The original publication is available at: https://www.actahort.org/books/1314/1314_2.htm
DOI: https://doi.org/10.17660/ActaHortic.2021.1314.2

Sensing fruit and tree performance under deficit irrigation in 'September Bright' nectarine

Mark O'Connell* and Alessio Scalisi

Agriculture Victoria, Tatura, VIC, 3616, Australia

Abstract

In the face of increased demand for food combined with water scarcity under changing climate, improvements are required in irrigation management and orchard production systems to meet consumer expectations of high-quality fruit. This study examined fruit and tree performance of 'September Bright' nectarine subjected to deficit irrigation in a modern high-density orchard. A deficit irrigation experiment was conducted over three consecutive seasons at Tatura, Australia. During fruit growth stage I, II and III, discrete irrigation levels were applied: 0, 20, 40 and 100% of crop evapotranspiration (ET_c). Trunk diameter, leaf photosynthetic performance (efficiency of photosystem II), leaf fluorescence, leaf chlorophyll concentration, leaf conductance, canopy light interception and harvested fruit yield and quality (size, colour, sweetness, maturity) of individual fruit were measured. Our findings showed that deficit irrigation had a significant effect on these fruit quality and tree parameters. Overall, yield and fruit quality was maintained at 40% ET_c during stage II, however, yield and fruit size were reduced in both stage I and III under 40% ET_c regimes. More severe deficits penalised yield and fruit size, irrespective of fruit growth stage timing. Relationships between key fruit and tree metrics, physiological responses and utility of sensing instruments and platforms for precision orchard irrigation management are discussed.

Keywords: drought stress, fruit size, *in situ* sensing, IoT, Open Tatura, *Prunus persica* (L.) Batsch, tree size.

Introduction

In Australia, production horticulture is dependent on irrigation in temperate climates. Increased demand for food combined with water scarcity under changing climate requires industry to improve irrigation efficiency and orchard production systems to meet consumer expectations of high-quality fruit and maintain a social licence to operate.

To deliver consistent high marketable yields and improve production efficiency, precision horticulture solutions are required to counter spatial and temporal effects of cultivar, orchard characteristics, weather, soil type and agronomic practices. Ideally, precision orchard management applies sensor systems for the assessment of fruit and tree performance to inform growers to monitor and/or adjust agronomic practices within a growing season. Nowadays, a range of sensors and platforms are available to measure *in situ* fruit ripening and quality (size, maturity, colour, sweetness) and tree performance (canopy size, leaf nitrogen, leaf gas exchange). Likewise, at harvest, commercial fruit graders record yield, fruit quality and defects. Together these sensors confer benefits of large sample size, and more detailed spatial and temporal scale information for improved horticultural outcomes compared to traditional, labour-intensive, small sample size and often ad-hoc measures or casual observations.

Improved water management is required to counter drought and water scarcity (Goodwin and O'Connell, 2017). However, in stonefruit, there is a lack of scientific information of the effects on fruit quality under water deficit (Fernandes-Silva et al., 2018). The effect of drought stress and recovery on stonefruit production varies with severity, duration and timing of water deficit. Typically, fruit size is reduced under water deficit, with concentration of soluble solids and effects on other important fruit quality parameters (e.g. maturity, firmness, skin colour) less well understood (Lopresti et al., 2014). This paper presents a study on sensing fruit and tree performance under deficit irrigation in 'September Bright' nectarine. Relationships between key fruit and tree metrics, physiological

*Email: mark.oconnell@agriculture.vic.gov.au

The original publication is available at: https://www.actahort.org/books/1314/1314_2.htm
DOI: https://doi.org/10.17660/ActaHortic.2021.1314.2

responses and utility of sensing instruments and platforms for precision orchard management are discussed.

