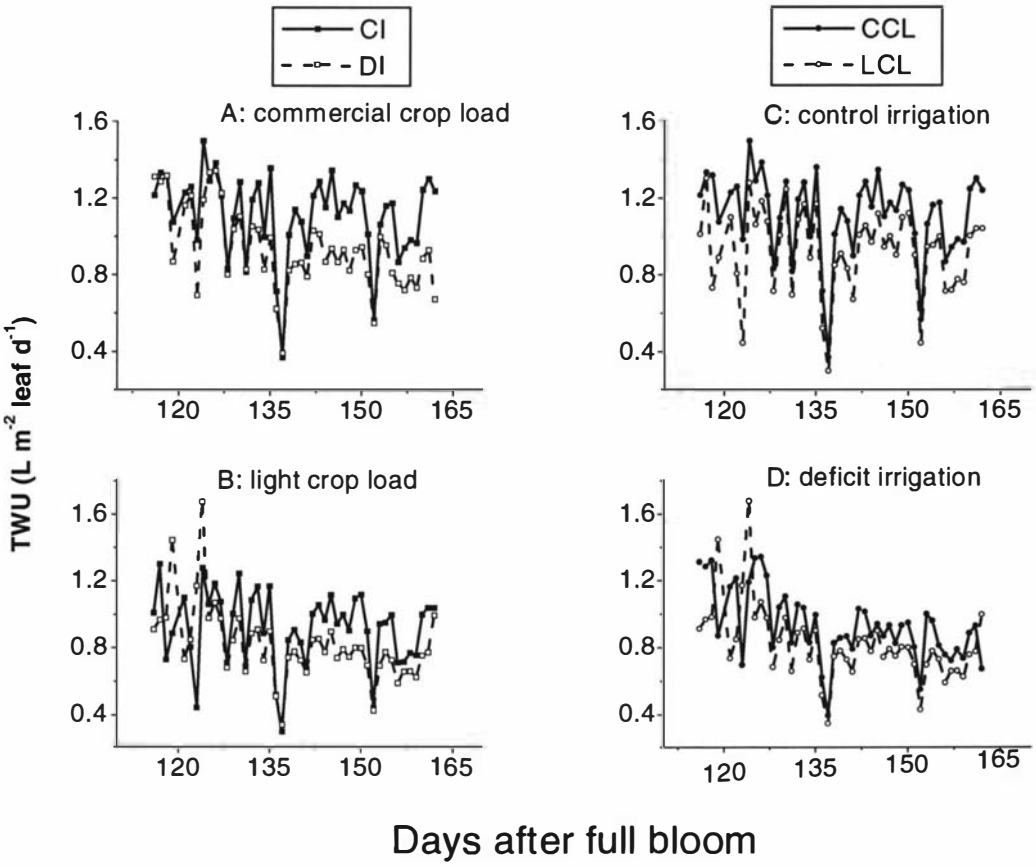

Figure 6.6 Daily tree water use (TWU) per unit leaf area, estimated from trunk sap flow using heat-pulse technique, for 'Braeburn' apple in response to irrigation treatments at different crop loads (A and B) and in response to crop load treatments under different irrigation regimes (C and D). The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load.

6.3.4 Fruit growth, yield and size distribution

Fruit volume at each measurement time tended to be higher in CI than in DI but the difference was significant ($P < 0.05$) only for the last measurement on 163 DAFB (Figure 6.7A). On 146 and 154 DAFB fruit volumes were higher in CI than in DI at $0.05 < P < 0.1$. Fruit growth rates were lower ($P < 0.05$) in DI than in CI in most of the measurement periods (Figure 6.7C). Mean fruit weight at harvest was approximately 12% lower in DI than in CI (Table 6.2). This confirmed that although DI was applied late in the growing season, when rapid fruit growth period had ceased, fruit size was still reduced. However, there was no significant difference in gross yield between CI and DI trees (Table 6.2). Kilili et al. (1996c) found that a late-season DI did not reduce mean fruit weight at harvest of field grown apple trees. The larger impact of late-season DI on fruit size reduction observed in this study could be due to the restricted soil and thus water volume in the lysimeters.

Fruit volume at each measurement period was similar in the two crop load treatments although there was a trend for higher fruit volume in the LCL (Figure 6.7B). Rates of fruit growth were higher ($P < 0.05$) in LCL than in CCL in three out of six measurement times (Figure 6.7D). Mean fruit weight at harvest was higher in LCL whereas gross yield per tree was higher in CCL (Table 6.2). Therefore fruit thinning to a crop load lower than the commercial level enhanced fruit size although it reduced gross yield. Similar fruit volumes during growth in both crop loads (Figure 6.7B) did not reflect their differences in mean fruit weight at harvest. This could be because measurements of fruit volume, which were done on selected fruit of similar sizes, started late after fruit thinning when the large impact of fruit thinning on fruit growth might have passed.

Both irrigation and crop load treatments had a measurable effect on fruit size distribution. Proportions of smaller fruit tended to be higher in DI and in CCL whereas that of larger fruit tended to be higher in CI and in LCL (Figure 6.8 A and B). However, there was no significant effect of either treatment on total export-size fruit (Table 6.2).

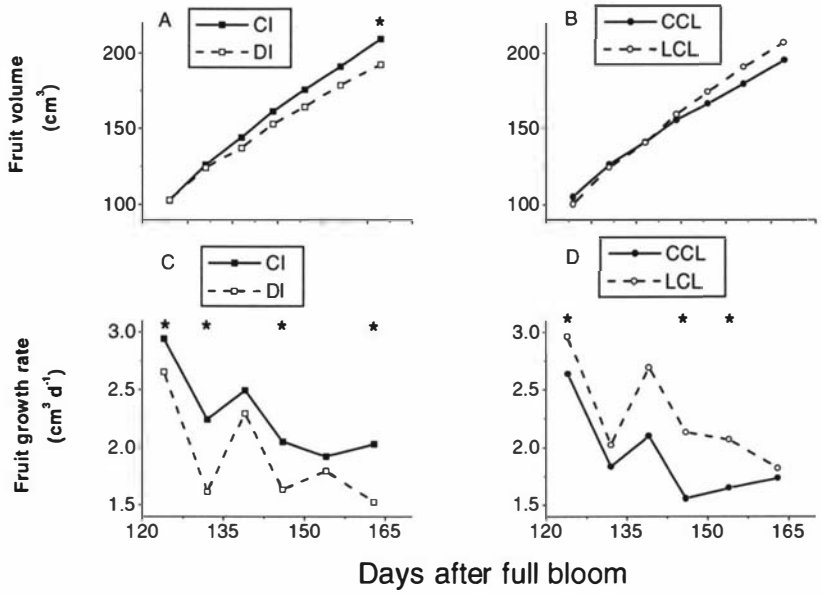

Figure 6.7 Fruit volume (A and B) and fruit growth rate (C and D) for 'Braeburn' apple grown in lysimeters under different irrigation (A and C) and crop load (B and D) treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

Table 6.2 Yield and mean fruit weight at harvest for 'Braeburn' apple grown in lysimeters under different irrigation and crop load treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load. Comparisons were made within each main effect, 'irrigation' and 'crop load'. Values across the row followed by different letters are significantly different at $P < 0.05$.

Yield and fruit size	**Irrigation treatment**		**Crop load treatment**	
	CI	DI	CCL	LCL
Gross yield (kg/tree)	11.53a	10.80a	13.98a	8.35b
Mean fruit weight (g/fruit)	185.01a	163.41b	160.36b	188.07a
Export-size fruit (% total yield)	92.12a	89.06a	86.82a	94.36a

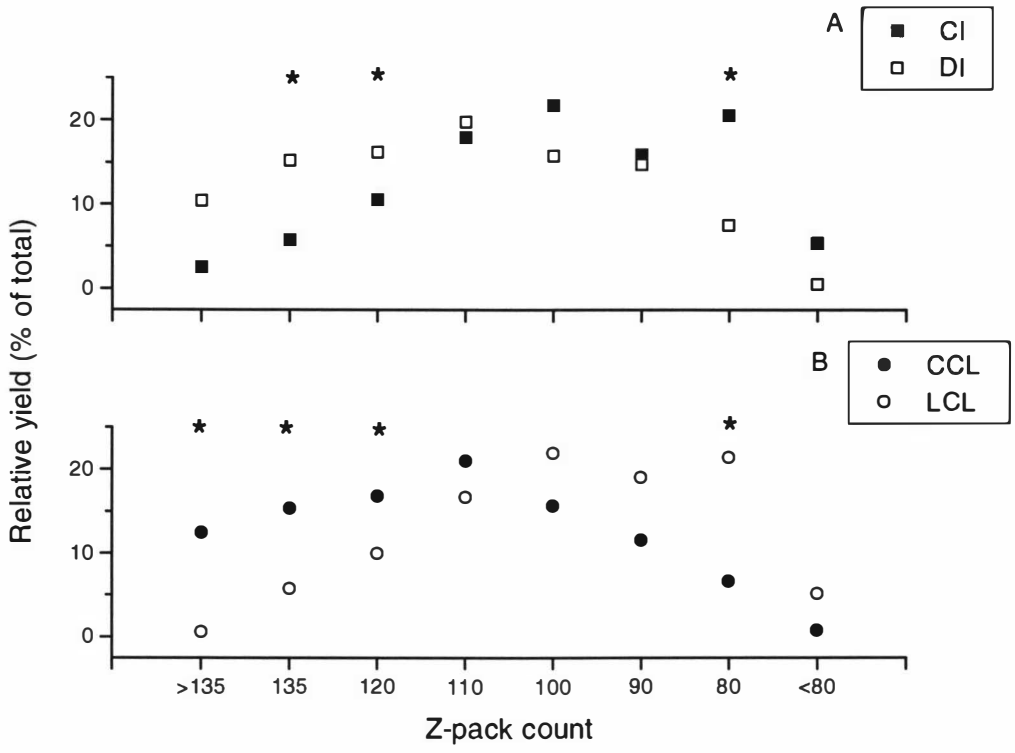

Figure 6.8 Fruit size distribution for 'Braeburn' apple grown in lysimeters under different irrigation (A) and crop load (B) treatments. The irrigation treatments were CI = control irrigation and DI = deficit irrigation. The crop load treatments were CCL = commercial crop load and LCL = light crop load. The higher Z-pack counts represent smaller fruit. Asterisks represent significant differences ($P < 0.05$).

6.3.5 Other fruit quality attributes

Deficit irrigation enhanced some fruit quality attributes both at harvest and after 12 weeks of cold storage. At harvest, DI fruit were firmer and had higher TSS, TSC, and DMC than CI fruit (Table 6.3). Decreased cellular hydration in DI fruit could have contributed to increased TSS and flesh firmness. The increased TSS in DI fruit may also be due to an enhanced conversion of starch to sugar (Kramer 1983) as indicated by higher SPI and TSC values in DI fruit (Table 6.3). After storage, there was no significant difference in fruit SPI but TSS was still higher in DI fruit (Table 6.3). Although their

firmness was lost at a greater rate, DI fruit were still firmer than CI fruit. The significance of the differences, however, decreased from P = 0.010 at harvest to P = 0.051 after storage (Table 6.3). Fruit skin colour and TA were not affected by irrigation treatments either at harvest or after storage (Table 6.3).

Table 6.3 Skin colour (Hue angle), flesh firmness, total soluble solids (TSS), total sugar concentration (TSC), titratable acidity (TA), dry matter concentration (DMC), and starch pattern index (SPI) at harvest and after 12 weeks of storage at 0°C for 'Braeburn' apple from different irrigation treatments: CI = control irrigation and DI = deficit irrigation. Comparison was made within each category 'at harvest' and 'after storage'. Values across the row followed by different letters are significantly different at $P < 0.05$. 'NA' means 'not available'.

Quality attribute	**At harvest**		**After storage**	
	CI	DI	CI	DI
Hue angle (°)				
Red blush	34.8 a	33.0 a	30.8 a	30.1 a
Background	107.4 a	107.3 a	85.2 a	93.1 a
Flesh firmness (N)	103.0 b	110.1 a	74.0 a*	78.6 a*
TSS (%)	11.8 b	13.0 a	13.9 b	14.6 a
TSC (mg g^{-1} FW)	83.5 b	91.5 a	NA	NA
TA (% malic acid)	0.68a	0.67a	0.57a	0.56a
DMC (mg g^{-1})	129.8 b	139.3 a	NA	NA
SPI	3.0 b	3.3 a	6.0 a	6.0 a

* significant at $0.05 < P < 0.1$

The LCL fruit had higher DMC at harvest than CCL fruit at $0.05 < P < 0.1$. Fruit DMC at harvest (mg g^{-1}) for, respectively, CCL and LCL were 131.98 and 137.15. Other fruit quality attributes were not affected by crop load (data not shown). There was no interaction effect between irrigation regime and crop load on fruit quality except for the SPI. The LCL fruit had higher SPI than the CCL fruit under control irrigation but CCL had higher SPI than LCL under DI. Fruit SPI for, respectively, CCL and LCL were 2.79 and 3.11 under CI and were 3.37 and 3.12 under DI. The small impact of crop load on fruit quality in this study could be due to late fruit thinning.

6.4 Summary

There was a trend for DI and light crop load to reduce tree water use. Although DI reduced mean fruit weight at harvest, gross yield per tree and total export-size fruit were not affected. Reducing crop load increased mean fruit weight at harvest but decreased gross yield per tree. Fruit quality in terms of increased firmness, total soluble solids, total sugar concentration, and dry matter concentration was improved by DI but was not affected by crop load. Since this study was carried out using lysimeter facilities, a field experiment using more tree replicates is required to confirm and expand results regarding yield, fruit size, and quality.

Acknowledgement

We thank Dr Tessa Mills of HortResearch for her critical comments on the manuscript.

Chapter Seven

Water Relations, Photosynthesis, Growth, Yield and Fruit Size of 'Braeburn' apple: Responses to Deficit Irrigation and to Crop Load

Abstract

This study investigated interactions between irrigation and crop load on fruit water relations, photosynthesis, and fruit growth and size of 'Braeburn' apple. The irrigation treatments were commercially irrigated control (CI) and deficit irrigation (DI) applied throughout the season. The crop load treatments were commercial crop load (CCL) having six fruit per cm^2 of trunk cross-sectional area and light crop load (LCL) having four. There were interactions between irrigation and crop load on fruit water potential (Ψ_{fw}), fruit turgor potential (Ψ_{fp}), and photosynthetic rate (Pn) during mid and late season, and on mean fruit weight at harvest. These parameters were the same for CCL and LCL under CI except for Ψ_{fp}, which was lower in CCL. Under DI they were lower in CCL than in LCL. On average for both crop loads, DI reduced Ψ_{fw} and Ψ_{fp} early in the season but from mid season Ψ_{fp} was maintained through osmotic adjustment. Photosynthetic rates were lower in DI than in CI for both crop loads but differences late in the season were only significant for CCL. Mean fruit weight at harvest was similar in CI and DI for LCL, but was lower in DI for CCL. Interactions between irrigation and crop load on fruit size could be due to effects on fruit water relations and on photosynthesis.

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Bussakorn S. Mpelasoka[1], M. H. Behboudian[1] and Tessa M. Mills[2]

[1]Institute of Natural Resources, College of Sciences, Massey University, Palmerston North, New Zealand

[2]Environment Group, HortResearch, New Zealand

7.1 Introduction

The study on lysimeter-grown apple trees in the former chapter showed that deficit irrigation (DI) reduced fruit size but this was counteracted by a lighter crop load. Little is known about the mechanisms for this counteraction. Turgor is required for fruit growth and it has been observed in peach that fruit water potential (Ψ_{fw}), fruit turgor potential (Ψ_{fp}), and fruit growth are reduced with a higher crop load (McFadyen et al., 1996). However, reduction in fruit size despite maintenance of fruit turgor has been reported with DI for Asian pear (Behboudian et al., 1994) and for apple (Mills et al., 1997). Decreased photosynthesis (Pn) observed under water deficit (Behboudian et al., 1994; Kilili et al., 1996c) may contribute to fruit size reduction under DI due to less assimilate availability. The lowering of crop load may counteract this effect. Information on interactions between irrigation and crop load on fruit water relations and on Pn will help improve our understanding of their implications for fruit size. This knowledge is required to optimise DI application with the possible choice of a suitable crop load. Although interaction between DI and crop load on stem water potential has been investigated (Naor et al., 1997b), there is no published information on interaction between DI and crop load on fruit water relations or on Pn for apple. This study focused on the interaction of DI and crop load on fruit water relations and Pn and the possibilities of these responses as the mechanisms for fruit size regulation.

7.2 Materials and methods

7.2.1 Experimental conditions and treatments

The study was done during the 1998-99 growing season at Massey University Fruit Crops Unit, Palmerston North (latitude 40° 2′ S, longitude 175° 4′ E), New Zealand. The area has a humid temperate climate with an average annual rainfall of 960 mm. The orchard soil is a Manawatu fine sandy loam. Ten-year-old 'Braeburn' apple trees (5 m between rows, 3 m within rows) on MM 793 rootstock were divided into four blocks of eight trees. Each block had two plots of four trees and each plot was divided into two sub plots of two trees. There were at least two guard trees in between each plot. Commercially irrigated control (CI) and deficit irrigation (DI) treatments were randomly applied to each

plot within each block. The CI trees were irrigated to maintain soil moisture at or close to field capacity. Because of the rainy conditions, soil in the DI plots was covered with clear polythene from 12 days after full bloom (DAFB) to exclude rainfall. Full bloom occurred on 20 October 1998. Due to high humidity and rainfall during winter months in the area, we expected that soil water deficit would not occur during the cell division period which is from full bloom to approximately 40 DAFB for apple (Westwood, 1993). The DI trees were irrigated twice late in the growing season when volumetric soil water content (θ) became lower than 0.15 m^3 m^{-3}. Commercial crop load (CCL) and light crop load (LCL) treatments were randomly applied to each sub plot within each plot. Trees were hand-thinned at 38 DAFB to leave either 6 or 4 fruit per cm^2 of trunk cross-sectional area, representing CCL and LCL, respectively.

7.2.2 Measurements of soil and plant water status

Volumetric soil water content was measured as detailed in Chapter 2 (section 2.1) at a depth of 400 mm. Two pairs of TDR probes were installed around the middle of each sub plot, one on each side of the row, at a distance of 500 mm from the tree trunk. Midday leaf water potential (Ψ_l) was measured as detailed in Chapter 2 (section 2.2.1) on two fully expanded sunlit leaves per sub plot. Diurnal measurements of Ψ_l were made on 109 and 133 DAFB. Fruit water potential (Ψ_{fw}) and fruit osmotic potential (Ψ_{fs}) were measured on one fruit picked at dawn from each sub plot in two blocks using a Wescor Psychrometer-Hygrometer employing C-52 sample chambers with a HR-33T Microvolt Meter as detailed in Chapter 2 (section 2.2.2). Fruit turgor potential (Ψ_{fp}) was calculated as the difference between Ψ_{fw} and Ψ_{fs}.

