Hort Innovation

Final Report

Improving citrus quality with regulated deficit irrigation

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Public summary

In highly competitive and consumer-driven markets, citrus growers face the challenge of consistently supplying fruit that meets or exceeds consumers' expectations. It is therefore essential for growers to adopt smart, innovative, agronomic practices that can deliver improved fruit quality suitable for Asian markets. Applying regulated deficit irrigation (RDI) is one such practice that can be used from February to April to enhance fruit sugar content and acid levels in fruit as well as saving irrigation water.

Local experiments were needed to strengthen recommendations of regulated deficit irrigation (RDI) strategies for growers to be applied in commercial situations. However, successful adoption of RDI techniques requires optimising irrigation scheduling, understanding the stage at which to apply deficit irrigation stress, and investigation of potential negative effects on fruit quality and long-term tree health. The RDI research work was mainly focused on 3 navel orange varieties (M7, Washington navel and Lane Late) grafted to *Poncirus trifoliata* or *Troyer citrange* rootstocks. The 4-year research program was conducted at Dareton Primary Industries Institute near the Sunraysia district. The trial site has deep sandy loam soil with an annual rainfall of 260 mm. The study assessed the fruit responses to different RDI treatments for fruit quality by enhanced sugar and acid levels in navel fruit. The tree and soil responses were monitored by recording stem water potential using pressure chambers, soil probes and tensiometers. Fruit quality (°Brix, acid %, BrimA) was assessed during the growing season and at harvest. Fruit yield, number and fruit size distribution data was also collected each experimental year using a commercial grading machine.

RDI treatments were applied in February, March, or April. The soil profile was dried for 2 weeks at the start of the treatment and irrigation was withheld, followed by 50% irrigation for 8 weeks as the control. In this way, it was possible to enhance the sugar in navel crop. The degree of stress was related to time of application. Earlier applied treatments were more responsive but quite sensitive to fruit size losses. Treatments applied in February had much greater effect on fruit than when applied in March and April. The sugar levels can be increased from 1 to 1.5 °Brix in March or April treatments during the dry season without significant losses in fruit size. There was a reduction of 10% for large sized fruit for every 1 °Brix increase and the reduction in fruit size was more severe in Troyer citrange than *Poncirus trifoliata* rootstock. It is recommended that RDI can be applied in the first week of April to Washington navel or Lane Late navels. The soil profile can be dried for 2 weeks to ensure stem water potential values reaches a value of 8–10 bar using a pressure chamber and the tensiometer/gypsum block value reaches more than -60 kPa for 30 mm depth of soil. Then apply 50% of the control for 8 consecutive weeks followed by 100% irrigation. There was a water saving of 0.77 mega litres per hectare for the duration of RDI treatment.

Technical summary

The production of a high-quality citrus fruit is critical to sustain and grow the consumer demand in domestic and export markets. Asia is the major market for Australian citrus, accounting for 86% of the total citrus fruit exports. The consumers in Asian countries prefer sweeter fruit. In highly competitive and consumer-driven markets, citrus growers face a challenge of consistently supplying fruit that meets or exceeds consumers' expectations. It is therefore essential for the growers to adopt smart, innovative, agronomic practices that can deliver improved fruit quality suitable for Asian markets. Regulated deficit irrigation (RDI) is one such practice that can be applied during the fruit growth period (from February to April) to enhance fruit sugar content and acid levels in fruit, while making water saving of 0.77 ML/ha during the RDI period (soil profile drying and 8 weeks of 50% irrigation) at Dareton site.

Therefore, an RDI research program was needed before recommending regulated deficit irrigation (RDI) strategies for growers to be applied in commercial situations. However, successful adoption of the RDI technique requires optimisation of irrigation scheduling, understanding the growth stage at which to apply RDI and the duration of the RDI to be applied. The knowledge of the severity and frequency of RDI application was also needed, along with the investigation of potential negative effects on fruit quality and long-term tree health. In the current research program, the RDI research work was mainly focused out on 3 navel orange varieties (M7, Washington navel and Lane Late) grafted to *Poncirus trifoliata* or *Troyer citrange* rootstocks. The 4-year research program was conducted at Dareton Primary Industries Institute near the Sunraysia district. The trial site has deep sandy loam soil with an annual rainfall of 260 mm. The study aimed to assess the fruit responses to different RDI treatments for improved fruit quality by enhanced sugar and acid levels in navel fruit. The tree and soil responses were monitored by recording stem water potential using pressure chamber, soil probes and tensiometers. Fruit quality (°Brix, acid %, BrimA) was recorded during the growing season and at each harvest. Fruit yield, number and fruit size distribution data were also collected on each experimental year using a commercial grading machine.