Material and methods

Experiment conditions

The experiment was conducted on 3-year-old nectarine trees (*Prunus persica* L. Batsch 'September Bright') grafted on 'Elberta' rootstock trained to an open Tatura system (2,222 tree/ha) during 2016/17, 2017/18 and 2018/19 growing seasons at Tatura (36.43°S, 145.28°E, elev. 114 m) in SE Australia. Climate is temperate, and rainfall is evenly distributed throughout the year. Irrigation is used to counter the high evaporative demand experienced in summer months. Between-row and between-tree spacings were 4.5 and 1.0 m, respectively, in North-South tree rows of a 3-ha experimental stonefruit orchard. Trees were fertilised, pruned, and pest/disease managed according to established local commercial practices. Fruiting levels were set to represent grower 'best practice' to maximise fruit size and fruit sweetness. The target cropping level of ~1 fruit per 10 cm of fruiting lateral, whereby fruit (fruit < 12 mm diameter) were manually thinned early in the season to maximise cell number and final fruit size.

Irrigation treatments

Experimental layout was a randomised block design with 12 irrigation treatments replicated 6 times. Each plot consisted of three adjacent rows of eighteen trees. The central 2 trees in each plot were used to record measurements of study variables. Irrigation requirements (crop evapotranspiration, ET_c) were determined using a weather-based evapotranspiration FAO-56 approach with a crop coefficient adjusted for tree size, measured as the fractional photosynthetically active radiation (PAR) interception (f_{PAR}) (Scalisi et al., 2019). Irrigation was applied daily via a single drip line comprising of in-line pressure compensating emitters (1.6 l/h discharge, 0.5 m spacing). Four irrigation levels were applied as fractions of ET_c: (i) control (100% ET_c), (ii) moderate deficit (40% ET_c), (iii) severe deficit (20% ET_c) and (iv) rainfed (no irrigation, 0% ET_c) during fruit growth Stage I (cell division), Stage II (commencement of pit hardening, slow fruit growth), Stage IIIa (cell expansion) and Stage IIIb (fruit maturation).

In situ *fruit size, leaf fluorescence, stomatal conductance and efficiency of photosystem II*

At the end of each fruit growth stage period, fruit diameter was measured on 5 fruit/tree on a weekly basis using a Bluetooth digital calliper (OriginCal® smart caliper, *iGaging,* San Clemente, California, USA) connected to a smartphone. Leaf anthocyanin indices (Multiplex® Force-A fluorometer, Orsay, France), chlorophyll concentration (SPAD 502 plus chlorophyll meter, Konica Minolta Inc., Osaka, Japan) and stomatal conductance (AP4 leaf porometer; Delta-T Devices Ltd, Cambridge, UK) were measured on 3–5 leaves/tree. The efficiency of photosystem II (ΦPSII) was measured on 3 leaves/tree at stages I, IIIa and IIIb, using a photosynthesis system (LI-6400XT, LI-COR Inc., Lincoln, USA).

Yield and fruit quality at harvest

Fruit maturity was determined from measurements of chlorophyll content (index of absorbance, I_{AD}) using a portable Vis/NIR spectrophotometer (DA-meter; Model 53500, TR Turoni, Italy). To determine optimal harvest date, fruit maturity was measured on duplicate (both hemispheres) samples *in situ* of ~20 fruit on the control trees at weekly intervals for 4 weeks prior to harvest. At harvest, all fruit for each of the 2 trees per plot was handpicked. Fruit weight, number, internal quality (maturity, firmness, sweetness) and external attributes (colour, blemish) were measured on each individual fruit and sorted on a tree-by-tree (2 trees/plot) basis using a commercial fruit grader equipped with optical sensors (Compac InVision 9000, Compac Sorting Equipment Ltd, Australia) and a near infra-red (NIR) reflectance spectrometer (Taste Technologies Ltd, New Zealand). A total of 16,191, 22,382 and 19,779 nectarines were assessed for 2016/17, 2017/18 and 2018/19 growing seasons, respectively. Fruit-size and quality distributions were determined from data sets obtained by the commercial grading machine. Yield was calculated as the product of fruit number and weight. The NIR spectrum (~30 scans per fruit) over the spectral range of 300–1100 nm was used to develop multivariate prediction models for sweetness (soluble solid concentration, SSC), maturity and firmness. Fruit NIR reference data were collected using the conventional destructive methods with local duplicate (paired hemispheres) measures (sample size ~125 fruit/season) to extend model application to the experimental data. Fruit flesh firmness (kgf) was measured after exposing the flesh to a penetrometer (Model FT10, Wagner Instruments, Connecticut, USA) fitted with an 8 mm tip. Fruit SSC was measured using a digital refractometer (Model PR-1, Atago Co., Japan). Fruit maturity (I_{AD}) was measured using a DA-meter. Premium packout was calculated the proportion of individual fruit meeting a 5-level threshold criteria of fruit quality (fruit weight ≥ 85 g and SSC ≥ 14 °Brix and 5 kgf ≥ firmness ≥ 6 kgf and $0.8 \geq I_{AD} \geq 1.2$ and red skin colour ≥ 50%).