7.2.3 Measurements of photosynthesis, stomatal conductance and gas exchange

Photosynthetic rates (Pn), stomatal conductance (g_s), and gas exchange were measured between 1200 and 1300 HR as detailed in Chapter 2 (section 2.3) on two fully expanded sunlit leaves per sub plot.

7.2.4 Measurements of shoot and fruit growth

Shoot and fruit growth were measured from eight shoots and eight fruit per sub plot using procedures listed in Chapter 2 (sections 2.4.1 and 2.4.2).

7.2.5 Measurements of fruit composition

Eight fruit per sub plot were randomly sampled from outer and mid-canopy positions at each sampling date for measurements of soluble sugars and dry matter concentration (DMC). There were nine sampling dates from 92 to 202 DAFB with the last three during commercial harvests on 187, 196, and 202 DAFB. Procedures for the assessments were listed in Chapter 2 (sections 2.7.8 and 2.7.9).

7.2.6 Statistical analysis

Data were subjected to analysis of variance as a split plot design with irrigation treatment as main plot and crop load as sub plot with four replicates (blocks). Comparisons of means were made using t-tests. When interactions between irrigation and crop load were observed, results for irrigation treatments were also analysed and compared separately for each crop load and those for crop load treatments were made separately for each irrigation treatment.

7.3 Results

7.3.1 Volumetric soil water content (θ)

Values of θ in DI plots were lower than those in CI plots throughout the season starting from the first measurement on 50 DAFB (Figure 7.1A). There was no difference in θ between the two crop load treatments (Figure 7.1B).

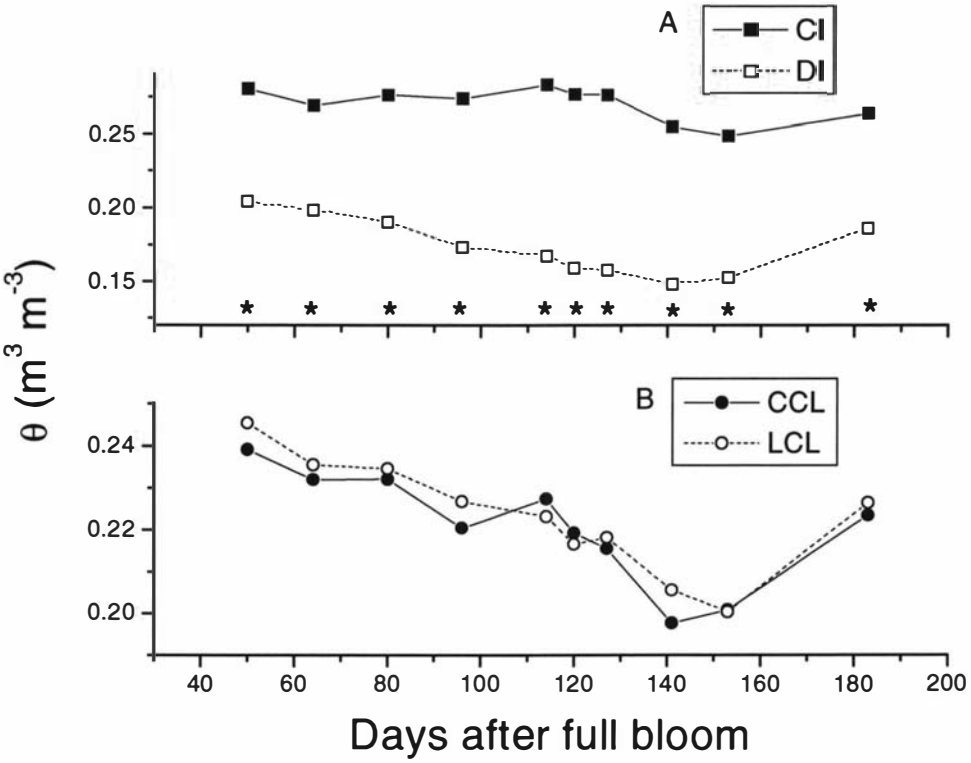

Figure 7.1 Volumetric soil water content (θ) during the growing season for 'Braeburn' apple under different irrigation (A) and crop load (B) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

7.3.2 Plant water relations

7.3.2.1 Leaf water potential (Ψ_l)

Midday Ψ_l became lower in DI than in CI from 70 DAFB (Figure 7.2A) and tended to be lower in CCL than in LCL but the differences were significant only on five occasions (Figure 7.2B). The differences in Ψ_l were greater between CI and DI than between CCL and LCL.

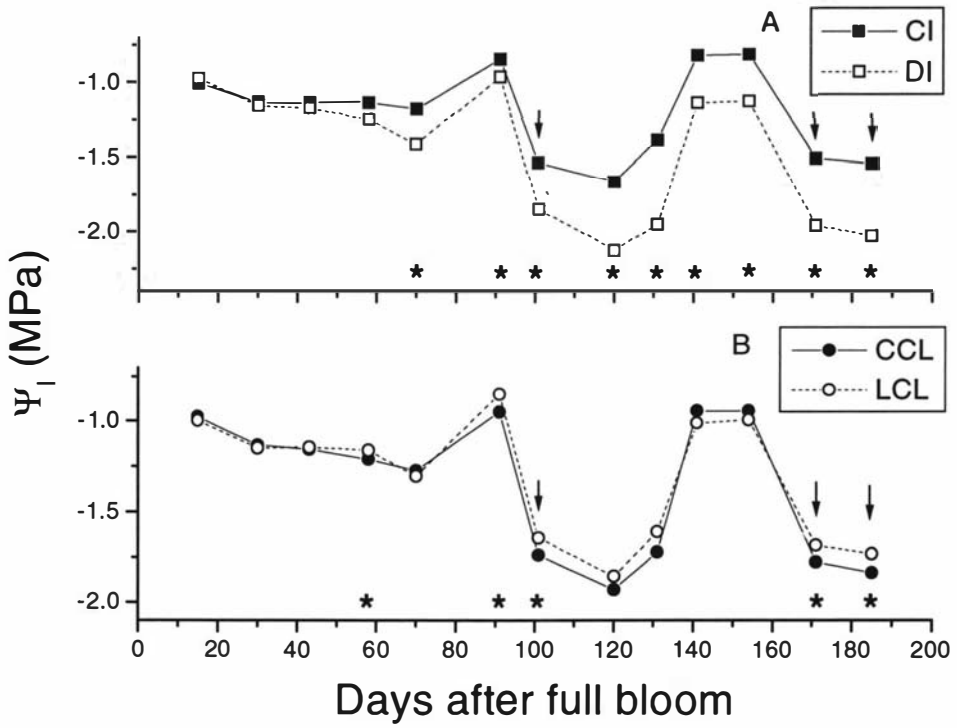

Figure 7.2 Midday leaf water potential (Ψ_l) for 'Braeburn' apple under different irrigation (A) and crop load (B) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$). Arrows indicate existences of interactions between irrigation and crop load as detailed in Table 7.1.

Diurnal values of Ψ_l, which were measured on two occasions, followed a similar pattern by decreasing from early morning reaching a minimum value between midday and early afternoon and then starting to recover in late afternoon (Figure 7.3). The variations in Ψ_l therefore depended on evaporative demand of the atmosphere as well as on soil water status as has been observed in many plant species (Jones et al., 1985). The Ψ_l was lower in DI than in CI at all times on both occasions (Figures 7.3 A and B). On 109 DAFB, CCL had a lower value of Ψ_l than LCL early in the morning (Figure 7.3C) and on 133

DAFB, it had lower values than LCL in most measurements between early morning and early afternoon but recovered late in the afternoon (Figure 7.3D).

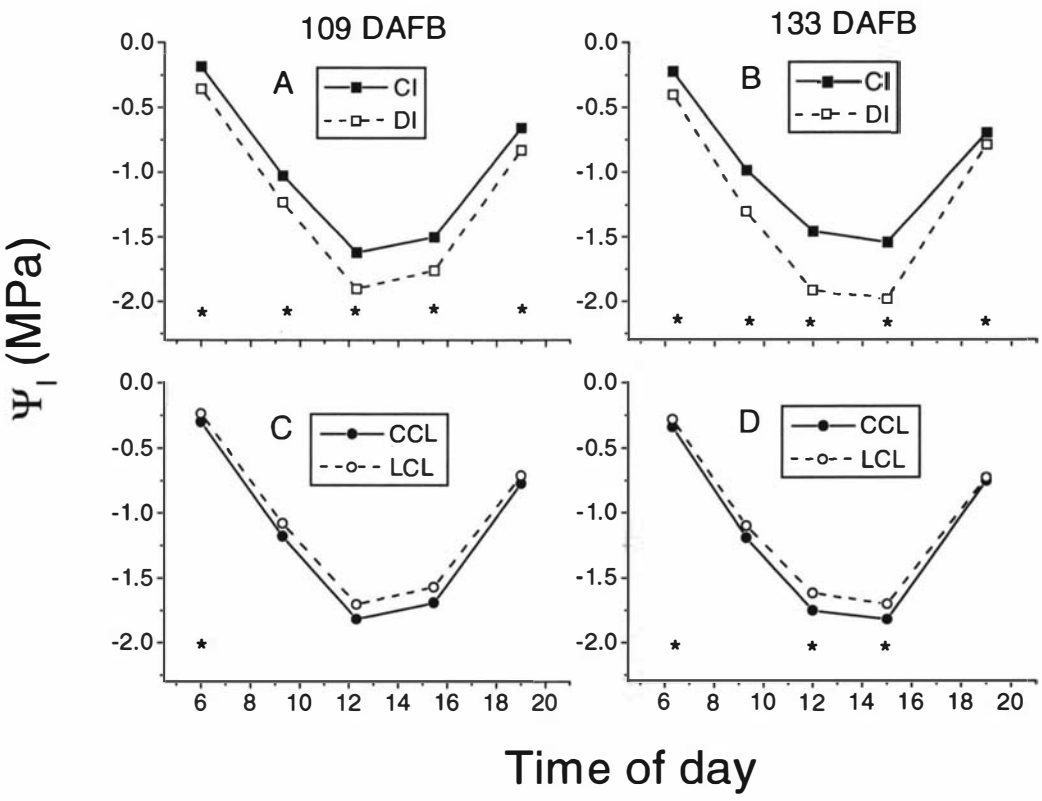

Figure 7.3 Diurnal values of leaf water potential (Ψ_l) on 109 days after full bloom (DAFB) (A and C) and on 131 DAFB (B and D) for 'Braeburn' apple under different irrigation (A and B) and crop load (C and D) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

7.3.2.2 Fruit water potential (Ψ_{fw}) and its components (Ψ_{fs} and Ψ_{fp})

Fruit water potential decreased over the season but to a greater extent earlier in the season (Figures 7.4 A and B). The decrease in Ψ_{fw} was generally greater in DI than in CI resulting in a lower value in the former for most measurements. It was steady in DI fruit later in the season whereas it continued to decrease in CI fruit and therefore the values for both treatments became similar late in the season. Fruit osmotic potentials were similar early in the season but DI fruit had lower Ψ_{fs} than CI fruit from 101 DAFB, although the difference on the last day of measurement (171 DAFB) was not significant (Figure 7.4C). Fruit turgor potential was lower in DI than in CI early in the season. As the reduction in Ψ_{fw} for DI was coupled with a similar reduction in Ψ_{fs} from 101 DAFB, Ψ_{fp} became similar between CI and DI (Figure 7.4E) indicating fruit osmotic adjustment. There was a trend for Ψ_{fw} to be lower (Figure 7.4B) and Ψ_{fs} to be higher (Figure 7.4D) in CCL than in LCL fruit. The Ψ_{fp} values were consistently lower in CCL than in LCL throughout the season (Figure 7.4F).

Interactions between irrigation and crop load on plant water relations were observed during mid and late season when Ψ_l and Ψ_{fw} were similar in CCL and LCL under CI but were lower in CCL under DI (Table 7.1). Although Ψ_{fp} was lower in CCL than in LCL under both irrigation regimes during this period, the magnitudes of the differences were higher under DI (Table 7.1). The Ψ_{fp} values were the same for CI and DI for both crop loads (Table 7.1). Values of Ψ_l and Ψ_{fw} for DI were generally lower than those for CI for both crop loads except that the values of Ψ_l on 101 DAFB and the values of Ψ_{fw} on 171 DAFB for DI and CI were similar for the LCL treatment (Table 7.1).

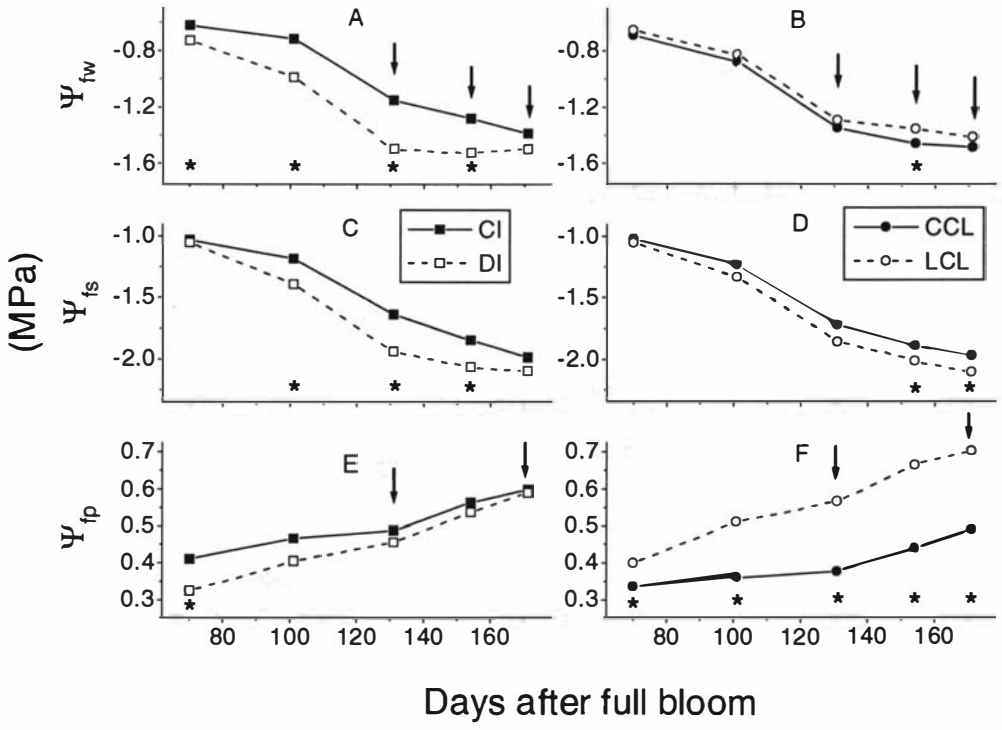

Figure 7.4 Fruit water potential (Ψ_{fw}) (A and B), fruit osmotic potential (Ψ_{fs}) (C and D), and fruit turgor potential (Ψ_{fp}) (E and F) for 'Braeburn' apple under different irrigation (A, C, and E) and crop load (B, D, and F) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$). Arrows indicate interactions between irrigation and crop load as detailed in Table 7.1.

Table 7.1 Interactions of irrigation and crop load on leaf water potential (Ψ_l), fruit water potential (Ψ_{fw}), and fruit turgor potential (Ψ_{fp}) for'Braeburn' apple. Irrigation treatments were: CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were: CCL = commercial crop load and LCL = light crop load. Comparisons of irrigation treatment were done at each crop load treatment and comparisons of crop load treatments were done under each irrigation treatment. For each treatment pair, values along the column followed by different letters are significantly different at $P < 0.05$

Comparing		Ψ_l			Ψ_{fw}			Ψ_{fp}	
Irrigation		101	171	185	131	155	171	131	171
Treatments		DAFB	DAFB	DAFB	DAFB	DAFB	DAFB	DAFB	DAFB
At CCL	CI	-1.5a	-1.5a	-1.4a	-1.1a	-1.3a	-1.4a	0.4a	0.5a
	DI	-1.9b	-2.0b	-2.1b	-1.6b	-1.6b	-1.6b	0.4a	0.4a
At LCL	CI	-1.5a	-1.5a	-1.4a	-1.2a	-1.3a	-1.4a	0.5a	0.7a
	DI	-1.8a	-1.9b	-1.9b	-1.4b	-1.5b	-1.4a	0.6a	0.7a
Comparing		Ψ_l			Ψ_{fw}			Ψ_{fp}	
Crop load		101	171	185	131	155	171	131	171
Treatments		DAFB	DAFB	DAFB	DAFB	DAFB	DAFB	DAFB	DAFB
Under CI	CCL	-1.5a	-1.5a	-1.4a	-1.6b	-1.6b	-1.6b	0.4b	0.5b
	LCL	-1.5a	-1.5a	-1.4a	-1.4a	-1.5a	-1.4a	0.6a	0.7a
Under DI	CCL	-1.9b	-2.0b	-2.0a	-1.1a	-1.3a	-1.4a	0.3b	0.4b
	LCL	-1.8a	-1.9a	-1.9a	-1.2a	-1.3a	-1.4a	0.6a	0.7a

7.3.3 Photosynthesis, stomatal conductance and gas exchange

Photosynthetic rate (Figure 7.5A) and stomatal conductance (Figure 7.5C), averaged over the two crop load treatments, were lower in DI than in CI in most measurements. There were no differences between CCL and LCL, averaged over the two irrigation treatments, for Pn (Figure 7.5B) or for g_s (Figure 7.5D). Both irrigation and crop load treatments had no effect on the leaf internal CO_2 concentration (C_i) with the exception on 125 DAFB when C_i was lower in DI than in CI and it was also lower in CCL than in LCL (Figure 7.5 E and F).

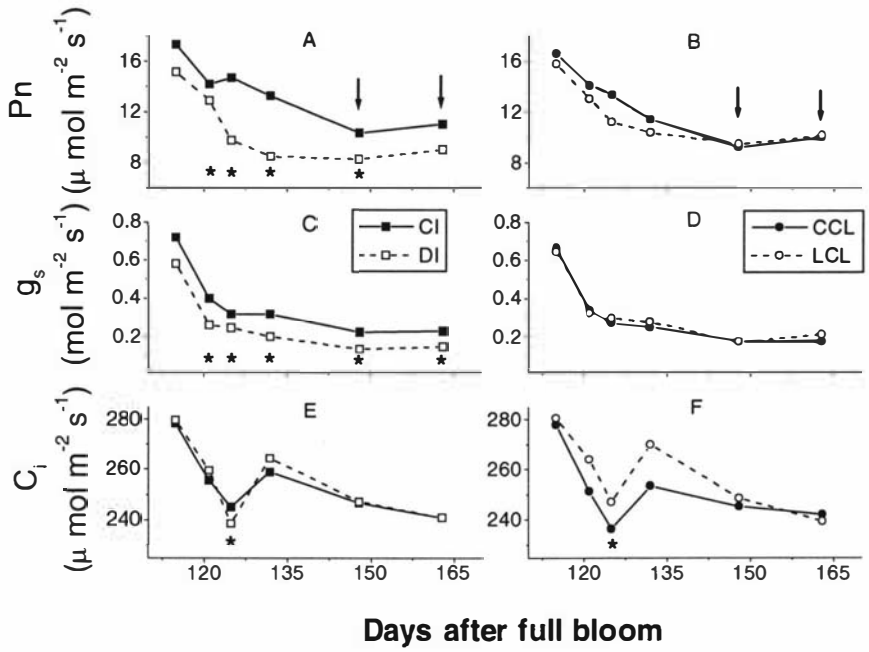

Figure 7.5 Photosynthetic rate (Pn) (A and B), stomatal conductance (g_s) (C and D), and internal CO_2 concentration (C_i) (E and F) for 'Braeburn' apple under different irrigation (A, C and E) and crop load (B, D and F) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$). Arrows indicate interactions between irrigation and crop load treatments as detailed in Table 7.2.