RDI treatments were applied in February, March or April in different years. In some treatments, the soil profile was dried for 2 weeks at the start of the treatment and irrigation was withheld; this was followed by 50% irrigation for 8 weeks. Once the 8-week period of 50% was over, trees were irrigated normally with 100% irrigation until harvest. These treatments occurred in each growing season. In this way, it was possible to enhance the sugar levels in navel fruit. In other treatments, the soil profile was not dried, and 50% irrigation was applied in February or March for 2020 and 2021. The degree of water stress was related to time of application. Earlier applied treatments were more responsive in terms of sugar increase, but quite sensitive to fruit size losses. While the March and April treatments did not affect the fruit size to the same effect as in February. The sugar levels were increased from 1-1.5 °Brix in the March and April treatments during the dry seasons without significant losses in fruit size. There is a reduction of 10% for large sized fruit (81–87 mm) for every 1 °Brix increase. The reduction in fruit size was more pronounced on *Troyer citrange* than *Poncirus trifoliata* rootstock. Therefore, it is recommended that RDI can be applied in the first week of April to Washington navel or Lane Late navels growing on *Troyer citrange* rootstock, while it would be possible to apply RDI from 15 March in Washington navel or Lane Late on trees growing on *Poncirus trifoliata* rootstocks. The soil profile can be dried for 2 weeks to insure a SWP reaches a value of 8-10 bar using a pressure chamber and the tensiometer/gypsum block value reaches more than -60 kPa or more for 30 mm soil depth. Then apply 50% of the control for 8 consecutive weeks followed by 100% irrigation.

In 'Afourer' mandarin, in some years there was an increase of 1 °Brix and no significant reduction on fruit size was noticed. However, the expectation was to increase the °Brix levels up to 2 degrees before it has a commercial value. Most of the seasons were affected with rainfall, especially the Riverina, where the growing season remained wet for May in 2018, for March–April in 2019 and 2020 and March–May in 2021. Therefore, trees were relieved from stress. In future, this trial needs to be conducted in clay soil condition of Curlwaa, NSW and the application of RDI needs to be applied around 15–30 March to have an effect.

Drone technology was also tried with thermal cameras fitted and using multi-spectral cameras. Flights were conducted in 2018, 2019 and 2020 using different commercial operators. The idea was to detect the differences in canopy temperatures in the different RDI treatments. In most cases the canopy temperature differences in RDI were 1 °C or less, therefore, no conclusion was reached. Using the multi-spectral camera, NDVI data was captured for the entire navel trial. The highest NDVI values (> 0.84) gave no indication of stress as the canopy was fully green for each RDI treatment. Perhaps in future, there is a need for advanced thermal cameras fitted to the drones that can record the canopy temperatures at lower altitudes, such as 50 m.

The sensory evaluation trials for the earlier applied RDI treatments were conducted for 2 years. In 2019, the sensory evaluation was conducted with students and staff of SuniTAFE. Although they were able to detect differences in sugar levels from different treatments, it was not easy for the public to detect a 1 °Brix difference for M7 or Lane Late navels. The detection difference between control and sweet fruit were 7% for M7 and Lane Late. In, 2020 the sensory evaluation was conducted with citrus growers and marketing experts and they were able to pick the difference of 1 °Brix much easier than the general public. The detection between control and treated was 35% for M7 and 27% for Washington navel.

The storage trials were also conducted in the last growing season of the project in 2021. M7 and Washington navel were stored at 5 °C for 7 weeks and Lane Late was stored for 3 weeks. The fruit quality was not affected for any navel variety during the storage period. However, a few fruits in Lane Late had some skin pitting for both control and treated fruit. Large scale simulated transit trials are needed in future for the fruit transported overseas.