Tree growth and phenology

Pruning biomass (winter and summer), bud break and floral development stages were measured on each plot. Seasonal change of trunk cross-sectional area (TCSA, cm^2) was calculated from trunk diameter measures using digital Bluetooth calipers at 15 cm above the graft union on each tree within a plot during winter prior to the commencement of the deficit irrigation treatments and again in the winter dormancy after harvest. Canopy size was represented in terms of f_{PAR}. Measurements of f_{PAR}) were carried out during summer (i.e. in the period of maximum foliage cover) on a clear day using a handheld ceptometer (Model SF80; Decagon Devices Inc., Pullman, Washington, USA) and a light trolley (Tranzflo NZ Ltd, Palmerston North, New Zealand) at 09.30, 12.30 (solar noon) and 15.30 h. f_{PAR} was calculated as: $f_{PAR} = 1\text{-}(PAR_T/PAR)$, where PAR was the incident flux of PAR measured above the canopy (i.e. an open region within the orchard), and PAR_T was the transmitted flux of PAR measured at the base of the canopy. Within each plot, the ceptometer was placed horizontally perpendicular to the row direction in the shaded and non-shaded area. Estimates of f_{PAR} were obtained from ~10 and ~200 PAR measurements above and below the canopy in each plot, respectively. Daily f_{PAR} was calculated as the mean of f_{PAR} at 09.30, 12.30 and 15.30 h (Goodwin et al., 2006).

Data was subject to analysis of variance (ANOVA) using GenStat 18.1 (VSN International Limited, Oxford, UK). Significant differences between treatments were determined using Fisher's unrestricted Least Significant Difference at $P = 0.05$.

Results

Figure 1 shows average fruit number per tree, yield, fruit quality (final fresh weight, sweetness, firmness) and premium packout under deficit irrigation regimes compared to the control (100% ET_c) for seasons 2016/17–2018/19. Yield penalties occurred on all deficit treatments except stage II 40% ET_c. Final fruit weight was reduced under severe deficit (0 and 20% ET_c) regimes irrespective of fruit growth stage. Greater fruit sweetness and higher red skin colour was observed under stage IIIb (0 and 20% ET_c) deficit irrigation treatments. Premium packout was reduced under deficit irrigation regimes during stage I and III periods, whilst, stage II 40% ET_c showed improved production outcomes.

Table 1 provides a summary of fruit and tree growth and production responses to deficit irrigation treatments for each fruit growth stage. Organ growth and yield components were impacted by water stress, however, phenology and TSCA were not influenced by irrigation regime. Pruning biomass, lateral strength (diameter, length) and floral behaviour (floral dry weight, abundance) was reduced under severe deficit irrigation regimes. Canopy radiation interception (f_{PAR}), leaf conductance, leaf chlorophyll concentration and photosystem II efficiency were reduced under deficit irrigation. Leaf anthocyanin levels increased on deficit irrigated trees. Fruit maturity (firmness, I_{AD}) was delayed under stage IIIb deficit irrigation.

Table 2 shows the utility of precision horticulture sensors and platforms used to measure fruit and tree performance. The index ranking is based on assessment of equipment and methods in terms of robustness, efficiency, accuracy, user friendliness, cost, maintenance and capacity of sensor to communicate wirelessly (i.e. IoT smart sensor) and ability to capture temporal and spatial variation in crop response to (drought) stress. Overall, very few sensors and platforms make the grade of a 'smart sensor'.