Interactions between irrigation and crop load on Pn were observed on 148 DAFB and 163 DAFB when Pn was higher in LCL than in CCL under DI whereas it was the same for both crop loads under CI (Table 7.2). On 148 DAFB, CI and DI had similar Pn for LCL but DI had lower Pn than CI for CCL (Table 7.2). There was no difference in Pn for CI and DI for both crop load treatments on 163 DAFB (Table 7.2).

Table 7.2 Interactions of irrigation and crop load on photosynthetic rate (μmol m^{-2} s^{-1}) for 'Braeburn' apple. Irrigation treatments were: CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were: CCL = commercial crop load and LCL = light crop load. Comparisons of irrigation treatment were done at each crop load treatment and comparisons of crop load treatments were done under each irrigation treatment. For each treatment pair, values across the row followed by different letters are significantly different at $P < 0.05$.

DAFB	**Comparing irrigation treatments**				**Comparing crop load treatments**			
	At CCL		At LCL		Under CI		Under DI	
	CI	DI	CI	DI	CCL	LCL	CCL	LCL
148	10.9 a	7.4 b	9.8 a	9.1 a	10.9 a	9.8 a	7.4 b	9.1 a
163	11.9 a	8.1 a	10.2 a	10.0 a	11.9 a	10.2 a	8.1 b	10.0 a

7.3.4 Growth

7.3.4.1 Shoot growth

Cumulative shoot growth (shoot length) was higher in CI than in DI from 63 DAFB (Figure 7.6A) and was higher in LCL than in CCL from 56 DAFB (Figure 7.6B). Reduction in final shoot length by DI was about 15% and that by CCL was about 16%. Shoot growth rate declined over the season in all treatments (Figures 7.6 C and D) and it was lower in DI than in CI (Figure 7.6C) and also lower in CCL than in LCL (Figure 7.6D). However, the differences decreased and became not significant in the later stages of shoot growth. A beneficial effect of DI on reduced vegetative growth in terms of

reduced pruning cost has been reported in several fruit species including apple (Kilili et al., 1996c), peach (Mitchell and Chalmers, 1982), and pear (Caspari et al., 1994).

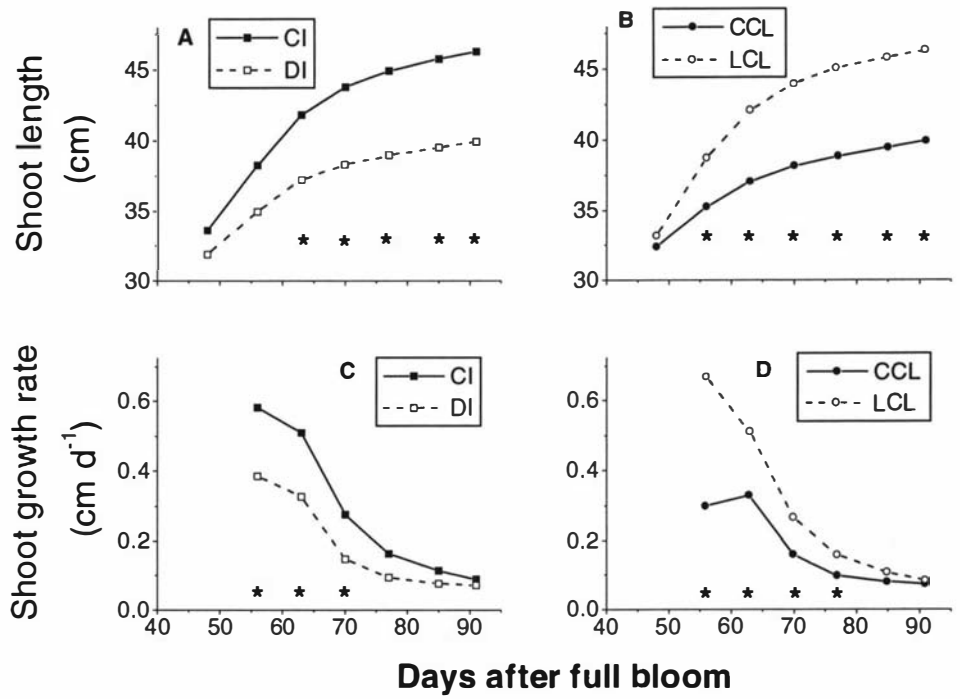

Figure 7.6 Cumulative shoot growth (A and B) and shoot growth rate (C and D) for 'Braeburn' apple under different irrigation (A and C) and crop load (B and D) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

7.3.4.2 Fruit growth

Cumulative fruit growth (fruit volume) was lower in DI than in CI late in the season (Figure 7.7A) while fruit growth rates were lower in DI early in the season (Figure 7.7C). Fruit growth rate fluctuated earlier in the season but consistently declined later in the season in all treatments (Figures 7.7 C and D). Fruit growth rate (Figure 7.7D) and fruit volume (Figure 7.7B) were lower in CCL than in LCL in most measurements. Reduction in final fruit volume by DI was about 4% whereas that by CCL was about 13%.

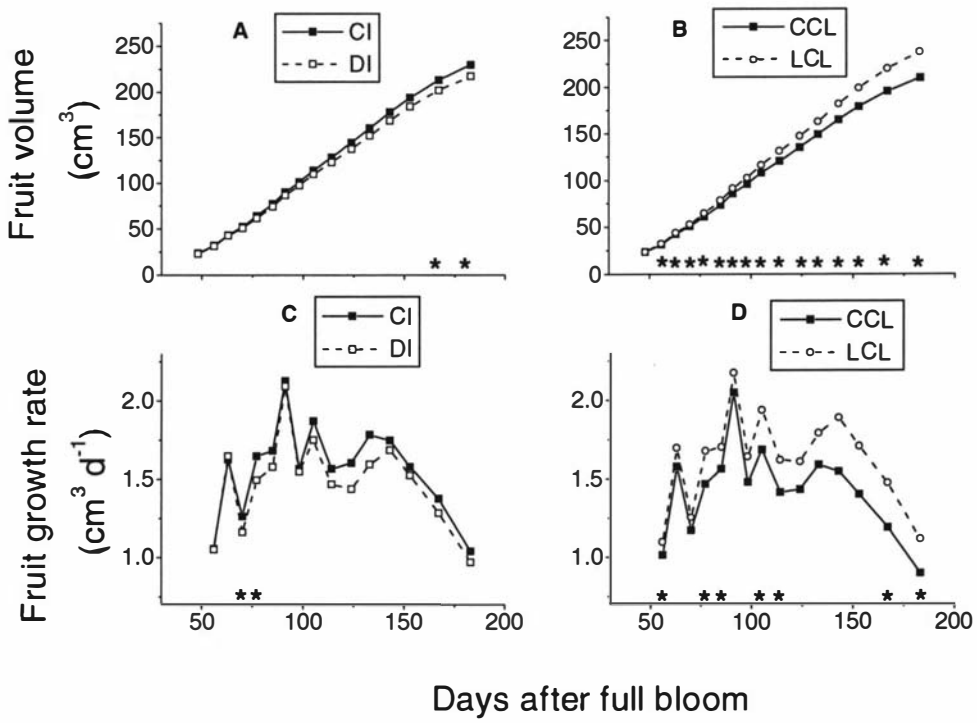

Figure 7.7 Fruit volume (A and B) and fruit growth rate (C and D) for 'Braeburn' apple under different irrigation (A and C) and crop load (B and D) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

7.3.5 Fruit composition

7.3.5.1 Soluble sugars

Total sugar concentration (TSC) increased over the season in all treatments (Figure 7.8) with DI fruit having higher values than CI fruit in most measurements (Figure 7.8A). The TSC was higher in LCL than in CCL only in a few measurements (Figure 7.8B).

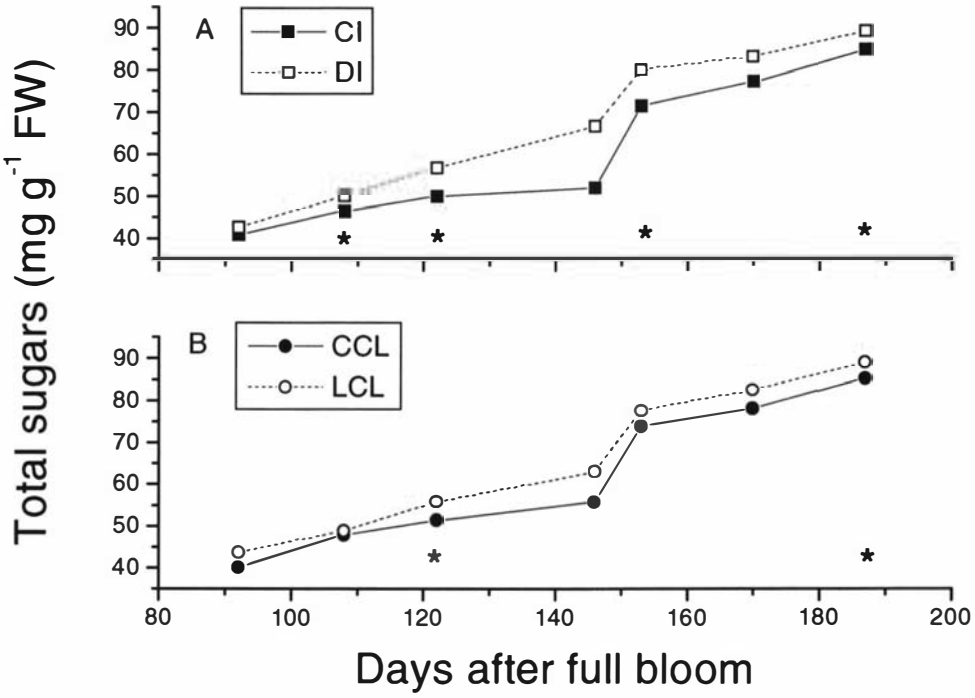

Figure 7.8 Fruit total sugar concentrations for 'Braeburn' apple under different irrigation (A) and crop load (B) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

Sucrose (Figures 7.9A and 7.10A) and fructose (Figures 7.9C and 7.10C) increased over the season but glucose (Figures 7.9B and 7.10B) and sorbitol (Figures 7.9D and 7.10D) fluctuated with a substantial decrease on 146 DAFB in all treatments. There was a sharp increase in the concentration of all sugars from 146 to 153 DAFB in all treatments (Figures 7.9 and 7.10).

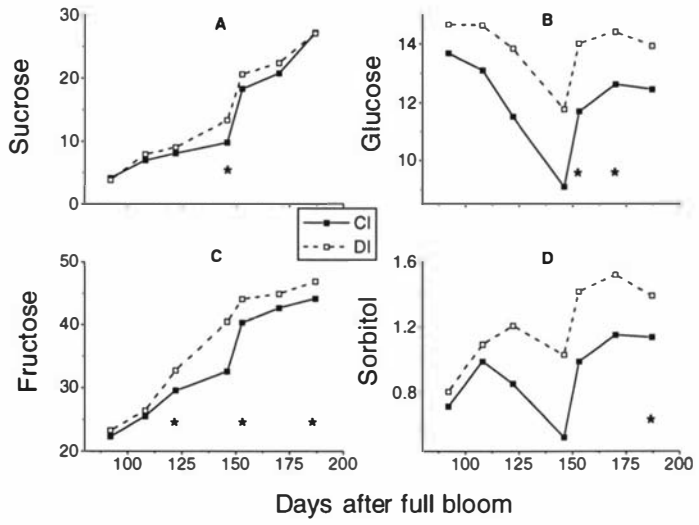

Figure 7.9 Concentrations (mg g^{-1} fresh weight) of sucrose (A), glucose (B), fructose (C), and sorbitol (D) for 'Braeburn' apple under different irrigation treatments. The treatments were CI = commercially irrigated control and DI = deficit irrigation. Asterisks represent significant differences ($P < 0.05$).

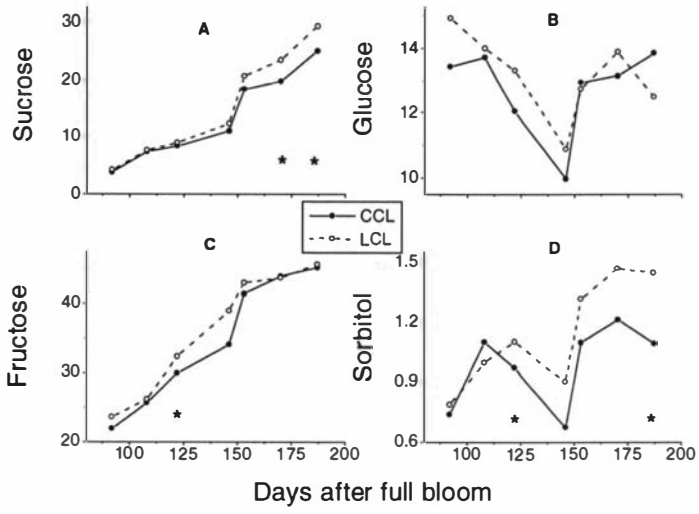

Figure 7.10 Concentrations (mg g^{-1} fresh weight) of sucrose (A), glucose (B), fructose (C), and sorbitol (D) for 'Braeburn' apple under different crop load treatments. The treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

7.3.5.2 Dry matter concentration

Fruit DMC was higher in DI than in CI from 146 to 202 DAFB (Figure 7.11A). Although fruit DMC tended to be higher in LCL than in CCL, the differences were only significant at the last two harvests (Figure 7.11B).

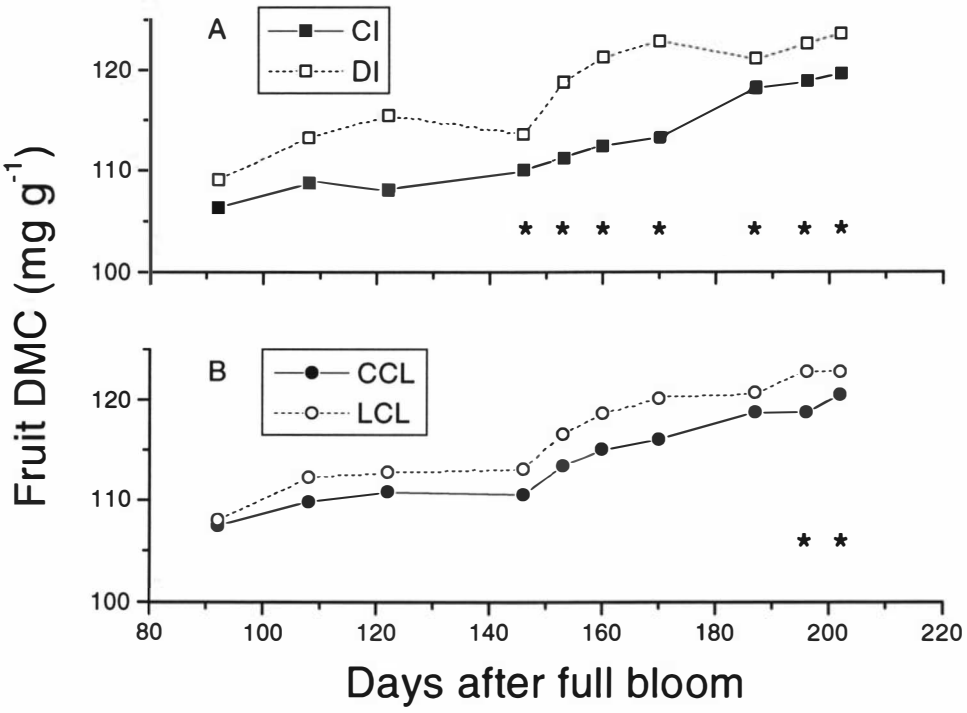

Figure 7.11 Fruit dry matter concentration (DMC) for 'Braeburn' apple under different irrigation (A) and crop load (B) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$).

7.3.6 Yield and mean fruit weight

Fruit yield per tree was the same in CI and DI for both crop loads (Table 7.3). Mean fruit weight was lower in DI than in CI for CCL but DI and CI had similar values for LCL (Table 7.3). Fruit yield per tree was lower in LCL than in CCL under both irrigation treatments (Table 7.3). Mean fruit weight was higher in LCL than in CCL under DI but was the same under CI (Table 7.3).

Table 7.3 Interactions of irrigation and crop load treatments on yield and on mean fruit weight at harvest for 'Braeburn' apple. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Comparisons of irrigation treatment were done at each crop load treatment and comparisons of crop load treatments were done under each irrigation treatment. For each treatment pair, values along the column followed by different letters are significantly different at $P < 0.05$.

Treatment		Yield (kg/tree)	Mean fruit weight(g)
		Irrigation treatments	
At CCL	CI	72.1a	206.1a
	DI	60.6a	182.8b
At LCL	CI	50.3a	222.6a
	DI	49.1a	217.0a
		Crop load treatments	
Under CI	CCL	72.1a	206.1a
	LCL	50.3b	222.6a
Under DI	CCL	60.6a	182.8b
	LCL	49.1b	217.0a

7.4 Discussion

Both Ψ_l and Ψ_{fw} were lower in DI than in CI. The lower Ψ_l was maintained throughout the growing season whereas Ψ_{fw} of DI became similar to that of CI late in the season. Total water movement out of the fruit into the leaves is dependent on water potential gradient. While Ψ_{fw} decreased over the growing season, Ψ_l did not show a consistent change. Because Ψ_{fw} was greater than Ψ_l (Figures 7.4 and 7.2), a decrease in the former led to a reduction in water potential gradient between leaf and fruit as the season progressed. Water movement out of the fruit into the leaves would therefore decrease which is consistent with the results of Mills et al. (1997). Differences between Ψ_{fw} and Ψ_l, averaged over all treatments, decreased from 0.6 MPa on 70 DAFB to 0.2 MPa on 171 DAFB. Mills et al. (1997) reported that Ψ_{fw} decreased during early-season DI but was not affected under late-season DI. In this study although Ψ_{fw}, averaged over the two crop loads, for CI and DI was similar late in the season (Figure 7.4A), it was still lower in DI than in CI for CCL at this stage (Table 7.1). This indicates that Ψ_{fw} was less affected under DI for LCL as water was shared among less numbers of fruit.

