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

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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 lost 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
°C	Degree celcius
Ca ²⁺	Calcium
CCL	Commercial crop load
CI	Commercially irrigated control
C _i	Intercellular CO ₂ concentration (μmol 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 (°)
HPLC	High performance liquid chromatography
HPV	Heat-pulse velocity
hr	Hour
I	Irrigation volume (L d ⁻¹)
IEC	Internal ethylene concentration (μL 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
<i>P</i>	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	Titrateable 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 ($\text{m}^3 \text{m}^{-3}$)
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)