The original publication is available at: https://www.actahort.org/books/1314/1314_2.htm
DOI: https://doi.org/10.17660/ActaHortic.2021.1314.2

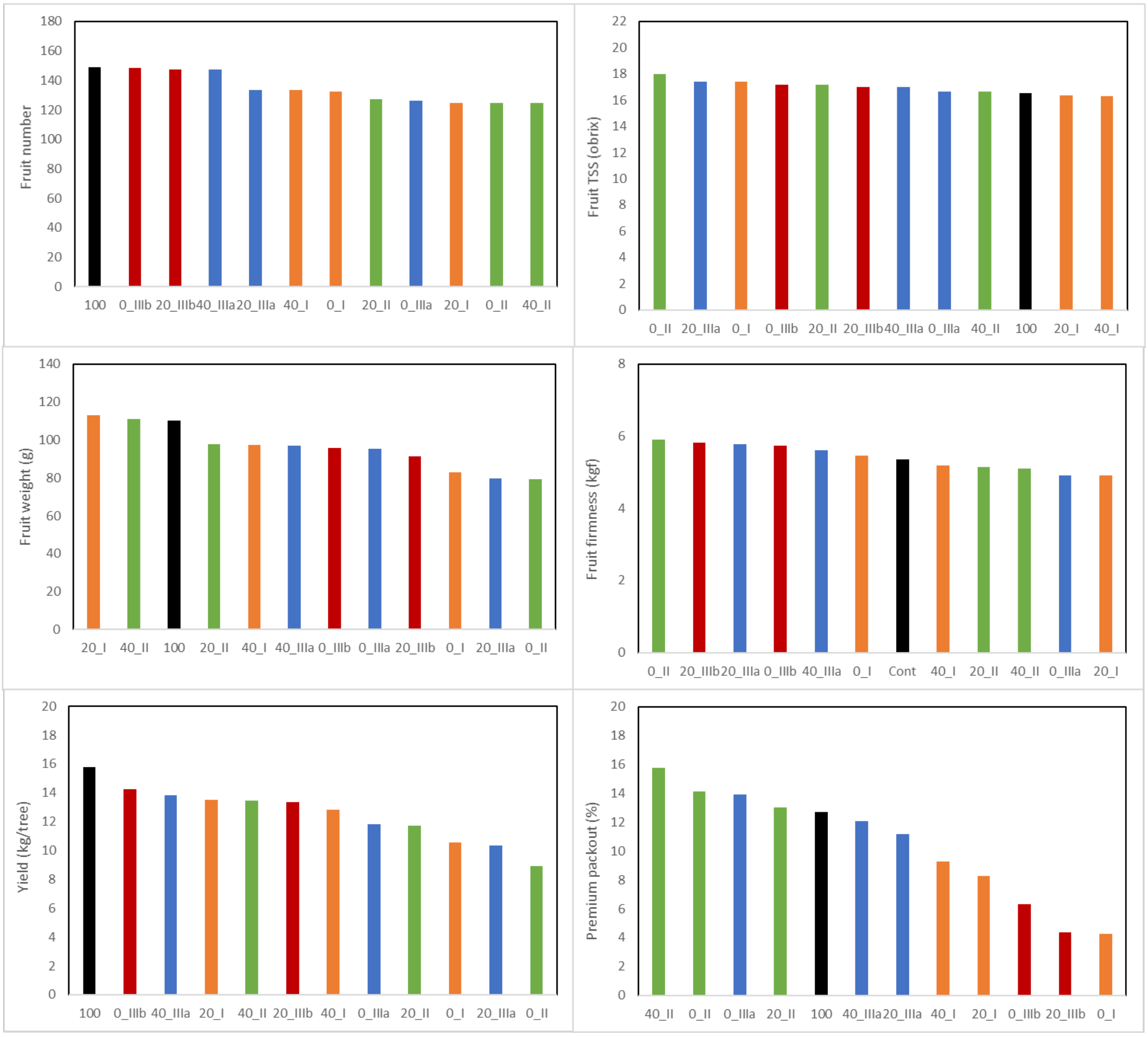

Figure 1. Average fruit number, yield, fruit quality (fresh weight, sweetness, firmness) and premium packout under deficit irrigation regimes of ‘September Bright’ nectarine for seasons 2016/17–2018/19. Bar colours are grouped by deficit irrigation treatments x fruit growth stage.