An early reduction in Ψ_{fw} of DI fruit resulted in decreased Ψ_{fp}. Reduction in Ψ_{fw} from mid-season was coupled with a similar decrease in Ψ_{fs} and therefore maintenance of Ψ_{fp}. Osmotic adjustment in fruit under reduced irrigation has been observed in apple (Mills et al., 1997), Asian pear (Behboudian et al., 1994), and strawberry (Pomper and Breen, 1997). Higher sugar concentration in DI than in CI fruit from mid season was a major contributing factor in lowering of Ψ_{fs} for DI fruit. For example, we calculated the contribution of increased sugars to the lowering of Ψ_{fs} at 155 DAFB in Figure 8.9. Using Van't Hoff's equation (Salisbury and Ross, 1992), it can be calculated that the increased sugars in DI fruit over CI fruit created an osmotic potential of approximately 0.12 MPa contributing 52% to the measured decrease in Ψ_{fs} of DI fruit.

In addition to reduced g_s, there should have been non-stomatal factors contributing to a decreased Pn under DI because C_i was the same in CI and DI in all but one measurement (Figure 7.5E). Lower Pn in response to water deficit along with a reduction in g_s without

any reduction in C_i has also been observed in other studies (Kilili et al., 1996c; Behboudian et al., 1994).

Turgor is required for cell growth (Cosgrove, 1993). Lower fruit growth rates in DI earlier in the season coincided with reduced Ψ_{fp} which later became similar in DI and CI fruit and these treatments were then showing the same fruit growth rate. Although turgor was maintained by mid season in DI fruit, mean fruit weight at harvest was still lower than CI for CCL. Final fruit size has been reported to be closely correlated with cell numbers in the cortex (Goffinet et al., 1995). In apple, cell division occurs from full bloom up to about 40 DAFB (Westwood, 1993). Water deficit did not occur during the cell division period as Ψ_l of DI was not lower than CI until 70 DAFB and therefore cell numbers should not have been affected by DI in this study. Effects of DI on reduced mean fruit weight at harvest which occurred for CCL in this study could be due to reduced fruit cell expansion through reduced fruit turgor early in the season and to reduced cell water content. Limitation of assimilate availability with lower Pn and more competition for assimilates among higher number of fruit on a tree at commercial crop load could also contribute to reduced mean fruit weight at harvest under DI. Although Pn decreased in DI, fruit DMC was higher than in CI. This could be because water deficit did not result in decreased translocation of assimilates to the fruit in proportion to a decrease in Pn or it could simply be due to the lower water content of fruit cells in DI.

Higher crop load had more effect on reduced fruit growth than did DI and this was associated with reduced fruit turgor (Figure 7.4F). Reduction in growth of peach fruit at a higher crop load was reported to be closely associated with decrease in Ψ_{fp} (McFadyen et al., 1996). Increased Pn has been observed with a higher crop load in 'Braeburn' apple (Wünsche et al., 2000). In this study, although Pn (averaged from both irrigation regimes) tended to be higher in CCL than in LCL from early to mid season, the differences were not significant at $P < 0.05$. The difference in our results with those of Wünsche et al. (2000) could be due to a larger difference in crop load treatments in their study which were 8.7, 3.3, 1.5, and 0 fruit per cm^2 TCA in comparison to 6 and 4 in ours. From mid to late season, Pn was lower in CCL than in LCL under DI leading to less assimilate availability and an adverse effect on fruit size for the CCL treatment.

Similar to this experiment, decreased fruit size in response to reduced irrigation has been reported to be dependent on crop load in apple (Naor et al., 1997b) and nectarine (Naor et al., 1999). Interactions between irrigation and crop load on fruit size could be due to their effects on fruit water relations and on photosynthetic rate, although these interactions were significant only from mid season. Reduced crop load enhanced mean fruit weight at harvest under DI through increased Ψ_{fw},Ψ_{fp}, and Pn.

7.5 Summary

This study showed that DI has the beneficial effect of reduced vegetative growth with an expected lower pruning cost. Compared to shoot growth, fruit growth was much less affected by DI. Gross yield was the same for CI and DI at light crop load. Mean fruit weight at harvest was reduced in DI at commercial crop load but still met standard export requirements. Interactions between irrigation and crop load on fruit size could be due to their effects on fruit water relations and on photosynthetic rate. Enhancement of fruit size in DI by reducing crop load could be due to increased fruit turgor, increased photosynthetic rates and assimilates being shared among less fruit. Reducing crop load from the commercial level by one third in this study did not enhance fruit size under commercial irrigation, indicating that there was adequate water and assimilates when trees were well watered at commercial crop load.

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Chapter Eight

Fruit Quality Attributes and their Interrelationships for 'Braeburn' Apple in Response to Deficit Irrigation and to Crop Load

Abstract

Information on the interaction between irrigation and crop load on fruit quality other than fruit size is lacking for apple. This study investigated this interaction on various fruit quality attributes individually and collectively for 'Braeburn' apple (*Malus domestica* Borkh.). Irrigation treatments were commercially irrigated control (CI) and deficit irrigation (DI) applied throughout the season. Crop load treatments were commercial crop load (CCL) having six fruit per cm^2 of trunk cross-sectional area and light crop load (LCL) having four. There was no interaction between irrigation and crop load on individual fruit quality attributes or on collective fruit quality for which many quality attributes were considered together. This was true both at harvest and after storage. Deficit irrigation improved fruit quality at harvest in terms of increased firmness, total soluble solids (TSS), total sugar concentration (TSC), and dry matter concentration. There was an irrigation effect on collective fruit quality both at harvest and after storage. Reduced crop load improved fruit quality at harvest in terms of increased firmness, TSS, TSC, and density. The LCL fruit had a higher ($P < 0.1$) weight loss during storage and a higher ($P < 0.1$) incidence of bitter pit after storage than did the CCL fruit. There was a crop load effect at harvest but not after storage on collective fruit quality. Increased weight loss and incidence of bitter pit during storage in light crop load may limit its application.

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B. S. Mpelasoka[1], M. H. Behboudian[1] and S. Ganesh[2]

[1]Institute of Natural Resources [2]Institute of Information Sciences and Technology

College of Sciences, Massey University, Palmerston North, New Zealand

8.1 Introduction

Both lysimetry (Chapter 6) and field (Chapter 7) studies showed that the effects of DI on fruit size reduction can be counteracted by reducing crop load. However, information on interaction of irrigation and crop load on fruit quality other than fruit size is lacking for apple. This information is needed to determine whether reduced crop load can be integrated with DI in order to maximise the beneficial effects of DI in apple production. Nevertheless, there is some information on the effects of crop load and DI, applied separately, on apple fruit quality. Reduced crop load increased firmness (Johnson, 1994; Elgar et al., 1999) but also increased the incidence of physiological disorders such as 'Braeburn' browning disorder (Tough et al., 1998; Elgar et al., 1999) and bitter pit (Ferguson and Watkins, 1992; Volz et al., 1993; Tough et al., 1998). Improved 'Braeburn' quality by DI in terms of increased firmness, total soluble solids, and total sugar concentration both at harvest and after storage has been demonstrated in Chapter 4. Fruit weight loss, one of the serious causes of fruit deterioration during storage, decreased in DI apple fruit (Kilili et al., 1996b; Chapter 4 of this thesis). There is no published information for crop load effect on this aspect. Little is also known about effects of crop load or DI on incidence of water core, a physiological disorder that has become significant in 'Braeburn' since the 1997/98 growing season (Clark and Richardson, 1999).

The aim of this study was to investigate the interaction of irrigation and crop load on various individual fruit quality attributes including the physiological disorders mentioned above. The interaction on collective behavior of various quality attributes was also explored by the application of multivariate statistics.

8.2 Materials and Methods

8.2.1 Experimental conditions and treatments

These are the same as those listed in Chapter 7 (section 7.2.1).

8.2.2 Fruit sampling and quality assessment protocols

After harvest, fruit for quality assessments were randomly selected from two weight groups, 161-190 g and 191-240 g, of each tree with equal numbers of fruit from each

group. Quality assessments at harvest were made on eight fruit per sub plot (four fruit per tree) harvested at 187 DAFB. The assessments included measurements of density, skin colour, soluble sugars, internal ethylene concentration (IEC), flesh firmness, starch pattern index (SPI), total soluble solids (TSS), titratable acidity (TA), dry matter concentration (DMC), and incidence of physiological disorders. Assessments after storage were made after seven-day shelf-life at 20°C following 17 weeks at 0°C on four fruit per sub plot (two fruit per tree) harvested at 202 DAFB. The assessments included skin colour, IEC, flesh firmness, SPI, TSS, TA, and incidence of physiological disorders. Fruit weight loss was determined from twelve fruit per sub plot (six fruit per tree) harvested at 202 DAFB. Individual fruit weight was monitored during 17 weeks at 0°C and fruit weight loss was calculated as percent reduction from initial weight.

Procedures of assessments for each quality attribute are described in Chapter 2 (sections 2.6 and 2.7).

8.2.3 Statistical analysis

Data of individual attributes were subjected to analysis of variance as a split plot design with irrigation treatment as main plot and crop load as sub plot with four replications (blocks). Comparisons of means were done using t-tests.

A multivariate analysis of variance (MANOVA) was carried out on fruit quality at harvest and after storage using data from individual trees. Canonical variate analysis (CVA) was carried out within the context of MANOVA to explore the differences within each group. Fruit quality attributes included in multivariate analysis were skin colour, density, DMC, firmness, TA, and TSS at harvest; and skin colour, firmness, TA, TSS, and incidence of physiological disorders after storage.

8.3 Results and discussion

8.3.1 Individual fruit quality (Univariate analysis)

There was no interaction between irrigation and crop load treatments on any individual quality attribute either at harvest or after storage. Therefore, only results of the main effect, 'irrigation' and 'crop load' are presented.

8.3.1.1 At harvest

At harvest, DI fruit were firmer and had higher TSS, DMC, and total sugar concentration (TSC) than CI fruit (Table 8.1). Fruit TA, density, IEC, SPI, and skin colour were similar for CI and DI (Table 8.1). Since DI fruit had higher DMC than CI fruit, the lower fruit TSC and TSS in CI was due to a dilution effect. The firmer fruit in DI than in CI was due to decreased cellular hydration in DI fruit. Effects of reduced irrigation on fruit skin colour are inconclusive. Some reports show that reduced irrigation does not affect apple skin colour (Proebsting et al., 1984; Ebel et al., 1993) while others indicate redder skin colour with reduced irrigation (Kilili et al., 1996b; Mills et al., 1994). Fruit skin colour is determined by several factors such as light interception, temperature, and fruit nutrients especially N (Daugaard and Grauslund, 1999). The unusually high temperatures during the growing season in this experiment could have masked the effects of DI on fruit skin colour.

Flesh firmness, TSC, TSS, and density at harvest were higher in LCL than in CCL but crop load did not affect TA, DMC, IEC, and SPI (Table 8.1). Increased firmness with light crop load in 'Cox's Orange Pippin' apple was also observed by Johnson (1994) and in 'Braeburn' apple by Tough et al. (1998). Increased firmness for LCL fruit could be due to a higher cellular density than CCL fruit (Table 8.1). Research findings on crop load effects on fruit TSS have been inconclusive. Tough et al. (1998) observed higher TSS in 'Braeburn' apple from light crop trees whereas Opara and Tadesse (2000) found no consistent effect of crop load on TSS for 'Pacific Rose' apple. Sugars are the major component of soluble solids (Wills et al., 1997). Higher TSS in LCL than in CCL in this research is in agreement with higher TSC in LCL. Inconsistent findings in crop load effects on fruit TSS from different experiments could be due to differences in time of thinning, cultivar, and level of crop load.

Table 8.1 Flesh firmness, total sugar concentration (TSC), total soluble solids (TSS), titratable acidity (TA), dry matter concentration (DMC), density, internal ethylene concentration (IEC), starch pattern index (SPI), and skin colour measured as hue angle (H) on red blush (Blush) and background green (Unblush) portion at harvest for 'Braeburn' apple. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Comparisons were made for each main effect, 'irrigation' and 'crop load'. For each treatment pair, values across the row followed by different letters are significantly different at $P < 0.05$.

Fruit attributes	**Irrigation treatment**		**Crop load treatment**	
	CI	DI	CCL	LCL
Firmness (N)	90.2 b	92.8 a	90.6 b	92.3 a
TSC ($mg.g^{-1}$ FW)	84.9 b	89.2 a	85.2 b	88.9 a
TSS (%)	11.8 b	12.3 a	11.9 b	12.2 a
TA (% malic acid)	0.76 a	0.75 a	0.75 a	0.76 a
DMC ($mg.g^{-1}$)	118.3 b	121.1 a	118.7 a	120.7 a
Density ($g.cm^{-3}$)	0.88 a	0.88 a	0.87 b	0.89 a
IEC ($\mu L.L^{-1}$)	0.33 a	0.31 a	0.31 a	0.33 a
SPI	2.2 a	2.5 a	2.1 a	2.6 a
Blush (H, °)	28.7 a	30.0 a	29.7 a	28.9 a
Unblush (H, °)	97.9 a	98.8 a	101.2 a	95.5 b

Hue angle on the red blush skin portion was similar for CCL and LCL fruit indicating that they had similar redness of blush colour. The LCL fruit had more yellow background skin colour because they had lower hue angle on the green background skin portion than CCL fruit (Table 8.1). Johnson (1995) observed more yellow background skin colour and an earlier increase in IEC in 'Cox's Orange Pippin' apple from thinned

trees. He therefore suggested that fruit from thinned trees were more advanced in maturity than fruit from unthinned trees. Background skin colour is often used as a maturity index because, as fruit mature, background skin colour changes from green to yellow through chlorophyll degradation and unmasking of carotenoids (Gorski and Creasy, 1977). In this research, however, LCL and CCL fruit had similar maturity based on IEC and SPI. Background skin colour may be influenced by other factors such as N levels. High N levels enhance chlorophyll retention hence retarding yellow background colour development (Magness et al., 1940). Vegetative growth is generally more vigorous with lighter crop load leading to less N availability to the fruit. Shoot growth was greater in LCL than in CCL (Figure 8.1). However, fruit N was not measured here for a definite conclusion. Water core was observed only in two fruit, one from a CCL tree under CI and the other from a LCL tree under DI. No incidence of other physiological disorders was observed at harvest.

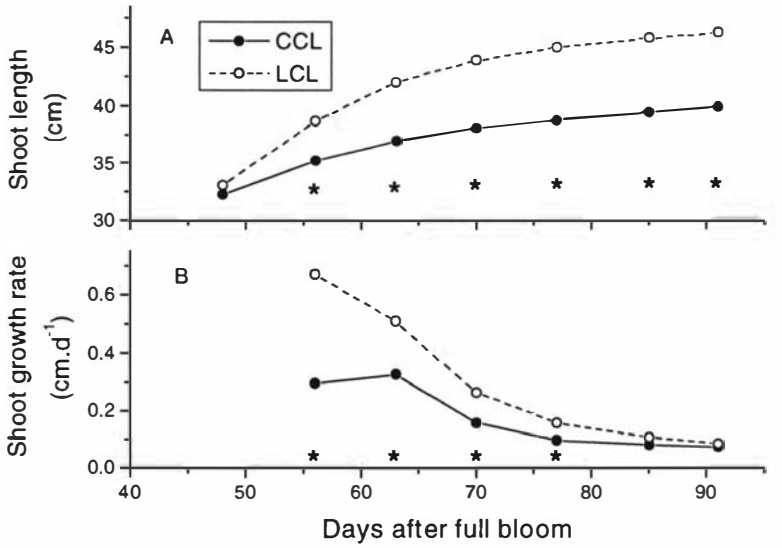

Figure 8.1 Cumulative shoot growth (A) and shoot growth rate (B) for 'Braeburn' apple under different crop load treatments: CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.05$)

8.3.1.2 Fruit weight loss during storage

Cumulative weight loss during 17 weeks at 0°C was higher ($P < 0.1$) in CI than in DI but on some occasions (Figure 8.2A). The LCL fruit had higher weight loss than CCL fruit ($P < 0.1$) throughout 17 weeks at 0°C (Figure 8.2B). Fruit weight loss is one of the serious causes of fruit deterioration during storage (Woods, 1990). After harvest fruit continue to transpire and respire resulting in weight loss. Fruit weight loss during storage for DI fruit was lower than for CI fruit in the other experiment presented in Chapter 4 and in Kilili et al., 1996b. However, irrigation treatments appeared to have little effect on weight loss in this experiment. A 6% loss in fruit weight after harvest results in shrivel and loss of marketability (Hatfield and Knee, 1988). Increased fruit weight loss in LCL is a disadvantage especially for fruit destined for long storage.

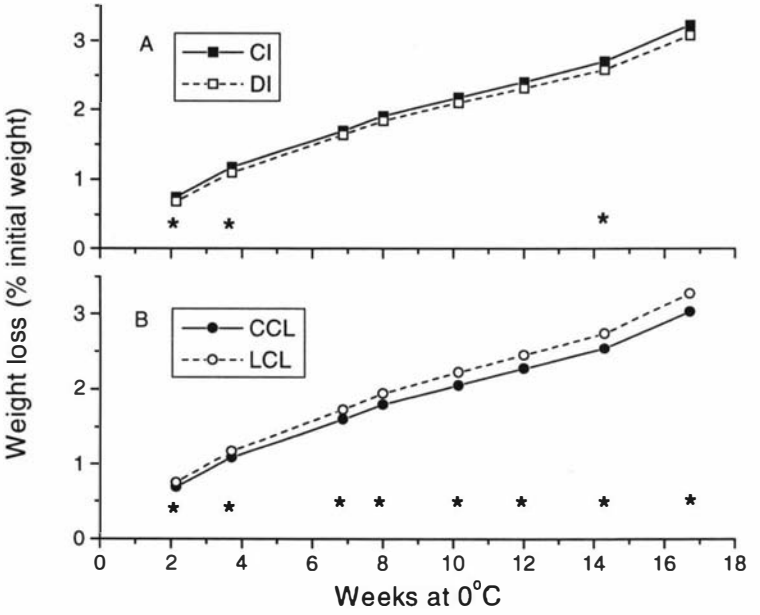

Figure 8.2 Cumulative weight loss at 0°C for 'Braeburn' apple under different irrigation (A) and crop load (B) treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Asterisks represent significant differences ($P < 0.1$).

8.3.1.3 After storage

After storage, SPI values reached the maximum (SPI = 6) for all fruit because most starch had been converted to sugars and the remaining starch was too low to be detected with iodine solution. The DI fruit had higher TSS and IEC than CI fruit but flesh firmness, TA, and skin colour were similar for DI and CI fruit (Table 8.2). No incidence of water core was observed after storage. Incidence of bitter pit was higher in LCL than in CCL ($P < 0.1$). Percentage of fruit with bitter pit ($LSD_{0.05} = 5.84$) was 6.25 and 1.56 for LCL and CCL, respectively. The LCL and CCL fruit were similar for all other quality attributes measured after storage (Table 8.2).

Table 8.2 Flesh firmness, total soluble solids (TSS), titratable acidity (TA), internal ethylene concentration (IEC), and skin colour measured as hue angle (H) on red blush (Blush) and green background (Unblush) after seven-day shelf life at 20°C following 17 weeks at 0°C for 'Braeburn' apple. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load. Comparisons were made for each main effect, 'irrigation' and 'crop load'. For each treatment pair, values across the row followed by different letters are significantly different at $P < 0.05$.