Keywords

Regulated deficit irrigation, 'M7', 'Washington navel', 'Lane Late', 'Afourer' mandarin, fruit quality, yield, stem water potential, fruit size distribution, sensory evaluation, fruit storage, drone, total soluble solids, BrimA, acid.

Introduction

The Australian citrus industry is one of Australia's largest horticultural industries, with over 28,300 ha planted in 5 states and one territory. In 2019, over 290,000 tonnes of citrus fruit valued at $524.5 million were exported. Sweet oranges accounted for 68% of the volume and 58% of the value, while mandarins accounted for 30% of the volume and 40% of the value. Australia exported fruit to 48 countries, with 24 of those countries in Asia (Milner 2021). The breakup of export tonnage is given in Table 1.

Table 1: Total export in tonnes and per cent of the total export to 48 different countries in 2019.

Countries	Export (tonnes)	Per cent of total export
China, Japan, Hong Kong	150,513	52
14 other Asian countries	112,643	39
US, Canada, New Zealand, PNG	23,660	8
Others	4,118	1

Increasing fruit sales at profitable prices is vital for the growth and sustainability of the citrus industry. Information on consumer preferences and motivators for purchase are important in that process. In general, a good external appearance will prompt consumers to buy, while an enjoyable flavour and texture will encourage them to make repeat purchases.

The goal is for consumers to have a great citrus eating experience they want to repeat. Australian consumer flavour preferences were evaluated in 2013 through a large-scale consumer sensory evaluation as part of a recently completed project CT12004 (Damiani 2016). An outcome from this report supported the use of the 'Australian Citrus Standard' (based on BrimA, an Australian quality standard used a maturity index) as a criterion for consumer flavour acceptability.

The main destination for Australian citrus exports is Asian markets, which are growing. A 2014 survey of Australian Murcott mandarins shipped to China as a part of CT12023 showed that consumers surveyed in Shanghai and Beijing preferred the lower acid fruit (Macnish 2015). A study tour to China found that Chinese consumers preferred fruit with low acidity (about 0.6%); fruit acidity above 0.8% was considered as lesser quality 'sour' fruit (Falivene and Creek 2016). Minimum acceptable individual fruit Brix levels were 10.5° to 12° and there was a high preference for around 14°. Therefore, increasing °Brix and maintaining acidity within acceptable levels are important factors for increasing fruit quality for fruit distanced for export.

Citrus growers often want to influence fruit quality, yield, tree vigour and precocity. There are several ways to do this, such as selecting specific rootstocks and varieties, as well as cultural practices such as manipulating irrigation. Various studies have used regulated deficit irrigation in oranges or mandarins for water savings (Gasque at al. 2010; Skewes 2013; Stango et al. 2015; Zapata-Sierra and Manzao-Agugliaro 2017) and to increase the total soluble solids in Lane late navels with a 30% to 50% reduction in water (Ballester et al. 2013). Total soluble solids in 11-year-old Navelina trees grafted to *Carrizo citrange* rootstock increased with a 45% reduction in water (Garcia-Tejero et al. 2010) and Romero et al. (2006) reported an increase in total soluble solids with deficit irrigation in 'Clemenule' mandarin on Carrizo and Cleopatra rootstocks in Spain. Although a few Australian growers have privately trialled regulated deficit irrigation during the growing season, there are no Australian research recommendations available for enhancing fruit quality with regulated deficit irrigation in navel oranges.

This project aimed to increase the sugar content (°Brix and acid) of navel oranges by placing the trees under irrigation stress (regulated deficit) at a specific phenological stage during the growing season.

Project objectives:

1. Improve the internal quality (°Brix and acid) of navel oranges by regulating deficit irrigation.
2. Develop a practical irrigation deficit method that uses simple soil moisture monitoring technologies (tensiometers and capacitance probe) to produce sweeter fruit.

Methodology

For detailed methods, refer to Appendix 1.

Trial site

A two-hectare site was established at NSW Department of Primary Industries Dareton in September 2010; this was used for the deficit irrigation research work. The trial site was 8 years old and in full commercial production at the start of the experimental program in 2018. There were 38 rows running North-South, with 27 trees per row, giving a total of 1,026 trees. Row to row distance was 5 m and the tree spacing within the row was 2.5 m, giving a tree density of 800 trees/ha. The soil was a deep loamy sand with all rootstocks having deep unimpeded root zones.