The original publication is available at: https://www.actahort.org/books/1314/1314_2.htm
DOI: https://doi.org/10.17660/ActaHortic.2021.1314.2

Table 1. Summary of fruit and tree responses to deficit irrigation (0, 20, 40% ET_c) compared to the control (100% ET_c) during fruit growth stages (I, II, IIIa, IIIb) for growing seasons 2016/17 – 2018/19 on 'September Bright' nectarine.

Response	**Parameter**	**I**	**II**	**IIIa**	**IIIb**
Phenology	Phenology	=	=	=	=
Yield components	Final fruit number	=	=	↓ 20	=
Yield components	Final fruit weight	↓ 0	=	↓ 0, 20, 40	↓ 0, 20
Yield components	Yield	↓ 0, 20, 40	↓ 0, 20	↓ 0, 20, 40	↓ 0, 20
Yield components	Final fruit sweetness	=	=	=	↑ 0, 20
Yield components	Final fruit maturity	=	↓ 0, 20	↓ 0, 20	↑ 0, 20
Yield components	Final fruit firmness	=	=	↓ 0, 20, 40	↑ 0, 20
Yield components	Final fruit colour redness	↓ 0, 40	=	=	↑ 0, 20
Plant water stress	Leaf conductance	nd	↓ 0, 20, 40	↓ 0, 20, 40	nd
Plant water stress	Efficiency of PSII	nd	nd	↓ 0, 20, 40	nd
Plant water stress	Leaf anthocyanin	nd	nd	↑ 0, 20	nd
Plant water stress	Leaf chlorophyll conc.	nd	↓ 0, 20	↓ 0, 20	nd
Canopy size	f_{PAR}	↓ 0, 20, 40	↓ 0, 20, 40	↓ 0, 20	=
Organ Growth	TCSA	=	=	=	=
Organ Growth	Winter pruning biomass	↓ 0, 20	↓ 0, 20	↓ 0, 20	↓ 0
Organ Growth	Summer pruning biomass	↓ 0	↓ 0, 20, 40	=	=
Organ Growth	Lateral diameter	↓ 0	↓ 0	↓ 20	↓ 20
Organ Growth	Lateral length	↓ 0, 20	↓ 0, 20	↓ 0, 20	↓ 20
Organ Growth	Flower per foot shoot	↑ 0	↑ 20	=	=
Organ Growth	Total floral buds	=	↓ 0, 20	↓ 0, 20	=
Organ Growth	Total vegetative buds	=	↓ 0, 20 ↑ 40	=	=
Organ Growth	Floral bud dry weight	=	↓ 0, 20	↓ 0, 20, 40	↓ 0, 20
Organ Growth	Vegetative bud d.w.	=	=	=	=

Key: 0, 20 and 40 depict deficit (0, 20, 40% ET_c) irrigation treatments, nd - not determined. ↑, ↓ and = represent increase, decrease and not significant responses relative to control (100% ET_c) irrigation treatment, respectively at a probability of $P \geq 0.05$.

Table 2. Utility of precision horticulture sensors and platforms used to measure fruit and tree performance. Index ranking based on equipment and method with consideration of factors such as sensor/technique: robust, efficient, sample size, accurate, user friendly, spatial and temporal scale, cost, maintenance and connectivity (e.g. IoT smart sensor).