Fruit attributes	**Irrigation treatment**		**Crop load treatment**	
	CI	DI	CCL	LCL
Firmness (N)	58.4 a	58.8 a	58.8 a	58.4 a
TSS (%)	13.4 b	14.1 a	13.7 a	13.8 a
TA (% malic acid)	0.56 a	0.55 a	0.56 a	0.55 a
IEC ($\mu L.L^{-1}$)	412.0 b	526.7 a	446.3 a	492.4 a
Blush (H, °)	31.8 a	32.1 a	32.9 a	30.9 a
Unblush (H, °)	85.9 a	95.1 a	90.0 a	91.0 a

8.3.2 Collective fruit quality (Multivariate analysis)

In univariate analysis a single response of each attribute is considered at one time whereas in multivariate analysis response of interrelationships among many quality attributes is considered (Manly, 1994). Here, we explored the interrelationships among many quality attributes in response to irrigation and crop load. More replications are needed to confirm the reliability of the following results. There was no interaction between irrigation and crop load on fruit quality either at harvest or after storage when many quality attributes were considered collectively (collective fruit quality). There were significant effects (Wilks' Lambda statistic: $P < 0.05$) of irrigation and crop load on collective fruit quality at harvest. Canonical variate analysis determines linear functions of several attributes that maximally separate the groups of apple fruit while keeping the variation within groups as small as possible. These linear functions are called canonical variates (Manly, 1994). Because there were only two levels of irrigation treatments and two levels of crop load treatments, differences between CI and DI or between CCL and LCL could be accounted for by only one canonical variate. The values of the canonical variates for each individual are called canonical scores (Manly, 1994). Plots of canonical scores associated with canonical variates showed grouping along the sole canonical variate for irrigation effect (Figure 8.3A) as well as for crop load effect (Figure 8.3B). After storage, there was still an irrigation effect (Wilks' Lambda statistic: $P < 0.05$) on collective fruit quality but there was no difference between CCL and LCL on collective fruit quality. The plot of canonical scores associated with canonical variates again showed grouping along the sole canonical variate for irrigation effect (Figure 8.4). Characteristic vector of each attribute indicates how much each attribute contributes to the difference along the canonical variate (Manly, 1994). The difference in collective fruit quality at harvest between CCL and LCL was mainly due to the difference in fruit density because the characteristic vector of density was by far the highest compared to those of other attributes. The characteristic vector was 13.0 for density and the second highest characteristic vector was –2.6 for TA. Density was not measured after storage, hence, was not included in collective fruit quality after storage. This could be the reason for similar collective fruit quality after storage between CCL and LCL.

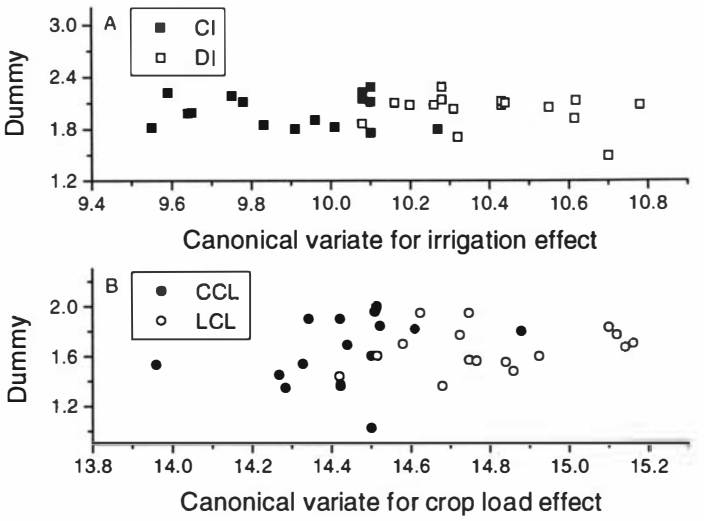

Figure 8.3 Plots of canonical scores for irrigation effect (A) and for crop load effect (B) on collective fruit quality at harvest for 'Braeburn' apple under different irrigation and crop load treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were CCL = commercial crop load and LCL = light crop load.

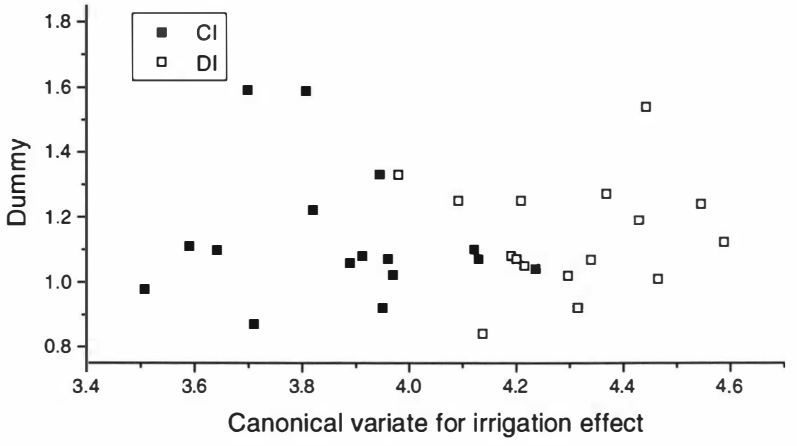

Figure 8.4 Plot of canonical scores for irrigation effect on collective fruit quality after storage for 'Braeburn' apple under different irrigation treatments. Irrigation treatments were CI = commercially irrigated control and DI = deficit irrigation,

8.4 Summary

Deficit irrigation improved individual fruit quality attributes at harvest in terms of increased firmness, TSS, TSC, and DMC. Collective fruit quality was also enhanced by DI both at harvest and after storage. Reduced crop load increased firmness, TSS, TSC, and density at harvest. However, increased weight loss during storage and higher incidence of bitter pit after storage in light crop load may limit its application for increasing fruit size under DI especially for fruit destined for long storage.

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Chapter Nine

Aroma Volatiles and Other Maturity-Related Quality Attributes in Response to Deficit Irrigation and to Crop Load and Their Relationships with Fruit Maturity Attributes for 'Braeburn' Apple

Abstract

Aroma volatiles are important quality attributes for apple and there is not enough information on how their production is affected by deficit irrigation or by crop load. This study investigated effects of irrigation, crop load, and their interaction on maturity-related quality attributes (aroma volatiles, total soluble solids (TSS), titratable acidity (TA), and firmness) and maturity attributes (internal ethylene concentration, "percent ripening fruit", and starch pattern index) for 'Braeburn' apple. Multivariate relationships between these two sets of attributes were also explored. Irrigation treatments were commercially irrigated control (CI) and deficit irrigation (DI) applied throughout the season. Crop load treatments were commercial crop load (CCL) having six fruit per cm^2 of trunk cross-sectional area and light crop load (LCL) having four. There was no interaction between irrigation and crop load on any individual quality attribute. Control and DI fruit had similar maturity at harvest but DI fruit became more advanced in maturity during storage at 20°C following harvest and after cold storage. Deficit irrigation enhanced volatiles production during ripening and after cold storage. Firmness and TSS also increased in DI

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Production of aroma volatiles in response to deficit irrigation and to crop load and their relationships with fruit maturity for 'Braeburn' apple

Bussakorn S. Mpelasoka and M. Hossein Behboudian

Horticultural Science Group, Institute of Natural Resources, College of Sciences, Massey University, Palmerston North, New Zealand

but the increased firmness was lost during subsequent storage. Firmness and TSS increased in LCL on some occasions but crop load had no effect on maturity or production of volatiles. Fruit TA was not affected by irrigation or crop load. Aroma volatiles poorly correlated with each individual maturity attribute. Canonical correlation analysis showed high multivariate correlation between the maturity attributes and maturity-related quality attributes with two underlying dimensions that characterised their relationships. Quality enhancement by DI was related, in part, to the advanced ripening of DI fruit.

9.1 Introduction

Improved quality by DI in terms of increased total soluble solids (TSS) and sugars, the components of taste; and increased firmness, the component of texture; has been demonstrated in the previous chapters. Aroma volatiles are responsible for odour and contribute greatly to overall flavour of the fruit and its processed products (Brackmann and Streif, 1994). There are limited and inconclusive reports on apple volatiles as affected by DI. While Behboudian et al. (1998) found increased total volatile concentration in fruit from late-season DI, results from this thesis presented in Chapter 4 showed no effect of late-season DI on total volatile concentration. This inconsistency could be due to different degrees of water deficit developed. Fruit maturity is a significant factor affecting production of volatiles (Song and Bangerth, 1996). Therefore the inconsistent results of DI effects on aroma volatiles could also be due to differences in fruit maturity at assessment. Information is lacking on how production of aroma volatiles is affected by crop load.

The aim of this study was to investigate the effects of DI, crop load, and their interaction on the production of aroma volatiles, both quantitatively and qualitatively, at different stages of fruit maturity. Effects on other maturity-related quality attributes (TSS, firmness, and acidity) and maturity attributes (internal ethylene concentration, "percent ripening fruit", and starch pattern index) were also investigated. Univariate and multivariate relationships among these two sets of attributes were explored.

9.2 Materials and methods

9.2.1 Experimental conditions and treatments

These are the same as those outlined in Chapter 7 (section 7.2.1).

9.2.2 Fruit sampling and quality assessment protocols

After harvest, fruit for quality assessments were randomly selected from two weight groups, 161-190 g and 191-240 g, of each tree with equal numbers of fruit from each group. Quality assessments at harvest were made on fruit harvested at 187 DAFB (Harvest 1) and 202 DAFB (Harvest 3) using eight fruit per sub plot (four fruit per tree) for each harvest. Quality assessments during 14 days of storage at 20°C were made at

three sampling dates on Days 2, 6, and 14 using fruit harvested at 196 DAFB (Harvest 2) with four fruit per sub plot (two fruit per tree) for each sampling date. Assessments after cold storage were made on Day 1 and Day 7 at 20°C following 17 weeks of storage at 0°C using fruit harvested at 202 DAFB with four fruit per sub plot (two fruit per tree) for each sampling date. Assessments included measurements of maturity attributes (internal ethylene concentration (IEC), "percent ripening fruit", and starch pattern index (SPI)) and maturity-related quality attributes (flesh firmness, total soluble solids (TSS), titratable acidity (TA), and aroma volatiles).

Procedures of assessments for each quality attribute are described in Chapter 2 (sections 2.6 and 2.7).

9.2.3 Statistical analysis

Data of individual attributes were subjected to analysis of variance (ANOVA) as a split plot design with irrigation treatment as main plot and crop load as sub plot with four replicates (blocks). Comparisons of means were done using t-tests. For aroma volatiles, data for individual concentration of each volatile compound, total volatile concentration, and total odour units were analysed and compared.

A canonical correlation analysis was carried out to describe the relationships between the maturity-related quality attributes and the maturity attributes using the combined data assessed at harvest, during storage at 20°C, and after cold storage. Total odour units were used for aroma volatiles.

9.3 Results and discussion

9.3.1 Fruit maturity and maturity-related quality

There was no interaction between irrigation and crop load treatments on any individual quality attributes at any assessment date.

At both Harvests 1 and 3, DI fruit were firmer and had higher TSS than CI fruit (Table 9.1). Fruit TA, IEC, and SPI were similar for CI and DI (Table 9.1). There was no "ripening fruit" at Harvest 1 in either treatment but this attribute was higher in CI than in DI at Harvest 3 (Table 9.1).

Table 9.1 Internal ethylene concentration (IEC), "percent ripening fruit", starch pattern index (SPI), flesh firmness, total soluble solids (TSS) and titratable acidity (TA) at harvest for 'Braeburn' apple under different irrigation treatments: CI = commercially irrigated control and DI = deficit irrigation. Comparison was made within each harvest. Values across the row followed by different letters were significantly different at $P < 0.05$.

Fruit attribute	**Harvest 1**		**Harvest 3**	
	CI	DI	CI	DI
IEC ($\mu L\ L^{-1}$)	0.33 a	0.31 a	1.76 a	1.08 a
% ripening fruit	0.0 a	0.0 a	18.8 a	6.3 b
SPI	2.2 a	2.5 a	2.9 a	2.8 a
Firmness (N)	90.2 b	92.8 a	85.6 b	89.3 a
TSS (%)	11.8 b	12.3 a	12.2 b	12.8 a
TA (% malic acid)	0.75 a	0.75 a	0.71 a	0.72 a

Aroma volatiles were generally higher at Harvest 3 than at Harvest 1 in both irrigation treatments (Table 9.2). Fruit from CI and DI trees had similar total volatile concentrations and similar total odour units but DI fruit had higher individual concentrations of propan-1-ol and butan-1-ol at Harvest 1 and ethyl hexanoate, butyl acetate, and hexyl acetate at Harvest 3 (Table 9.2).

Table 9.2 Concentrations of aroma volatiles (μmol L^{-1}) and total odour units in juice of 'Braeburn' apple at harvest from different irrigation treatments: CI = commercially irrigated control and DI = deficit irrigation. Comparison was made within each harvest. Values across the row followed by different letters were significantly different at $P < 0.05$.

Volatiles	**Harvest 1**		**Harvest 3**	
	CI	DI	CI	DI
Alcohols				
Propan-1-ol	62.9 b	90.7 a	252.7 a	434.8 a
Butan-1-ol	782.3 b	816.1 a	2906.5 a	2679.8 a
Pentan-1-ol	32.4 a	30.5 a	96.6 a	82.8 a
Hexanol-1-ol	143.6 a	143.7 a	176.4 a	156.4 a
2&3 Methyl butan-1-ol	431.3 a	415.3 a	494.4 a	519.1 a
Aldehydes				
Hexanal	259.5 a	328.9 a	257.2 a	332.9 a
trans-2-hexenal	1061.7 a	1569.7 a	1331.4 a	2084.2 a
Ethyl esters				
Ethyl propionate	81.0 a	66.4 a	197.6 a	159.6 a
Ethyl butanoate	46.2 a	43.1 a	51.1 a	50.8 a
Ethyl-2-methyl butanoate	1.6 a	2.9 a	6.2 a	8.4 a
Ethyl pentanoate	147.9 a	162.0 a	255.2 a	214.0 a
Ethyl hexanoate	12.5 a	13.4 a	23.8 b	34.9 a
Non-ethyl esters				
Propyl acetate	63.7 a	104.3 a	69.3 a	114.1 a
Butyl acetate	228.6 a	280.5 a	301.6 b	520.9 a
Pentyl acetate	29.1 a	28.4 a	58.5 a	61.1 a
Hexyl acetate	55.4 a	61.0 a	47.4 b	61.1 a
Propyl butanoate	8.5 a	14.8 a	9.1 a	16.0 a
2 Methyl butyl acetate	479.9 a	704.7 a	680.5 a	989.7 a
Methyl hexanoate	107.4 a	98.9 a	170.9 a	159.8 a
Total concentration	4035.6 a	4975.0 a	7386.6 a	8680.4 a
Total odour units	365457a	469990a	524537a	676820a

During 14 days at 20°C following harvest, DI fruit were firmer than CI fruit on Days 2 and 6 but they had similar firmness on Day 14 (Table 9.3). There was no irrigation effect on fruit TA but fruit TSS was higher in DI than in CI throughout the period (Table 9.3). Fruit IEC was similar on Day 2 but DI fruit had higher IEC than CI fruit thereafter (Table 9.3). "Percent ripening fruit" was also similar on Day 2, DI had higher "percent ripening fruit" than CI on Day 6, but all fruit were ripe in both treatments on Day 14 (Table 9.3). Fruit SPI was lower in DI than in CI on Day 2 but from there on DI and CI fruit had similar values (Table 9.3).

Table 9.3 Internal ethylene concentration (IEC), "percent ripening fruit", starch pattern index (SPI), flesh firmness, total soluble solids (TSS) and titratable acidity (TA) during 14 days of storage at 20°C for 'Braeburn' apple under different irrigation treatments: CI = commercially irrigated control and DI = deficit irrigation. Comparison was made within each sampling date. Values across the row followed by different letters were significantly different at $P < 0.05$.

Attribute	**Day 2**		**Day 6**		**Day 14**	
	CI	DI	CI	DI	CI	DI
IEC ($\mu L\ L^{-1}$)	0.42 a	0.39 a	82.8 b	131.9 a	595.5 b	823.1 a
% ripening fruit	15.6 a	3.1 a	85.0 b	100.0 a	100.0 a	100.0 a
SPI	3.1 a	2.7 b	3.8 a	3.7 a	6.0 a	6.0 a
Firmness (N)	78.9 b	84.4 a	75.6 b	80.5 a	56.6 a	56.2 a
TSS (%)	12.0 b	12.9 a	12.5 b	13.2 a	13.1 b	13.8 a
TA (% malic acid)	0.72 a	0.73 a	0.71 a	0.70 a	0.59 a	0.60 a

During 14 days at 20°C, total volatile concentration and total odour units were similar for CI and DI on Day 2. The values increased from Day 2 to Day 6, with both values being higher in DI. The values decreased from Day 6 to Day 14 and total volatile concentration became similar for CI and DI but total odour units remained higher in DI (Table 9.4). DI fruit also had higher concentrations of some individual volatile compounds than CI fruit, most of which occurred on Day 6 except for 2- methyl butyl acetate on Day 2 and *trans*-2-hexenal on Day 14 (Table 9.4).

Table 9.4 Concentrations of aroma volatiles (μmol L^{-1}) and total odour units in juice during 14 days of storage at 20°C for 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control and DI = deficit irrigation. Comparison was made within each sampling date. Values across the row followed by different letters were significantly different at $P < 0.05$.

Volatiles	**Day 2**		**Day 6**		**Day 14**	
	CI	DI	CI	DI	CI	DI
Alcohols						
Propan-1-ol	117.9 a	123.1 a	279.1 b	516.0 a	317.6 a	394.5 a
Butan-1-ol	1063.2 a	954.4 a	3344.4 b	4733.8 a	2429.5 a	2515.5 a
Pentan-1-ol	43.1 a	40.2 a	116.3 a	102.2 a	34.8 a	33.2 a
Hexanol-1-ol	122.6 a	117.6 a	248.5 a	325.9 a	127.8 a	131.5 a
2&3 Methyl butan-1-ol	397.6 a	429.8 a	525.9 b	1080.1 a	188.1 a	189.1 a
Aldehydes						
Hexanal	279.5 a	283.3 a	371.5 a	441.1 a	123.2 a	123.3 a
trans-2-hexenal	1284.8 a	1490.8 a	1088.2 b	2197.8 a	469.5 b	617.4 a
Ethyl esters						
Ethyl propionate	96.2 a	78.2 a	237.1 a	216.0 a	160.4 a	165.0 a
Ethyl butanoate	54.0 a	50.2 a	104.2 a	94.2 a	46.1 a	42.5 a
Ethyl-2-methyl butanoate	2.4 a	3.7 a	71.1 b	135.3 a	9.6 a	13.0 a
Ethyl pentanoate	221.3 a	184.6 a	231.2 a	233.9 a	54.3 a	59.7 a
Ethyl hexanoate	16.3 a	18.5 a	42.2 b	68.7 a	20.9 a	22.4 a
Non-ethyl esters						
Propyl acetate	79.7 a	113.7 a	118.3 b	211.5 a	101.5 a	113.0 a
Butyl acetate	282.6 a	347.9 a	608.6 a	831.1 a	248.6 a	227.5 a
Pentyl acetate	58.2 a	56.7 a	77.1 a	99.7 a	18.8 a	17.8 a
Hexyl acetate	43.3 a	46.9 a	103.6 b	134.4 a	159.5 a	137.1 a
Propyl butanoate	9.9 a	16.7 a	40.6 b	66.1 a	264.1 a	206.8 a
2 Methyl butyl acetate	611.1 b	860.7 a	917.4 a	1350.5 a	281.8 a	311.9 a
Methyl hexanoate	159.8 a	149.6 a	189.9 a	208.0 a	73.4 a	73.3 a
Total concentration	4943.3 a	5366.5 a	8705.1 b	13056.2 a	5107.1 a	5416.8 a
Total odour units	446555a	514128a	1330360b	2202683a	396353b	458496a

During seven days at 20°C after cold storage, SPI value reached the maximum (SPI = 6) for all fruit because most starch had been converted to sugars and the remaining starch was too low to be detected with iodine solution. All fruit were ripe ("percent ripening fruit" = 100) in all treatments. Flesh firmness and TA were similar for DI and CI but DI fruit had higher TSS at both sampling dates (Days 1 and 7) and higher IEC on Day 7 (Table 9.5).