Trees were drip-irrigated with 5 emitters per tree, each delivering 1.2 L/h, located on a double lateral with 0.6 m dripper spacing. Every winter the trees were lightly hand pruned and skirted after harvest. All other cultural activities were applied according to local practices. Readily available water (RAW) was calculated in the root zone and dripper-wetted area. Next, the irrigation was estimated for the control (T1) by measuring the evapotranspiration (ETc) using the FAO56 Penman Monteith method (ETc = ETo * Kc). The investigations of root zone for this site for readily available water (RAW) indicated that the profile would completely dry out to 80 cm depth. The installed soil moisture probes confirmed this to be correct.

Experimental design

The experiment was conducted for 4 consecutive years (2018–2021) at NSW DPI, Dareton. There were 5 rootstocks (*Poncirus trifoliata*, *Troyer citrange*, *Swingle citrumelo*, *Citrus volkameriana* and *Citrus macrophylla*) and 3 navel varieties with different maturing times including M7 (early maturing), Washington navel (mid maturing) and Lane Late (late maturing). In each row, 3 varieties were randomly allocated as a single tree plot to each set of rootstocks within the row. The experimental plots were guarded with additional trees within the rows. The guard trees are shown in the trial plan as a non-coloured cell. Six regulated deficit irrigation treatments were randomly applied to the entire row within a block. There was a total of 6 blocks, therefore each irrigation treatment is replicated 6 times. This arrangement was suited well to a large scientifically designed and replicated trial. Six irrigation treatments were applied in each year for 2018 to 2021. The treatments varied every year and were determined by the project reference group after evaluating the results from the previous year's research work. A detailed treatment structure for each growing year is given later in the report (Appendix 2). For RDI treatments soil profile was dried for 2 weeks (irrigation water withheld) followed by 50% irrigation of the control for 8 weeks. After 8 weeks full irrigation was resumed until harvest.

Plant responses to RDI were recorded using a pressure chamber. Pressure chamber measurements were made between January and August in 4 growing seasons. Tensiometer were installed for Washington navel (mid maturing) trees at depths of 30, 60 and 90 cm to assess the soil tension. Data were manually collected every second day at about 10.00 am between January and August for 4 growing seasons. Soil response to RDI was recorded using Enviro probes. Enviro probes (Entelechy Pty Ltd) provides an estimation of the soil moisture status for each sensor at 80 cm depth. Physiological responses were measured by fruit growth increments, from twenty fruit around tagged around the tree canopy. Fruit growth data was recorded from January to harvest for each navel variety for 4 growing seasons.

The internal fruit quality measurements were carried out at harvest and fruit were assessed for ^{o}Brix and % acid. The juice sugar:acid ratio and BrimA was calculated from this data. BrimA is an Australian quality standard used a maturity index and is calculated as (^{o}Brix-(% Acid × 4)) × 16.5. Fruit and tree yield for each experimental tree were recorded at harvest (Table 2.6). Fruit size (diameter) was sorted into 5 classes based on < 65 mm (> 138 fruit/carton), 65–67 mm (138–125 fruit/carton), 69–75 mm (113–100 fruit/carton), 75–81 mm (88 fruit/carton) and 81–87 mm (< 80 fruit/carton) using a commercial grader [Colour Vision Systems Pty. Ltd., Australia (MAF Oceania group)].

Results and discussion

For detailed results and discussion, refer to Appendix 2.

The experimental program for the RDI treatments was conducted over 4 years from 2018 to 2021. This program involved 5 rootstocks (*Poncirus trifoliata*, *Troyer citrange*, *Citrus macrophylla*, *Citrus volkameriana* and *Swingle citrumelo*). Data were collected for each rootstock and their responses in relation to each variety are mentioned in the recommendation section. However, the focus of this study was *Poncirus trifoliata* and *Troyer citrange*. Therefore, the results from these 2 extensively used rootstocks are presented in this final report. These two rootstocks are used in the major citrus growing regions of Australia. *Troyer citrange* is used in the light or deep sandy loam soils of Sunraysia, while *Poncirus trifoliata* is used in heavy or clay soils of the Riverina. All other parts of Australia use these two rootstocks accordingly as per their soil conditions. The RDI program was applied to 3 navel varieties. These varieties are harvested from May to August due to the different maturity dates. M7 navel is an early-maturing variety and usually harvested in May, Washington navel is mid-maturing variety and harvested in June, and the late-maturing Lane Late navels are harvested in July–August. The different maturity times of these 3 varieties provided a better understanding about their responses to RDI and its interaction with rootstocks.