Parameter	**Technology**	**Robust**	**Non-destructive**	**User friendly**	**Sample size**	**Spatial scale**	**Temporal scale**	**IoT**	**User skill**	**Sensor cost**	**Overall score**
Trunk diameter	Digital caliper	Yes	Yes	Yes	Medium	Tree	Seasonal	Yes	Low	Low	High
Fruit diameter	Digital caliper	Yes	Yes	Yes	Medium	Fruit	Weekly	Yes	Low	Low	High
Fruit number	Fruit grader- load cell	Yes	Yes	Yes	Large	Fruit	Seasonal	No	Medium	High	High
Fruit weight	Fruit grader- load cell	Yes	Yes	Yes	Large	Fruit	Seasonal	No	Medium	High	High
Fruit sweetness	Fruit grader-NIR	Yes	Yes	Yes	Large	Fruit	Seasonal	No	High	High	High
Fruit maturity	Fruit grader-NIR	Yes	Yes	Yes	Large	Fruit	Seasonal	No	High	High	High
Fruit firmness	Fruit grader-NIR	Yes	Yes	Yes	Large	Fruit	Seasonal	No	High	High	High
Fruit colour	Fruit grader- RGB camera	Yes	Yes	Yes	Large	Fruit	Seasonal	No	Medium	High	High
Light interception	Ceptometer, light trolley	Yes	Yes	No	Medium	Tree	Monthly	Yes	Medium	High	High
Irrigation volume	Water flow meter	Yes	Yes	Yes	Small	Orchard	Daily	Yes	Low	Low	Medium
Fruit chlorophyll	DA meter	Yes	Yes	Yes	Medium	Fruit	Weekly	No	Medium	Medium	Medium
Leaf anthocyanin	Fluorometer	Yes	Yes	No	Small	Leaf	Monthly	No	Medium	High	Medium
Leaf chlorophyll	SPAD meter	Yes	Yes	No	Medium	Leaf	Monthly	No	Medium	High	Medium
Leaf conductance	Porometer	Yes	Yes	No	Small	Leaf	Monthly	No	High	High	Low
Leaf PSII efficiency	LICOR	No	Yes	No	Small	Leaf	Monthly	No	High	High	Low
Pruning biomass	Digital scales	Yes	No	No	Medium	Tree	Seasonal	No	Low	N/A	Low
Lateral strength	Digital scales, caliper	Yes	No	No	Medium	Shoot	Seasonal	No	Low	N/A	Low
Phenology	Visual observations	Yes	Yes	No	Medium	Tree	Seasonal	No	Low	N/A	Low

Discussion

This study induced water stress responses during fruit growth stages: I, II, IIIa and IIIb each growing season in 'September Bright' nectarine using a statistically designed deficit irrigation experiment. From a crop physiological perspective, the first plant response to drought is stomatal closure (Porometer; Table 1), preventing transpiration and evaporative cooling. Persistent drought stress damages photosynthesis machinery via loss of chlorophyll (SPAD meter; Table 1). A third response to water deficit is reduced photochemistry, the degradation of photoinhibition mechanisms (more photoinhibition), including reduced sun-induced leaf fluorescence (Fluorescence meter; Table 1). From an agronomic viewpoint, severe water deficit induced a reduction in vegetative and reproductive growth. Here, reduced canopy size (light interception), decreased pruning biomass, lower lateral strength, reduced fruit size, and decreased yield were consistently observed under deficit irrigation regimes (Table 1, Fig. 1). Furthermore, important fruit quality attributes were affected under severe water deficit. For example, stage IIIb water deficit (0, 20 and 40% ET_c) increased the accumulation of soluble solids, delayed fruit maturity, increased firmness and increased red skin colour. However, the moderate deficit (stage II: 40% ET_c) treatment confirmed earlier RDI studies whereby no effect on yield and fruit size (Mitchell and Chalmers, 1982) when deficit irrigation is applied from pit hardening, and maintained key fruit quality attributes (sweetness, maturity, firmness, red skin colour) (Table 1).

From a sustainability production perspective, the lack of recovery from drought stress can be observed in crop response each subsequent growing season on trees subjected to repeated water deficit. Here, stage I and III deficit irrigation consistently induced poor fruiting wood (lateral size, floral bud dry weight, pruning biomass), small fruit size, low yields, degradation of leaf pigments (chlorophyll, carotenoids, anthocyanins) that control photosynthesis, and loss of efficiency in leaf photochemistry machinery (carotenoids, anthocyanins) (Table 1).