Table 9.5 Internal ethylene concentration (IEC), flesh firmness, total soluble solids (TSS) and titratable acidity (TA) on Day 1 and Day 7 at 20°C following 17 weeks at 0°C for 'Braeburn' apple grown under different irrigation and crop load treatments. Irrigation treatments were: CI = commercially irrigated control and DI = deficit irrigation. Crop load treatments were: CCL = commercial crop load and LCL = light crop load. Comparison was made within each main effect 'Irrigation' and 'Crop load'. Values across the row followed by different letters were significantly different at $P < 0.05$.

Fruit attribute	**Irrigation treatment**		**Crop load treatment**	
	CI	DI	CCL	LCL
Day 1				
IEC (μL L^{-1})	147.7 a	167.5 a	137.6 a	177.6 a
Firmness (N)	62.8 a	64.6 a	65.2 a	62.1 a
TSS (%)	13.2 b	14.0 a	13.4 b	13.8 a
TA (% malic acid)	0.60 a	0.63 a	0.61 a	0.61 a
Day 7				
IEC (μL L^{-1})	412.0 b	526.7 a	446.3 a	492.4 a
Firmness (N)	58.4 a	58.8 a	58.8 a	58.4 a
TSS (%)	13.4 b	14.1 a	13.7 a	13.8 a
TA (% malic acid)	0.56 a	0.55 a	0.56 a	0.55 a

On Day 1 during seven days at 20°C after cold storage, total volatile concentration and total odour units were higher in DI than in CI fruit. The values decreased from Day 1 to Day 7 and total volatile concentrations became similar for CI and DI but total odour units remained higher in DI fruit (Table 9.6). DI fruit also had higher concentrations of some

individual volatile compounds than CI fruit, most of which occurred on Day 1 except for *trans*-2-hexenal, ethyl-2-methyl butanoate, and 2 methyl butyl acetate which were higher in DI fruit and for butyl acetate which was higher in CI fruit on Day 7 (Table 9.6).

Table 9.6 Concentrations of aroma volatiles (μmol L^{-1}) and total odour units in juice on Day 1 and Day 7 at 20°C following 17 weeks at 0°C for 'Braeburn' apple from different irrigation treatments: CI = commercially irrigated control and DI = deficit irrigation. Comparison was made within each sampling date. Values across the row followed by different letter were significantly different at $P < 0.05$.

Volatiles	**Day 1**		**Day 7**	
	CI	DI	CI	DI
Alcohols				
Propan-1-ol	310.1 b	629.8 a	321.7 a	423.3 a
Butan-1-ol	3520.4 b	5168.4 a	2541.3 a	2667.5 a
Pentan-1-ol	122.3 a	102.4 a	35.0 a	31.9 a
Hexanol-1-ol	208.5 a	187.0 a	146.4 a	144.5 a
2&3 Methyl butan-1-ol	584.2 b	973.7 a	202.7 a	170.9 a
Aldehydes				
Hexanal	285.8 a	369.9 a	104.1 a	101.4 a
trans-2-hexenal	1341.1 b	2050.7 a	353.4 b	673.9 a
Ethyl esters				
Ethyl propionate	279.6 a	227.5 a	169.7 a	182.0 a
Ethyl butanoate	104.9 a	81.4 a	50.0 a	39.7 a
Ethyl-2-methyl butanoate	59.5 b	116.0 a	5.1 b	11.7 a
Ethyl pentanoate	331.9 a	276.0 a	80.7 a	83.8 a
Ethyl hexanoate	33.8 b	53.0 a	41.8 a	37.9 a
Non-ethyl esters				
Propyl acetate	101.8 a	166.3 a	97.2 a	111.7 a
Butyl acetate	403.0 b	773.1 a	274.5 a	251.1 b
Pentyl acetate	82.9 a	84.4 a	24.8 a	23.0 a
Hexyl acetate	72.4 b	99.9 a	166.5 a	186.8 a
Propyl butanoate	13.7 a	24.1 a	303.0 a	281.6 a
2 Methyl butyl acetate	995.8 b	1504.3 a	563.6 b	880.5 a
Methyl hexanoate	197.0 a	214.6 a	86.4 a	85.6 a
Total concentration	9066.3 b	13084.9 a	5568.2 a	6388.7 a
Total odour units	1236270b	1965738a	446976b	590160a

Although CI and DI fruit had similar maturity at harvest, during subsequent storage at 20°C (Day 6) and after cold storage (Day 7), DI fruit became more advanced in maturity than CI fruit. As fruit matured, TSS increased while firmness and TA decreased. The consistently lower fruit TSS in CI, even at harvest when CI and DI fruit had similar maturity, was due to dilution effect as DI fruit had higher dry matter concentration (DMC) than CI fruit. The DMC (mg g^{-1}, $LSD_{0.05}$ = 2.4) were 118.3 and 121.1 for, respectively, CI and DI fruit harvested at 187 DAFB; the correspondent values for fruit harvested at 202 DAFB were 119.7 and 123.6 ($LSD_{0.05}$ = 2.2). The firmer fruit in DI than in CI at harvest and during the early period of storage at 20°C could be due to decreased cellular hydration in DI fruit. This advantage for DI was lost during the later period of storage at 20°C and after cold storage because of the advanced ripening of DI fruit during these periods.

Increase production of most volatiles coincides with an increase in ethylene production of the fruit (Song and Bangerth, 1996) with production decreasing as fruit senesce (Paillard, 1990; Dirinck et al., 1989). This is confirmed by our results. The increased total volatile concentration in DI fruit during ripening observed was due, in part, to the more advanced maturity of DI compared to CI fruit. Behboudian et al. (1998) found higher total volatile concentration in fruit from late-season DI than in CI fruit. In contrast, results from the other experiment of this thesis presented in Chapter 4 showed no difference in total volatile concentration between CI and DI fruit. In Chapter 4, total volatile concentration at harvest was higher than in this experiment and in the study of Behboudian et al. (1998) which could be because the fruit were more mature as the assessments were done five days after harvest. Because DI fruit ripen more quickly than CI fruit, it is expected that total volatile concentration would reach the maximum earlier in DI than in CI fruit. It is therefore speculated that, during the assessments in Chapter 4, total volatile concentration for DI might be in the declining phase while it might still be at the maximum for CI.

In addition to concentration, each volatile compound varies in contribution to fruit aroma due to its odour threshold and sensory characteristics (Dixon, 1999). For example, volatile compounds that have very low odour threshold but potent aroma characteristics, such as ethyl-2-methyl butanoate, are considered important for typical apple aroma (Flath

et al., 1967). *Trans*-2-hexenal is considered important in contribution to the aroma intensity (Dürr and Schobinger, 1981). Therefore, the proportion of certain volatile compounds produced by the fruit is more important than the total volatile concentration which may not necessarily reflect the highest aroma. Therefore odour units have been used extensively in applied flavour research (Frijters, 1979). Total odour units increased when total volatile concentration increased in DI. Moreover, during late period of ripening when total volatile concentration decreased in both CI and DI to similar levels, total odour units were still higher in DI (Tables 9.4 and 9.6). Therefore, in addition to difference in maturation and ripening, there could be other mechanisms modified under DI that altered the proportion of volatile compounds produced by the fruit and/or lost from the fruit. This possibility deserves investigation. Although, by definition, odour units of a mixture is the sum of odour units of individual compounds, total odour units may not necessarily describe odour quality of a mixture. Therefore, sensory evaluation is required to confirm the impact of DI on fruit aroma.

Fruit from LCL trees were firmer than from CCL trees at both harvests (Table 9.7). During 14 days of storage at 20°C, LCL fruit were firmer on Day 2 but LCL and CCL fruit had similar firmness on Day 6 and 14 (Table 9.8) and also after cold storage (Table 9.5). Fruit TSS was higher in LCL at Harvest 1 (Table 9.7) and on Day 1 at 20°C after cold storage (Table 9.5). Crop load had no effects on fruit TA, aroma volatiles, IEC, "percent ripening fruit", or SPI at any assessment date (Tables 9.5, 9.7, and 9.8).

Literature information on the effects of crop load on fruit TSS is not conclusive. Tough et al. (1998) observed higher TSS in 'Braeburn' apple from light cropping trees whereas Opara and Tadesse (2000) found no consistent effect of crop load on TSS for 'Pacific Rose' apple. Possible reasons are differences in time of thinning, cultivar, and levels of crop load.

Table 9.7 Internal ethylene concentration (IEC), "percent ripening fruit", starch pattern index (SPI), flesh firmness, total soluble solids (TSS), titratable acidity (TA), total volatile concentration (TVC), and total odour units at harvest for 'Braeburn' apple grown under different crop load treatments: CCL = commercial crop load and LCL = light crop load. Comparison was made within each harvest. Values across the row followed by different letters were significantly different at $P < 0.05$.

Fruit attribute	**Harvest 1**		**Harvest 3**	
	CCL	LCL	CCL	LCL
IEC ($\mu L\ L^{-1}$)	0.31 a	0.32 a	1.68 a	1.16 a
% ripening fruit	0.0 a	0.0 a	15.6 a	9.4 a
SPI	2.1 a	2.6 a	2.8 a	2.9 a
Firmness (N)	90.6 b	92.3 a	86.7 b	88.2 a
TSS (%)	11.9 b	12.2 a	12.4 a	12.6 a
TA (% malic acid)	0.75 a	0.76 a	0.71 a	0.72 a
TVC ($\mu mol\ L^{-1}$)	4839.3 a	4171.3 a	8550.0 a	7517.0 a
Total odour units	435132 a	400315 a	632005 a	569352 a

Table 9.8 Internal ethylene concentration (IEC), % ripening fruit, starch pattern index (SPI), flesh firmness, total soluble solids (TSS), titratable acidity (TA), total volatile concentration (TVC), and total odour units during 14 days of storage at 20°C for 'Braeburn' apple grown under different crop load treatments. The treatments were CCL = commercial crop load and LCL = light crop load. Comparison was made within each sampling date. Values across the row followed by different letters were significantly different at $P < 0.05$.

Attribute	**Day 2**		**Day 6**		**Day 14**	
	CCL	LCL	CCL	LCL	CCL	LCL
IEC ($\mu L\ L^{-1}$)	0.38a	0.44a	94.2 a	120.4 a	710.2 a	708.4 a
% ripening fruit	6.3 a	12.5 a	92.5 a	92.5 a	100.0 a	100.0 a
SPI	3.0 a	2.8 a	3.7 a	3.8 a	6.0 a	6.0 a
Firmness (N)	80.9 b	82.4 a	78.4 a	77.7 a	56.2 a	56.7 a
TSS (%)	12.3 a	12.5 a	12.8 a	12.9 a	13.5 a	13.5 a
TA (% malic acid)	0.71a	0.75a	0.71a	0.71a	0.58a	0.60a
TVC ($\mu mol\ L^{-1}$)	5477.0 a	4832.9 a	11340.0 a	10422.0 a	4911.6 a	5612.3 a
Total odour units	514712 a	445971 a	1708475 a	1824568 a	415632 a	439216 a

Increased firmness for LCL fruit observed at harvest (Table 9.7) could be due to higher cellular density. Values of fruit density (g cm^{-3}, $LSD_{0.05} = 0.015$) at Harvest 1 were 0.89 and 0.87 for LCL and CCL, respectively. However, the increased firmness in LCL at harvest disappeared during storage (Table 9.8) and after cold storage (Table 9.5). Increased fruit firmness at harvest with light crop loads was observed in 'Cox's Orange Pippin' by Johnson (1994) and in 'Braeburn' by Tough et al. (1998). Firmness of LCL fruit decreased at a faster rate (Johnson, 1994) and became similar to that of CCL fruit after storage (Tough et al., 1998; Johnson, 1994). Johnson (1995) suggested that the loss of this advantage from LCL during and after storage probably relate to enhanced maturity of LCL fruit. However, we found no difference in maturity between LCL and CCL fruit at any assessment date. The differing effects of crop load on fruit maturity could be due to different levels and times of thinning. While fruit from early-thinned trees (at full bloom or 5 DAFB) were more mature than fruit from unthinned trees, later thinning had no clear effect on fruit maturity (Johnson, 1995).

9.3.2 Relationships between maturity attributes and maturity-related quality attributes

Fruit TSS, TA, firmness, and aroma volatiles, the "maturity-related quality" attributes, change in association with maturation and ripening. Except for aroma volatiles which require more sophisticated analysis, these attributes are often used as maturity indices to identify optimum harvest time. Many workers have agreed that IEC can be used as an indicator of fruit physiological maturity (e.g. Beaudry et al., 1993; Johnson, 1995; Plotto et al., 1995). The IEC value of a fruit that has passed climacteric rise may increase several folds resulting in a substantially high average value for the whole group. "Percent ripening fruit" was therefore integrated as another maturity index.

In the univariate relationship, correlation between individual maturity-related quality attributes and individual maturity attributes were considered. Firmness was highly correlated with SPI (-0.95), "percent ripening fruit" (-0.85), and IEC (-0.82). There were also good correlations between TA and SPI (-0.86), "percent ripening fruit" (-0.73), and IEC (-0.71). Moderate correlations existed between TSS and SPI (0.68), "percent

ripening fruit" (0.66), and IEC (0.58). However, total odour units was poorly correlated with IEC (-0.16), SPI (0.17), or "percent ripening fruit" (0.44).

It can be expected that each quality attribute contributes to overall fruit quality collectively rather than individually. The same applies to maturity attributes. Therefore in addition to relationships between each pair of individual attributes, it is appropriate to investigate interrelationships between the two sets of attributes. Canonical correlation, the procedure used to determine relationships between two sets of attributes (Manly, 1994) was used in this study to examine the relationships between maturity-related quality attributes and maturity attributes. The "likelihood ratio test" suggested that the first two canonical correlation were significant (P = 0.0001) in explaining the relationships between the two sets of attributes. Both canonical correlation were high and positive being 0.98 and 0.77, respectively. The canonical variates associated with the first canonical correlation explained about 95% of the variation and those associated with the second canonical correlation explained about 59% of the variation. The canonical variates represent underlying dimensions that identify structural relationships between the two data sets. These dimensions can be described in terms of the contribution from each of the original attributes (Manly, 1994). The first canonical variate of the maturity-related quality attributes (QUALITY I) correlated highly with firmness, TSS, and TA while the corresponding maturity canonical variate (MATURITY I) was correlated with all the three maturity attributes (Table 9.9). In contrast, the second canonical variate of the maturity-related quality attributes (QUALITY II) correlated highly with total odour units while the corresponding canonical variate of maturity attributes (MATURITY II) was correlated with IEC and "percent ripening fruit" (Table 9.9).

From these results we could interpret that QUALITY I (the quality dimension of taste and texture) was correlated with all the "maturity" attributes i.e. IEC, "percent ripening fruit", and SPI as reflected in MATURITY I. The quality dimension of aroma, QUALITY II, showed some correlation with IEC and "percent ripening fruit" but not with SPI as reflected in MATURITY II.

Table 9.9 Canonical correlation between individual original attributes and their canonical variates for 'Braeburn' apple

Original attributes	"Maturity-related quality" canonical variates		Original attributes	"Maturity" canonical variates	
	QUALITY I	QUALITY II		MATURITY I	MATURITY II
Firmness	-0.98	0.15	IEC	0.81	-0.45
TSS	0.72	0.02	% ripening fruit	0.93	0.32
TA	-0.87	0.18	SPI	0.99	-0.06
Aroma	0.22	0.97			

In addition to relationships between the two sets of attributes, canonical correlation analysis can also be used to examine how well the data of one set of attributes can be used to explain the variation in the other set of attributes. Results from canonical redundancy analysis indicated that maturity-related quality attributes could be used to explain the variation in maturity attributes better than using maturity attributes to explain the variation in maturity-related quality attributes. About 85% of the variation in the maturity data could be explained by the first two canonical variates of the maturity-related quality attributes (79% by QUALITY I and 6% by QUALITY II). Whereas about 69% of the variation in the maturity-related quality data could be explained by the first two canonical variates of the maturity attributes (54% by MATURITY I and 15% by MATURITY II).

Compared to other maturity-related quality attributes, lower correlation between aroma and the maturity attributes could be because the response of aroma to maturity is not continuous in one direction. While firmness and TA decrease and TSS increases as fruit mature and ripen, aroma increases as fruit mature and ripen reaching a maximum then decreases.

Results obtained when canonical correlation analyses were made separately for data assessed during 14 days of storage at 20°C (data not shown) were somewhat similar to

the results when combined data were used. However, both univariate correlation and multivariate correlation were lower when analyses were made separately for data assessed at harvest and for data assessed after cold storage (data not shown) than when combined data were used. This indicated that correlation between maturity attributes and maturity-related quality attributes increased as variation in fruit ripeness increased.

9.4 Summary

Deficit irrigation enhanced aroma volatiles quantitatively in terms of concentration and qualitatively in terms of odour units. Crop load had no effect on aroma volatile production. The enhancement of volatile production in DI was related, in part, to the advancement in ripening of DI fruit. However, univariate correlation for aroma volatiles and each of the individual maturity attributes was low. Nevertheless, there was high multivariate correlation between maturity-related quality attributes and maturity attributes. Canonical correlation analysis effectively described their relationships and variability with two underlying dimensions. There is potential to use data from one set of attributes to explain the variation in data for the other set of attributes.

Acknowledgements

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SECTION FOUR

DEFICIT IRRIGATION AND FRUIT MATURITY

This section covers Chapters 10 and 11. Chapter 10 presents background information for Chapter 11 as well as identifying the areas of knowledge which need further research regarding deficit irrigation and fruit maturity.