Six RDI treatments were used every year, however, these irrigation treatments were modified every year after the presentation of the project results to the project reference group (PRG) committee. The objective was to test a range of treatments better suited to enhance sugar levels and with minimum effect on fruit size. Therefore, the treatments were proposed and consulted with the PRG committee before being applied to the experimental trees every year.

Irrigation treatments were applied in February, March, and April during the program (details are given in Chapters 1 to 4 for each year – Appendix 2). There was a control where 100% irrigation was applied. In most RDI treatments, the soil profile was dried for 2 weeks to impose stress and this was monitored by tensiometers and pre-dawn stem water potential readings throughout the growing season. The trees were regarded to have achieved the desired stress levels when stem water potential values were between 8-10 bar. The stem water potential measurements with a pressure chamber are the most employed methods to determine the plant water status in citrus trees (Goldhamer et al., 2012). At the same time, the tensiometer reading for 30 cm depth was above -60 kPa, which indicates negative soil tension. After 2 weeks of drying, 50% irrigation was applied for 8 weeks followed by 100% irrigation until harvest. For some treatments the soil profile was not dried, however, 50% irrigation was applied for 8 weeks followed by 100% irrigation until harvest. Every year had different treatments and timing. How these treatments affected the fruit quality and fruit size is discussed below. The detailed results and discussion for other components of the project can be found in chapter 10 (Appendix 2).

Fruit quality and fruit size (2018–2021) for navel oranges

M7 navel

M7 navel is an early maturing variety and is ready for harvest in early May to mid-May in the Sunraysia district. In 2018, fruit were harvested on 16 May. The sugar levels were increased by 1 °Brix in fruit that had RDI applied in February 2018. Although the April applied RDI (T6) did not increase °Brix levels generally, it did increase °Brix by 1.6 in fruit from *Poncirus trifoliata* rootstock. In 2018, the distribution of fruit in the different size classes did not change significantly, however, the treatments with increased °Brix levels had reduced percentage of fruit in size class 81–87 mm. In 2019, RDI treatments were not applied in February. The RDI treatments applied in March or April had no effect in increasing °Brix values. One of the reasons for the this could be the absence of a February treatment in 2019. Generally, the warm conditions in February are suitable for imposing water stress and sugar levels do increase in those conditions. The second reason could be the late harvest (3 June) of M7 in 2019. If M7 is harvested late, then the differences in sugar levels become minimal. The growing season generally remained dry, which is well suited to RDI, however, 26 mm of rain was received on 2 May, which meant that T2 and T6 could not complete their 50% RDI duration. In 2019, T2 was the worst treatment for reducing fruit size. In this treatment, the soil profile was dried and then fully irrigated once desired stress levels were reached, and this dry and wet pattern continued until harvest. Clearly fruit growth of navel oranges is sensitive to this wet and dry pattern. Once fruit growth stopped due to water stress, it took at least 2 weeks before growth started after full irrigation was applied. In T2, fruit received 8 occasions of dry and wet patterns and they never attained their full growth. Therefore, T2 is not recommended for further use as an RDI treatment. The other treatment, T4, which was applied in early March which reduced fruit size by7%. The April treatments did not reduce the fruit size, however, at the same time it did not increase the sugar levels either.