The fruit sorting grader affords data sets of large sample size (individual fruit data; $n \approx$ 20,000/season) and rapid assessment of multiple fruit quality factors compared to traditional labour-intensive (and expensive) and small sample size laboratory ‘wet chemistry’ approaches. Figure 1 showed the responses to deficit irrigation of yield and fruit quality. For example, analysis based on strict ‘premium packout’ criteria derived from data on each individual fruit scanned by the fruit grader show a clear distinction between irrigation treatments.

Table 2 provided a summary of the utility of sensors and technologies used in this study. From the perspective of precision horticulture, field-based sensors ideally acquire large sample size, ability to capture temporal and spatial variation in crop response to (drought) stress and have application of IoT technologies and data communications. However, very few sensors and platforms make the grade of a ‘smart sensor’. Clearly, more product development is required to meet these criteria. To meet some of these challenges work is currently underway at Tatura - Agriculture Victoria. Here, a few systems are being investigated, such as: (i) tree and fruit tracking systems using devices (e.g. colour meter, PAR sensor, digital callipers) reading smart tags (e.g. NFC) with data connection via Bluetooth to smartphone APPs for spot non-destructive measurements, (ii) low-cost radio connected permanent or semi-permanent sensors for plant-based continuous measurements (e.g. fruit and trunk dendrometers), (iii) light spectrum devices for remote and proximal sensing (e.g. LiDAR and PAR sensors), (iv) UAV-based imaging for remote sensing (e.g. thermal infrared and multispectral cameras), and (v) closed-loop irrigation systems (i.e. SupPlant by Goldtech).

Conclusions

This study conducted sensing of fruit and tree performance under deficit irrigation in 'September Bright' nectarine. Key information of the effects on tree and fruit performance under severe water deficit were lower yield, decreased canopy size, lower stomatal conductance, reduced chlorophyll, decreased photoinhibition, reduced fruit size, increased soluble solids, increased firmness, decreased maturity and increased red skin colour. Moderate water deficit (40% ET_c) during the traditional RDI period (Stage II of fruit growth) showed no effect on yield or fruit quality. The utility of sensing instruments and platforms for precision orchard management were reviewed. More product development is required to achieve field-based ‘smart’ sensors to acquire large sample size, ability to capture temporal and spatial variation in crop responses and the application of IoT technologies and data communications.

Acknowledgements

The technical support and assistance of Dave Haberfield, Jim Selman, Andrew O’Connell, Cameron O’Connell, Athulya Jancy-Benny, Santana Papa, Madeleine Peavey and Danielle Cook is gratefully acknowledged. Advice and feedback from the Stonefruit Field Laboratory Advisory Committee is acknowledged. This project ‘SF17006: Summerfruit orchard – phase II’ was funded by Horticulture Innovation Australia Limited using Summerfruit levy and funds from the Australian Government with co-investment from Agriculture Victoria.

Literature cited

Fernandes-Silva, A, Oliveira, M., Paco T.A., and Ferreira, I. (2018). Deficit irrigation in Mediterranean fruit trees and grapevines: water stress indicators and crop responses. In: Irrigation in Agroecosystems. Ed. G. Ondrasek. doi:10.5772/intechopen.80365

Goodwin, I., Whitfield, D.M., and Connor, D.J. (2006). Effects of tree size on water use of peach (*Prunus persica* L. Batsch). Irr. Sci., 24(2), 59-68. doi:10.1007/s00271-005-0010-z

Goodwin, I., and O’Connell, M.G. (2017). Drought water management: an Australian perspective. *Acta Hort*. 1150, 219-232. doi:10.17660/ActaHortic.2017.1150.31

Lopresti, J., Goodwin, I., McGlasson, B., Holford, P., and Golding, J. (2014). Variability in size and soluble solids concentration in peaches and nectarines. *Horticultural Reviews 42,* 253–311

Mitchell, P.D., and Chalmers, D.J. (1982). The effect of reduced water supply on peach tree growth and yield. J. Am. Soc. Hortic. Sci. *107*, 853–856.

Scalisi, A., O'Connell, M., Lo Bianco, R., & Stefanelli, D. (2019). Fruit and leaf sensing for continuous detection of nectarine water status. Frontiers in Plant Science, 10, 805. doi:10.3389/fpls.2019.00805