In Chapter 11, the effect of DI on fruit maturation and ripening which is not the main focus in the former chapters are presented and discussed. Results from two experiments are combined in order to explore the timing effects of DI on this aspect. Experiment 1, which involves early-season and late-season DI, was conducted on field-grown apple in Marlborough region during 1997/98 growing season (the same experiment as that for Chapter 4). Experiment 2, which involves whole-season DI, was conducted on field-grown apple in Manawatu region during 1998/99 growing season (the same experiment as that for Chapters 7, 8, and 9). Relationships between fruit maturity and fruit quality as affected by DI are also discussed. Fruit IEC, "percent ripening fruit", and SPI are used as maturity indices. Fruit quality attributes investigated include firmness, TSS, TA, and skin colour.

Chapter Ten: Literature Review

Deficit Irrigation and Fruit Maturity

10.1 Introduction

Fruit quality and storage potential is highly dependent on fruit maturity at harvest. Fruit harvested too early will not develop full quality potential after harvest and can undergo shrivel and excessive weight loss during storage. On the other hand, over-mature fruit usually do not store well as they are more susceptible to bruising, physiological disorders and are prone to excessive ripening resulting in a great loss of firmness (Beaudry et al., 1993). It is therefore essential to identify a harvest period that optimises the relationship between increasing eating quality and decreasing storage potential. Most quality attributes involving eating quality and storage potential such as total soluble solids (TSS), acidity, skin colour, starch content, and firmness change as fruit mature and ripen and are therefore often used as maturity indices. Because such maturity-related quality attributes like firmness, skin colour, and TSS may be altered under water deficit conditions (Chapter 3, section 3.3), the target values of these indices for optimum harvest period of fruit under DI may be different from well-watered fruit. To maximise the beneficial effects of DI, there is need to identify the optimum harvest period for DI fruit. This requires an understanding of DI effects on fruit maturation and ripening characteristics and the relationships between fruit maturity and fruit quality as affected by DI.

10.2 Physiological maturity, ripening, and senescence

A fruit is physiologically mature when the stage is set for ripening to ensue. Ripening is the process by which physiologically mature fruit are transformed from a relatively unfavorable to a favorable condition with respect to taste, texture, colour, and aroma. In apple, ripening can occur while the fruit is still attached to the tree or after harvest but in both cases the fruit has to be physiologically mature. Senescence is a series of endogenously controlled deteriorating changes that result in the natural death of cells, tissues, organs, and organisms. Ripening is therefore a transition phase between maturity and senescence and all changes that occur during ripening lead to senescence.

10.3 Maturity indices

Various fruit quality attributes such as TSS, TA, flesh firmness, skin colour, and starch content change in association with fruit maturation and ripening and hence are often used as maturity indices to identify optimum harvest time. During fruit development and maturation, TSS increases with concomitant decreases in firmness and in concentrations of starch and acids (Smock and Neubert, 1950). As fruit mature, background skin colour changes from green to yellow due to chlorophyll breakdown and unmasking of carotenoids (Gorski and Creasy, 1977). In addition to fruit maturity, these maturity-related quality attributes are also influenced by several other factors. For example, skin colour is determined by light interception, temperature, and fruit nutrients (Daugaard and Grauslund, 1999). Firmness is partly determined by the ratio of dry matter (cell wall material) to that of cell volume; and TSS is influenced by amount of water in the fruit or dry matter content (Atkinson et al., 1995). Hence, they are not necessarily good indicators of physiological maturity especially to be used to compare maturity among fruit that have been exposed to different growing conditions. A higher TSS in DI fruit than in well-watered fruit often occurs at an early stage well before fruit maturation as exemplified by Asian pears (Behboudian et al., 1994) and apple (Proebsting et al., 1984; Kilili et al., 1996a). In apple, while TSS was higher in fruit from non-irrigated trees indicating their more advanced maturity, these fruit were firmer than fruit from well-watered trees which suggested the opposite (Kilili et al., 1996b).

Apple fruit are climacteric (Biale and Young, 1981), characterised by transient increases in ethylene synthesis at an early stage of ripening. Fruit ripening processes are initiated when ethylene concentration in the fruit increases (Sfakiotakis and Dilley, 1973). Development of desirable taste and aromatic flavour, colour changes, and softening are associated with the climacteric cycle (Biale and Young, 1981). Fruit enter the ripe edible stage at or shortly after the climacteric peak. Therefore, internal ethylene concentration (IEC) and/or rate of ethylene production is a useful indicator of physiological maturity of the fruit (Fidler and North, 1971; Wills et al., 1997). Many workers have agreed that IEC can be used as fruit maturity indicator successfully (e.g. Liu, 1986; Beaudry et al., 1993; Johnson, 1995). Good correlation between IEC or rate of ethylene production and starch pattern index (SPI, an indicator of starch content), fruit weight, background colour,

firmness, and TSS has been observed (Walsh and Altman, 1993). Lau et al. (1986) and Graell et al. (1993) argued that significant changes associated with ripening such as firmness, skin colour, TSS, and starch content take place prior to a detectable increase in IEC. This raises a question whether ethylene is not involved in the changes associated with ripening or only very small undetectable amount of ethylene is required for such changes. Recent research on antisense ACC oxidase melon plants, in which ethylene production is suppressed, have shown that some processes that normally occur during maturation and ripening are ethylene-dependent and some are ethylene-independent (Pech et al., 2000). For instance, yellowing of the skin, softening, climacteric respiration, and production of aroma volatiles are clearly regulated by ethylene whereas accumulation of sugars and acids are ethylene-independent processes (Pech et al., 2000). Ethylene is therefore a good indicator of physiological maturity of the fruit. However, measurement of ethylene appears to be not a practical maturity index for growers and hence a more practical maturity index, such as those maturity-related quality attributes, which is well-correlated with ethylene is still desirable (Walsh and Altman, 1993). It is interesting to investigate whether these relationships between ethylene and maturity-related quality attributes are modified under DI.

10.4 Deficit irrigation and fruit maturity

Most studies have indicated that DI fruit are more advanced in maturity than well-watered fruit based on maturity-related quality attributes such as increased TSS and/or redder blush or more yellow background colour for DI. There are limited data available on physiological maturity of the fruit as affected by water deficit and these findings are contradictory (Ebel et al., 1993; Kilili et al., 1996b). Kilili et al. (1996b) reported that withholding irrigation late or throughout the growing season caused advanced maturity and early ripening in 'Braeburn' apple as indicated by an increased IEC but early withholding of irrigation had no effect on fruit maturity. In 'Delicious' apple, Ebel et al. (1993) reported that fruit from trees exposed to DI early in the growing season were more mature than fruit from well-watered trees as indicated by a higher IEC in DI fruit. The DI fruit also entered the logarithmic rise in ethylene evolution earlier than fruit from well-watered trees (Ebel et al., 1993).

Chapter Eleven

Effects of Deficit Irrigation on Fruit Maturity and Quality of 'Braeburn' Apple

Abstract

Effects of deficit irrigation (DI) on fruit maturity at harvest, ripening characteristics, and changes in fruit quality during and after storage of 'Braeburn' apple were studied in two experiments. In Experiment 1, irrigation treatments were a commercially irrigated control (CI), an early deficit irrigation (EDI) applied from 63 to 118 days after full bloom (DAFB), and a late deficit irrigation (LDI) applied from 118 DAFB to final harvest on 201 DAFB. Irrigation treatments in Experiment 2 were a commercially irrigated control (CI) and a whole-season deficit irrigation (WDI). These deficit irrigation treatments all reduced volumetric soil water content. The LDI and WDI advanced fruit ripening but EDI did not. All deficit irrigation treatments increased fruit total soluble solids (TSS) and firmness regardless of maturity but had little or no effect on titratable acidity. The differences in TSS started during fruit growth much earlier than the onset of ripening and were maintained during and following storage at 0°C. The differences in firmness also started during fruit growth and were maintained for at least 10 weeks of storage at 0°C. The DI fruit appeared to have a wider range of optimum harvest maturity due to their earlier increased TSS and their higher firmness before harvest and for most of the storage period.

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B. S. Mpelasoka[1], M. H. Behboudian[1] and T. M. Mills[2]

[1]Institute of Natural Resources, College of Sciences, Massey University, Palmerston North, New Zealand

[2]Environment Group, HortResearch, Palmerston North, New Zealand

11.1 Introduction

The majority (93%) of New Zealand apples is exported as fresh fruit to markets in Europe, North America, and the Asia/Pacific region. Fruit for export are stored before reaching far destinations. Consumers are increasingly demanding that stored apple more closely match the appearance, taste, and texture of freshly-harvested apple. Fruit quality after storage is largely determined by maturity at harvest. Fruit harvested too early do not develop full quality potential whereas over-mature fruit do not store well and undergo high firmness loss (Beaudry et al., 1993). The relationship between fruit maturity and fruit quality has not been researched under DI. Information on effects of DI on fruit maturation and ripening is scant and inconclusive. Kilili et al. (1996) reported that ripening is enhanced in fruit from late-season and whole-season DI treatments but not from early-season DI treatment. Ebel et al. (1993), however, reported advanced ripening in fruit from early-season DI. This study reports the effects of DI applied at different times during the growing season on changes in fruit quality during growth and maturation, on maturity at harvest, on ripening characteristics, and on changes in quality during storage at 0°C and subsequent shelf-life at 20°C.

11.2 Materials and methods

11.2.1 Experimental conditions and treatments

The study was conducted at two sites, a relatively dry region and a humid region in New Zealand. Experiment 1 was conducted during the 1997-98 growing season in a commercial orchard in Marlborough, a relatively dry region with average annual rainfall of 640 mm. Irrigation treatments were: commercially irrigated control (CI), early deficit irrigation (EDI) applied from 63 to 118 days after full bloom (DAFB), and late deficit irrigation (LDI) applied from 118 DAFB until final harvest on 201 DAFB. The CI trees were irrigated to maintain soil moisture at or close to field capacity. During deficit periods DI trees were irrigated with the same amount of water but at approximately half the frequency of CI trees. They were irrigated the same as CI trees outside the deficit periods. More details of experimental conditions and treatments are described in Chapter 4.

Experiment 2 was conducted during the 1998-99 growing season at the Fruit Crops Unit, Massey University, Palmerston North, Manawatu, a relatively humid region with average annual rainfall of 960 mm. Irrigation treatments were commercially irrigated control (CI) and whole-season deficit irrigation (WDI). The CI trees were irrigated to maintain soil moisture at or close to field capacity. Due to the rainy conditions, soil in the WDI plots was covered with clear polythene from 12 DAFB to exclude rainfall. The WDI trees were irrigated only twice during the late growing season when volumetric soil water content (θ) fell below 0.15 m^3 m^{-3}. More details of experimental conditions and treatments are described in Chapter 7 where WDI was referred to as DI.

11.2.2 Measurements of fruit quality during fruit growth

Changes in fruit quality during growth were assessed in Experiment 2 at seven sampling dates prior to commercial harvest from 80 to 170 DAFB using 16 fruit per replicate for each sampling date. Fruit were randomly sampled from outer and mid-canopy positions.

11.2.3 Fruit harvest, sampling, and assessments of fruit maturity and quality

Fruit were picked at three commercial harvests on 180, 192, and 201 DAFB in Experiment 1 and on 187, 196, and 202 DAFB in Experiment 2. In both experiments, fruit samples for assessments of maturity and quality were randomly selected from different weight groups of each tree with equal number of fruit from each group. The weight groups were 131-160 g, 161-190 g, and 191-240 g for Experiment 1 and were 161-190 g and 191-240 g for Experiment 2.

Assessments of fruit maturity and quality at each commercial harvest were made on 60 fruit per replicate for Experiment 1 and on 16 fruit per replicate for Experiment 2. Changes in fruit quality during cold storage were assessed only in Experiment 2 at six sampling dates from 2 to 17 weeks after storage at 0°C, using fruit harvested at 202 DAFB with 16 fruit per replicate for each sampling date. Fruit maturity and quality after cold storage for Experiment 1 were assessed after 7-day shelf-life at 20°C following 12 weeks at 0°C, using 30 fruit per replicate harvested at 201 DAFB. Fruit maturity and quality after cold storage for Experiment 2 were assessed at three sampling dates during 7-days shelf-life at 20°C following 17 weeks at 0°C, using fruit harvested at 202 DAFB with 8 fruit per replicate for each sampling date. Ripening characteristics were investigated only in Experiment 2 at

seven sampling dates during 14 days at 20°C after fruit harvest, using fruit harvested at 196 DAFB with 8 fruit per replicate for each sampling date.

Procedures for the assessments of each maturity and quality attribute are described in Chapter 2 (sections 2.6 and 2.7). "Percent ripening fruit" was defined as percentage of fruit with an IEC greater than 1 μL L^{-1} (Lau and Lane, 1998).

11.2.4 Statistical analysis

Data were averaged for each replicate and were analysed for analysis of variance as a randomised complete block design with four blocks (replicates). Comparison of means was performed using t-tests.

11.3 Results

11.3.1 Fruit quality during fruit growth

During fruit growth in Experiment 2, flesh firmness and TA decreased whereas TSS and SPI increased in both CI and WDI fruit (Figure 11.1). TheWDI fruit were firmer than control fruit at all sampling dates and had higher TSS from 108 DAFB (Figure 11.1). Neither TA nor SPI were affected (data not shown).

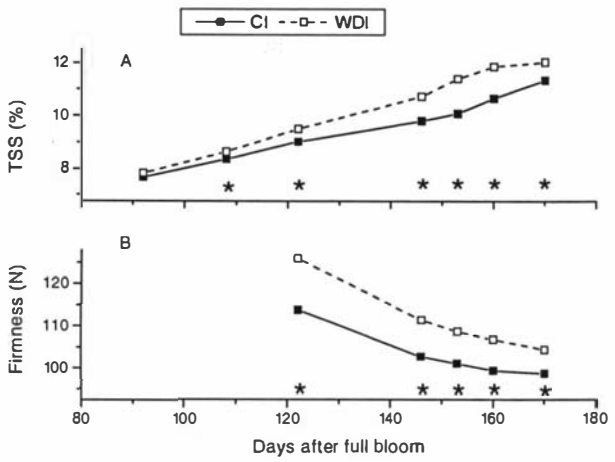

Figure 11.1 Experiment 2: Total soluble solids (TSS) (A) and flesh firmness (B) during fruit growth in 'Braeburn' apple under different irrigation treatments. The treatments were CI = commercially irrigated control and WDI = whole-season deficit irrigation. Asterisks represent significant differences ($P < 0.05$).

11.3.2 Fruit maturity and quality at commercial harvests

In Experiment 1, LDI advanced the rise in IEC, which was accompanied by higher SPI, "percent ripening fruit", and TSS (Table 11.1). Both EDI and LDI increased fruit firmness (Table 11.1). Early deficit irrigation also had higher TSS than control fruit but had little effect on other attributes (Table 11.1).

Table 11.1 Experiment 1: Starch pattern index (SPI), internal ethylene concentration (IEC) ($\mu L\ L^{-1}$), "percent ripening fruit" (%RF), flesh firmness (N), total soluble solids (TSS) (%), and titratable acidity (TA, expressed as % malic acid) at commercial harvests for 'Braeburn' apple from different treatments. The treatments were CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Within each harvest, values across the row followed by different letters are significantly different at $P < 0.05$. 'NA' means not available.

Attribute	**Harvest 1** (180 DAFB)			**Harvest 2** (192 DAFB)			**Harvest 3** (201 DAFB)		
	CI	EDI	LDI	CI	EDI	LDI	CI	EDI	LDI
SPI	3.0 b	2.7 b	3.7 a	3.1 b	2.9 b	3.9 a	3.9ab	3.6 b	4.6 a
IEC	1.07a	0.46a	3.35a	1.62a	0.32a	3.84a	1.08b	0.52b	4.22a
%RF	12.3 b	10.0 b	22.1 a	14.5 b	10.0 c	20.4 a	13.8 b	12.1 b	35.7 a
Firmness	84.8 c	91.8 a	88.2 b	82.9 b	89.1 a	87.3 a	82.5 b	88.9 a	87.1 a
TSS	10.6 b	11.9 a	11.9 a	11.7 b	13.0 a	13.0 a	13.3 b	14.3 a	14.2 a
TA	NA	NA	NA	NA	NA	NA	0.69b	0.79a	0.72ab

In Experiment 2, WDI had little or no effect on IEC, SPI, "percent ripening fruit", or TA but increased fruit firmness and TSS (Table 11.2). Irrigation treatments did not affect fruit skin colour in either experiment (data not shown).

Table 11.2 Experiment 2: Starch pattern index (SPI), internal ethylene concentration (IEC) (μL L^{-1}), "percent ripening fruit" (%RF), flesh firmness (N), total soluble solids (TSS) (%), and titratable acidity (TA, % malic acid) at commercial harvests for 'Braeburn' apple from different treatments. The treatments were CI = commercially irrigated control and WDI = whole-season deficit irrigation. Within each harvest, values across the row followed by different letters are significantly different at $P < 0.05$.

Fruit attribute	**Harvest 1** (187 DAFB)		**Harvest 2** (196 DAFB)		**Harvest 3** (202 DAFB)	
	CI	WDI	CI	WDI	CI	WDI
SPI	2.2 a	2.5 a	2.7 a	2.5 a	2.9 a	2.8 a
IEC	0.33a	0.31a	0.36a	0.32b	1.76a	1.08a
% RF	0.0 a	0.0 a	0.0 a	0.0 a	18.8 a	6.3 b
Firmness	90.2 b	92.8 a	87.9 b	92.4 a	85.6 b	89.3 a
TSS	11.8 b	12.3 a	12.1 b	12.8 a	12.2 b	12.8 a
TA	0.76a	0.75a	0.74a	0.73a	0.71a	0.72a

11.3.3 Fruit quality during cold storage

In Experiment 2, WDI fruit had higher TSS throughout and were firmer than CI fruit for at least 10 weeks (Figure 11.2) with little or no effect on TA or SPI (data not shown).

11.3.4 Fruit quality after cold storage

In Experiment 1, after 7-days shelf life at 20°C following 12 weeks at 0°C, both EDI and LDI fruit had higher IEC, which was accompanied by higher TSS, than control fruit (Table 11.3). However, fruit firmness remained higher in both EDI and LDI fruit (Table 11.3).

In Experiment 2, during 7-days shelf life at 20°C following 17 weeks at 0°C, IEC and TSS were higher in WDI fruit but firmness and TA were similar between WDI and control fruit (Table 11.4).