In the 2020 growing season, fruit were harvested on 5 May. The °Brix value was increased in T6 (February applied treatment), although other treatments were affected due to significant rainfall in March (26 mm) and April (72 mm) during the RDI period. There were no °Brix differences for the RDI treatments at harvest apart from the February applied treatment (T6); evidently T6 carried the sugar levels to harvest. This could be because it was stressed 3 times due to stopping and starting irrigation in March and April, as shown by the enviro probe measurements (Figure 3.2 – Appendix 2). The growing season of 2020 was affected by rainfall, so the fruit was not reduced by any treatments apart for T6, which was applied in February. This produced high sugar levels but at a cost of 12% reduction in large fruit size. In 2021, T6 (February applied treatment) increased sugar levels by 1.2 °Brix. In this instance, the T3 applied in February and T2 in March without the 2 weeks drying of profile increased sugar levels by 0.6 and 0.3 °Brix respectively. This shows the significance of drying the soil profile before applying 50% irrigation. T7, which was applied in April, increased °Brix by 0.5 in M7 navels. This treatment only received 50% irrigation for less than 4 weeks, as fruit were harvested on 10 May. The result confirms that at least 8 weeks of 50% irrigation is needed to enhance at least 1 °Brix in M7 navels. Generally, there were no differences in °Brix value for the 2 rootstocks, apart from in 2021, and most of the interaction effects were not significant. However, in both 2018 and 2021, *Poncirus trifoliata* rootstock had 1 °Brix increase with April applied treatments. This shows that the late application of RDI can increase °Brix in *Poncirus trifoliata* rootstock, but not in *Troyer citrange*. To increase sugar levels in *Troyer citrange* rootstock, probably 3 weeks of soil profile drying is needed with the stem water potential values of 9-10 bar before any sugar increase is expected. In growing season 2021, the reduction of fruit size was 12% when the soil profile was not dried in February–March (T2 and T3). The reduction was 18% when the soil profile was dried in early March (T4) and the reduction was 22% when the soil profile was dried in February (T6). There was a 14% reduction with the April treatment (T7) with an increase of 1 °Brix for *Poncirus trifoliata* rootstock. This finding confirms the data for 2018 for the same treatment. These results concluded that M7 trees grown on *Poncirus trifoliata* or *Troyer citrange* should not be exposed to RDI treatments.

Washington navel

Washington navel is a mid-maturing variety and is ready for harvest in early June in the Sunraysia district. In 2018, fruit were harvested on 6 June. The sugar levels increased by 1.6-1.8 °Brix with T2 and T3 (February applied irrigation treatments) and by 1 with T4 (March applied treatment) in 2018. Although T6 (April applied treatment) increased °Brix levels by 0.7, this increase was 1.1 on *Poncirus trifoliata* rootstock. In 2018, the amount of fruit in the 81–87 mm class was significantly reduced by 20–23% with T2 and T3 (February applied treatments), 15% with T4 and T6 (RDI in March) and 10% with T6 (RDI in April). T6 also had an increase of 0.7 °Brix, suggesting that 10% reduction in fruit size came with increased sugar levels. Although, there were no treatments applied in February 2019, °Brix values were increased by T2 and T5 (March and April applied treatments). 2019 was a dry year, which was well suited to RDI experiments. Even though 26 mm of rain fell on 2 May, it did not affect the RDI treatments because Washington navel was harvested on 2 July and the RDI duration for all treatments was completed without any rainfall interruptions. In the 2019 growing season, T2 (the wet and dry treatment applied in early March) reduced the amount of fruit in the 81–87 mm class by 19%, while T3 (also applied in early March) reduce the fruit size by 21%. T4, applied in mid-March, reduced the fruit size by 13%. T4 had only 4% reduction in *Poncirus trifoliata* rootstock and an increase of 1 °Brix, suggesting that RDI in mid-March will be desirable for this rootstock. Applying RDI early has a profound effect on reducing large fruit size. While the April applied treatments (T5 and T6) reduced fruit size by only 5%, this would be more acceptable to citrus growers. T5 and T6 were able to achieve up to 0.8 °Brix without compromising the fruit size.