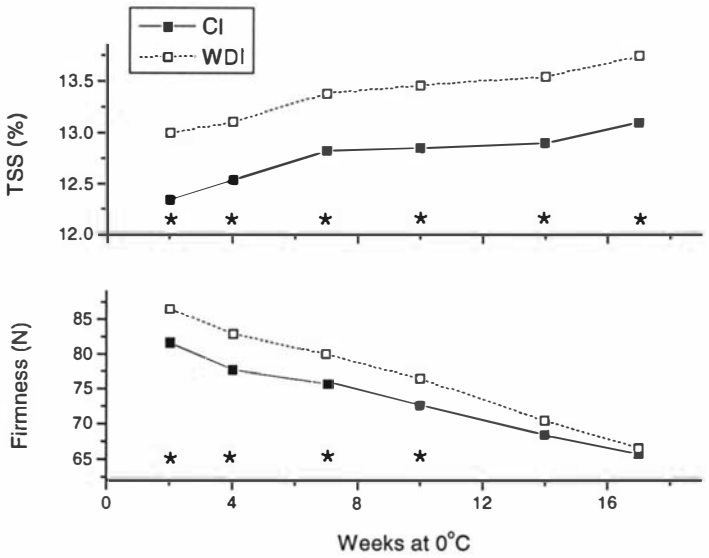

Figure 11.2 Experiment 2: Total soluble solids (TSS) (A) and flesh firmness (B) during storage at 0°C for 'Braeburn' apple under different irrigation treatments. The treatments were CI = commercially irrigated control and WDI = whole-season deficit irrigation. Asterisks represent significant differences ($P < 0.05$).

Table 11.3 Experiment 1: Fruit internal ethylene concentration (IEC), flesh firmness, total soluble solids (TSS), and titratable acidity (TA) after seven days shelf life at 20°C following 12 weeks at 0°C for 'Braeburn' apple under different irrigation treatments. The treatments were CI = commercially irrigated control, EDI = early deficit irrigation, and LDI = late deficit irrigation. Values in a column followed by different letters are significantly different at $P < 0.05$.

Treatment	IEC ($\mu L\ L^{-1}$)	Firmness (N)	TSS (%)	TA (% malic acid)
CI	303.5 b	66.6 b	14.3 b	0.59 a
EDI	418.4 a	70.8 a	14.9 a	0.60 a
LDI	422.2 a	70.1 a	14.9 a	0.60 a

Table 11.4 Experiment 2: Fruit internal ethylene concentration (IEC), flesh firmness, total soluble solids (TSS), and titratable acidity (TA) during 7 days at 20°C following 12 weeks at 0°C for 'Braeburn' apple from different irrigation treatments. The treatments were CI = commercially irrigated control and WDI = whole-season deficit irrigation. Comparison was made for each measurement dates. Within each day, values across the row followed by different letters are significantly different at $P < 0.05$.

Quality attributes	Day 1		Day 4		Day 7	
	CI	WDI	CI	WDI	CI	WDI
IEC ($\mu L\ L^{-1}$)	147.7a	167.5a	230.3b	307.5a	412.0b	526.7a
Firmness (N)	62.8a	64.6a	60.1a	61.2a	58.4a	58.8a
TSS (%)	13.2b	14.0a	13.4b	14.1a	13.4b	14.1a
TA (%malic acid)	0.60a	0.63a	0.60a	0.60a	0.55a	0.56a

11.3.5 Fruit ripening characteristics

In Experiment 2, during 14 days at 20°C after fruit harvest, WDI advanced the rise in IEC and "percent ripening fruit", which was accompanied by higher TSS (Figure 11.3). However, WDI fruit were firmer than control fruit for at least eight days (Figure 11.3). Fruit SPI and TA were generally not affected except that control fruit had higher SPI during the first two days (Figure 11.3).

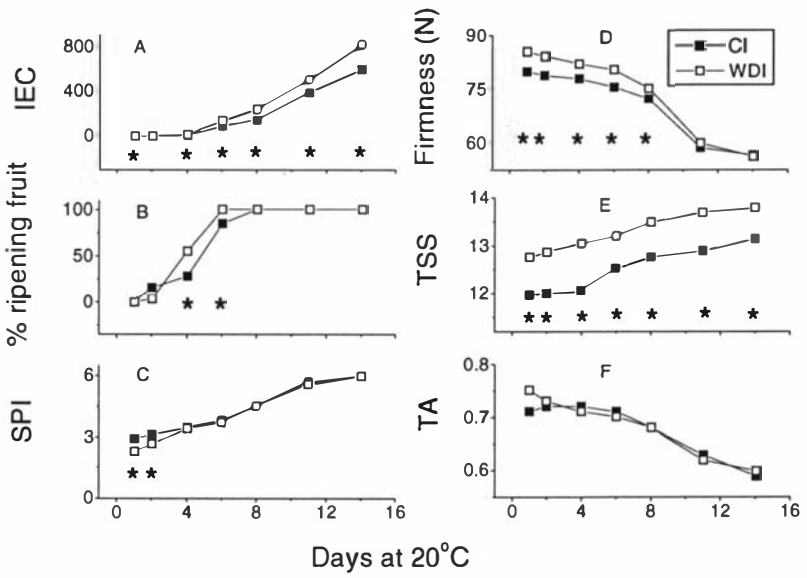

Figure 11.3 Experiment 2: Internal ethylene concentration (IEC, μL L^{-1}) (A), "percent ripening fruit" (fruit with IEC > 1 μL L^{-1}) (B), starch pattern index (SPI) (C), flesh firmness (D), total soluble solids (TSS, %) (E), and titratable acidity (TA) expressed as % malic acid (F) during 14 days at 20°C for 'Braeburn' apple under different irrigation treatments. The treatments were CI = commercially irrigated control and WDI = whole-season deficit irrigation. Asterisks represent significant differences ($P < 0.05$).

11.4 Discussion

Effects of DI on fruit maturation and ripening depended on timing of application with late-season and whole-season DI advanced fruit ripening but early-season DI did not. Kilili et al. (1996b) observed advanced fruit ripening in 'Braeburn' apple from late-season and whole-season DI but not from early-season DI. Ebel et al. (1993) reported that fruit ripening of 'Delicious' apple was more advanced in early-season DI than in control irrigation. Although DI was applied for 12 weeks early in the season in the latter study, soil moisture became lower in DI than in control from eight weeks after the imposition of DI and remained lower until harvest even after irrigation was resumed. Their DI treatment may therefore be similar to our LDI or WDI treatments and achieved the same results.

Differences in fruit quality between DI and control fruit are not solely due to the advanced ripening of DI fruit. Increased TSS in DI fruit was observed as early as 108 DAFB, well before the onset of fruit ripening. All the DI treatments increased both TSS and firmness at harvest despite differences in harvest maturity. Sugars are the major component of soluble solids (Wills et al., 1997). Fruit sugars were higher in all DI treatments than in CI treatment ($P < 0.05$). Total sugar concentrations (TSC, mg g^{-1} FW) at harvest in Experiment 1 were 82.5, 97.5, and 95.6 for CI, EDI, and LDI fruit, respectively. In Experiment 2 they were 84.9 and 89.2 for CI and WDI fruit, respectively. Dry matter concentration (DMC) was also higher in DI fruit than in CI fruit ($P < 0.05$). The values (mg g^{-1}) at harvest in Experiment 1 were 141.5, 154.1, and 150.6 for CI, EDI, and LDI fruit, respectively. In Experiment 2 they were 118.3 and 121.1 for CI and WDI fruit, respectively. The lower TSC and TSS of CI fruit could therefore be due to a dilution effect. Osmotic adjustment was observed in DI fruit (Chapter 7), therefore increased TSC in DI fruit could be the mechanism for osmotic adjustment. Smaller fruit are firmer than larger fruit (Chapter 4). However, here, quality was assessed using fruit of similar sizes with equal number of fruit from each size. The firmer fruit in DI than in CI was due to decreased cellular hydration in DI fruit. Irrigation did not affect fruit skin colour in this study. Literature information regarding effects of DI on fruit skin colour is inconclusive because fruit skin colour is determined by several factors as has been discussed in Chapters 4 and 8.

Firmness, TSS, SPI, and background skin colour are commonly used in commercial practice to monitor fruit maturity and to determine optimum harvest time. This study confirms that DI increases firmness and TSS. As fruit mature and ripen, starch degrades resulting in increased SPI. Fruit SPI was lower in WDI than in CI when their IEC were similar (Fig. 11.3: Day 2) and when IEC was higher in WDI than in CI, their SPI were similar (Fig. 11.3: from Day 4) suggesting that increase in SPI was slower in DI fruit. This slower increase in SPI could be due to a higher initial starch concentration in the DI fruit. Although Fan et al. (1995) reported that SPI did not relate well to starch concentration, Brookfield et al. (1997) observed delayed increase in SPI at higher starch concentrations. Apple fruit from DI trees have higher starch concentration (Powell, 1976) and increase in SPI begins later in the DI fruit (Ebel et al., 1993). It is also possible that the higher TSS in

DI fruit may be sufficient to maintain accelerated respiratory rate in ripening fruit leading to delayed starch hydrolysis (Ebel et al., 1993).

11.5 Summary

This research showed that DI has effects on fruit maturation and ripening depending on timing of application. The LDI and WDI advanced fruit ripening whereas EDI did not. Quality enhancement by DI in terms of increased TSS and firmness are not solely through advanced ripening of DI fruit. The advanced ripening of the DI fruit is, however, responsible for the loss of advantage by DI regarding firmness after long term storage. The DI fruit may be harvested over a longer period due to their earlier increased TSS and their higher firmness prior to harvest and for most of the storage period.

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SECTION FIVE

GENERAL DISCUSIION, CONCLUSIONS, AND RECOMMENDATIONS

This section covers Chapter 12 which addresses general discussion and conclusions of all the studies involved in this thesis as well as recommendations for future research.

Chapter Twelve

General Discussion, Conclusions, and Recommendations

12.1 General discussion and conclusions

Allocation of water for agriculture has decreased and will continue to decrease due to the increased demand for water as a result of population growth and industrial development. Water pollution and climate change characterised by the frequent occurrence of drought also serves to make water an increasingly precious and limited resource (Kirda and Kanber, 1999). Irrigation management aiming at efficient use of water has therefore become a high priority. Deficit irrigation is one such option. To maximise the efficiency of DI, a comprehensive understanding of its impact on tree water use, yield, and fruit quality together with plant mechanisms behind such responses is required. The primary objective of this study was to investigate the impact of DI on tree water use, water relations parameters, growth, yield, and fruit quality. Under-researched aspects of fruit quality such as aroma volatiles, fruit maturity, physiological disorders, and storage potential were included. Since DI often reduces fruit size, relationships between fruit size and quality were addressed in order to confirm DI effects. Interactions between irrigation and crop load on the aforementioned parameters were investigated in order to explore the possibility of integrating light crop load with DI to increase fruit size. Possible mechanisms for fruit size regulation were explored. It can be expected that each quality attribute contributes to overall fruit quality collectively rather than individually. Therefore, multivariate analysis was also included in this study to explore interrelationships among various quality attributes and to explore the impact of treatments on the overall fruit quality along with individual quality attributes.

Three experiments were conducted: one on lysimeter-grown trees and two on field-grown trees (Experiments 1 and 2). Experiment 1 was conducted in Marlborough region during the 1997/98 growing season and Experiment 2 in Manawatu region during the 1998/99 growing season. For the lysimeter experiment, late-season DI was applied from 115 DAFB until final harvest on 187 DAFB. Two crop load treatments, commercial crop

load (CCL) and a lighter crop load (LCL) equivalent to 60% of CCL, were used. Experiment 1 (in Marlborough) involved early-season DI applied from 63 to 118 DAFB and late-season DI applied from 118 DAFB until final harvest on 201 DAFB. Experiment 2 (in Manawatu) involved whole-season DI with two crop load treatments: CCL and LCL (67% of CCL). The DI treatments were studied in comparison with control irrigation or commercially irrigated control (CI) in all experiments.

Tree water use was investigated in the lysimeter experiment which was conducted in Manawatu region, a relatively humid area of New Zealand, where irrigation is predominantly applied during late summer when rainfall is low and therefore late-season DI was applied. During the irrigation treatment period of 10 weeks, DI trees were irrigated at approximately 40% of CI trees. Tree water use per unit leaf during this period was about 20% less in DI than in CI, indicating a more efficient use of irrigation water in DI. In peach, DI trees used 30-50% less water than CI trees (Boland et al., 1993). A smaller reduction in tree water use observed in this study could be due to the lower evaporative demand in the experimental area. In addition to water saving, drainage seldom occurred in DI. This would have positive impact on the environment as groundwater pollution is minimised. Reduced tree water use for DI was attributed to reduced stomatal conductance.

Trees with light crop load used about 15% less water than trees with commercial crop load. Higher water use at commercial crop load is not closely related to stomatal conductance. Since water contributes to 84-87% of the fruit weight, more sink (fruit) demand for water could contribute to a higher water use in trees with commercial crop load. Fruit transpiration is usually small compared to leaves, however, whether or not fruit transpiration is modified by crop load deserves investigation.

Deficit irrigation applied at any time during the growing season had negative influence on fruit growth. Proportion of smaller fruit tended to be higher in DI whereas that of larger fruit tended to be higher in CI. Mean fruit weight at harvest was lower in DI than in CI in all experiments. Although the lower mean fruit weight at harvest for EDI and LDI in field Experiment 1 was not statistically significant, the reduction was about 16% of CI. Lack of significance for this reduction was due to large variation in the data,

which was probably caused by the biennial bearing habit of the trees. Other studies in this laboratory showed no effect of late-season DI on fruit size (Kilili et al., 1996a; Mills et al., 1996). These studies were conducted in Manawatu region which is a relatively humid area in New Zealand. There is the possibility that greater impact of LDI on fruit size in field Experiment 1 was due to the drier condition with higher evaporative demand of the atmosphere in Marlborough region. The greater impact of late-season DI on fruit size for the lysimeter experiment, which was conducted in Manawatu region, could be due to restricted soil and thus less water volume in the lysimeters.

Fruit size reduction by DI was counteracted by a lighter crop load, and therefore there was no difference in mean fruit weight at harvest between CI and DI at light crop load but DI fruit were smaller at commercial crop load. The interaction of DI and crop load on photosynthesis, fruit water potential, and fruit turgor potential are possible mechanisms for this counteraction. These parameters were generally lower in CCL under DI but were similar between CCL and LCL under CI. Increased weight loss and incidence of bitter pit during storage in light crop load may, however, limit its application. 'Braeburn' is a large-size cultivar and although DI reduced mean fruit weight at harvest, the size of DI fruit still met standard export requirements.

Among the quality attributes investigated, only firmness and dry matter concentration were influenced by fruit size with their values being higher in smaller fruit. When comparing fruit of similar sizes, fruit quality improvement by DI was consistent in terms of increased total soluble solids, total sugar concentration, dry matter concentration, and firmness. Fruit density was higher in DI in one experiment. Quality improvement by DI was partly due to the advanced ripening of DI fruit. For example, in one experiment, enhanced production of aroma volatiles was observed in DI during ripening as a result of the more advanced ripening of the DI fruit. This also suggested that the inconsistency of research results regarding DI effects on aroma volatiles (Behboudian et al., 1998 and Chapter 4 of this thesis) could be due to differences in maturity of fruit samples during the assessments. This study showed that DI also enhanced aroma volatiles qualitatively by increasing total odour units even in the occasions where the total volatile concentrations were similar between CI and DI. The possibility that DI modified some mechanisms resulting in alteration of the proportion of volatile compounds produced by

the fruit and/or lost from the fruit deserves investigation. Increased TSS in DI was observed as early as 108 DAFB, well before fruit maturation. Firmness and TSS are important quality components and they change in association with fruit maturation and ripening. They are therefore often used as maturity indices. As fruit mature, TSS increases whereas firmness decreases. While TSS was higher in DI fruit, firmness was also higher in DI fruit in most occasions. This confirmed that enhanced quality by DI was not solely through advanced ripening of DI fruit. This advanced ripening of DI fruit is, however, responsible for the loss of advantage by DI regarding flesh firmness after long term storage. Sugars are the major components of soluble solids (Wills et al., 1997) and therefore the observed increase in soluble sugars was responsible for increased TSS in DI fruit. Increased fruit soluble sugars for DI could be the mechanism for osmotic adjustment in fruit under reduced water status. The dilution effect also contributed to lower TSS and firmness for CI fruit.

Important fruit factors determining storage potential include rates of weight loss and firmness loss and incidence of physiological disorders during storage. There was no effect of DI on incidence of physiological disorders. Loss of firmness was greater in DI fruit due to their advanced ripening but DI fruit were still firmer than CI fruit after 12 weeks of cold storage in two experiments and at least for 10 weeks of cold storage in the other experiment. Physiological basis of the advanced ripening by late-season and whole-season DI deserves investigation. Fruit weight loss during storage, investigated in two experiments, was lower in DI in both experiments but the difference was less significant in one experiment. There is possibility that DI might have modified structure, composition, or thickness of fruit skin or cuticle that covers the skin, which act as barrier to water vapour movement. This possibility deserves investigation. Increased storage potential for DI fruit has great benefit because apple fruit are often subjected to some period of storage before reaching consumers, especially those for export.

Apart from the enhancement on individual quality attributes, DI also improved overall fruit quality when many quality attributes were considered collectively. This was true both at harvest and after storage.

Overall, this study demonstrates that DI has a great potential as an irrigation strategy in sustainable apple production to save water, minimise groundwater pollution, and improve fruit quality.

12.2 Recommendations for future research

This study opens various channels through which future research may be directed. These include:

1) the study of the physiological basis for the differences in fruit water loss during storage, flesh firmness, and proportion of volatile compounds observed between DI fruit and fruit from control irrigation,

2) sensory evaluation to confirm the impact of deficit irrigation on fruit aroma to consumers,

3) the study of the physiological basis for the advanced ripening of DI fruit and the study to examine optimum harvest time for apple orchards where DI is practised,

4) the study to examine the responses of DI fruit in terms of changes in fruit quality in controlled atmosphere storage,

5) fruit transpiration in response to irrigation and to crop load, and

6) studies aimed at a more precise recommendation of the timing of DI and the degree of water deficit developed that will maximise the beneficial effects of DI on fruit quality improvement without or with minimum adverse effects on yield and fruit size. This may involves irrigation/crop response modelling. Crop response includes, for example, plant water status, growth, yield, and fruit quality.

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APPENDIX

Odour threshold (ppm in water) of each volatile compound

Volatile compound	Odour threshold	References
Alcohols		
Propan-1-ol	9	Flath et al. (1967)
Butan-1-ol	0.5	Flath et al. (1967)
Hexanol-1-ol	0.5	Flath et al. (1967)
2&3 Methyl butan-1-ol	0.25	Buttery (1973)
Aldehydes		
Hexanal	0.005	Paillard (1990)
trans-2-hexenal	0.017	Flath et al. (1967)
Ethyl esters		
Ethyl propionate	0.01	Teranishi et al. (1987)
Ethyl butanoate	0.001	Takeoka et al. (1995)
Ethyl-2-methyl butanoate	0.0001	Flath et al. (1967)
Ethyl pentanoate	0.005	Flath et al. (1967)
Ethyl hexanoate	0.001	Takeoka et al. (1995)
Non-ethyl esters		
Propyl acetate	2	Takeoka et al. (1995)
Butyl acetate	0.066	Takeoka et al. (1995)
Pentyl acetate	0.005	Teranishi et al. (1987)
Hexyl acetate	0.002	Flath et al. (1967)
Propyl butanoate	0.018	Teranishi et al. (1987)
2 Methyl butyl acetate	0.005	Teranishi et al. (1987)
Methyl hexanoate	0.07	Kollmannsberger and Berger (1992)