In 2020, fruit were harvested on 17 June. The °Brix value was increased by 1˚ with T6 (February applied treatment) and the increase was 1.1˚ on *Poncirus trifoliata* rootstock. All other treatments were affected due to significant rainfall during the RDI period and no °Brix differences were found. The February applied treatment (T6) still carried its sugar levels to harvest. As the 2020 growing season was affected by rainfall, so fruit size was not reduced by any treatments apart from T6. T6 was applied in February and produced 1 °Brix, but this was coupled with a 12% reduction in large fruit size. In 2021, T6 increased sugar levels by 1.4 °Brix. In this instance, T3 was applied in February without 2 weeks drying of the soil profile, and °Brix increased by 0.6˚. T2 and T7 did not influence °Brix, but the latter only received 50% irrigation for less than 4 weeks, as fruit were harvested on 15 June. This result confirms that at least 8 weeks of 50% irrigation is needed to achieve 1 °Brix in general. Generally, there were no differences for °Brix found for 2 rootstocks. In all RDI treatments per cent acid levels were slightly higher than the control. In the 2021 growing season, the reduction in fruit size was 20% with T3 (no soil profile drying was carried out in February). When the soil profile was dried in February (T6), the reduction was 22% with an increase of 1.5 °Brix. T4, the early March treatment, also reduced the fruit size by 22%. In T5 where 100% water was applied straight after 2 weeks of drying, fruit size was reduced by 10%. The April applied treatment (T7) reduced the fruit size by 5%, but no gain in sugar. Most of the fruit size reduction was observed in *Troyer citrange* rootstock with 33% for T6.

Lane Late

Lane Late is a late-maturing variety and is ready for harvest in early late July to early August in the Sunraysia district. In 2018, fruit were harvested on 31 July. The sugar levels were increased by 1.8-2.1 °Brix with T2 and T3 (February applied irrigation treatments) and by 1.8 and 2.0 with T4 and T5 (March applied treatment) in 2018. T6 (April applied treatment) increased °Brix levels by 0.8. It was interesting to notice that the sugar increase was 2.2 °Brix in *Troyer citrange* rootstock for all RDI treatments apart from T6, which increased °Brix by 1.0. In 2018, the amount of fruit in the 81–87 mm size class was reduced by 21% with T2 and T3 (RDI in February), and 15% and 22% with T4 and T5 (RDI in March). T5 was quite a severe treatment, with the soil profiles dried for almost 3 weeks. T6 (RDI in April) had a 10% reduction in large fruit size, and this was coupled with an increase of 1 °Brix. In 2019 fruit were harvested on 5 August.

T2 and T3 (RDI in March) increased °Brix by 1.3 and 1.7 respectively. T3 was more effective because the profile was dried in early March. 26 mm of rain fell on 2 May, but it did not affect the treatments because Lane Late navels were harvested on 5 August, and the RDI duration for all treatments was completed without any rainfall interruptions. In 2019, the amount of fruit in the 81–87 mm size class was reduced by 26% with T2, 28% with T3 and 17% with T4. These reductions were observed in both rootstocks and shows that the applying RDI early has a profound effect on reducing large fruit size but also increases °Brix levels. While T5 and T6 reduced fruit size by only 5%, which is likely to be more acceptable to growers, the °Brix was only 0.5, therefore these treatments failed to achieve the desired sugar levels.

In 2020, the °Brix value was increased by 1.3 in T6 (February applied treatment), and the increase in °Brix was 1.5 for *Poncirus trifoliata* rootstock. All other treatments were affected due to a heavy rainfall during the RDI period, and there were no °Brix differences found. It appeared that the February applied treatment (T6) still carried its sugar levels to harvest, which is excellent for a late maturing variety. However, the stopping and starting of irrigation could have also contributed to T6, which was stressed 3 times (Figure 3.2 – Appendix 2). In 2020, fruit were harvested on 29 July and growing season was affected by rainfall, so the fruit size was not reduced by any treatments apart from T4 and T6. T4 increased °Brix by 1 and had 11% fewer large size fruit. T6, which was applied in February, produced 1.3 °Brix at the cost of 14% reduction in large fruit size. In 2021, T6 (February applied treatment) increased sugar levels by 1.6 °Brix. T3 was applied in February without 2 weeks drying of the soil profile and increased °Brix by 1.6. T2 did not influence °Brix levels. T4 (applied in early March) increased °Brix by 2.1 and this was due to drying the profile for 2 weeks followed by 50% reduction in irrigation for 8 weeks. T7 generally increased °Brix by 0.9. This treatment only received 50% irrigation for 4 weeks and fruit were harvested on 29 July. The result confirms that at least 8 weeks of 50% irrigation is needed to achieve 1 °Brix in general. There was 1 °Brix increase for *Troyer citrange*. In all RDI treatments, per cent acid levels were slightly higher than the control. In 2021, fruit were harvested on 29 July. T3 reduced the amount of large fruit by 16% and increased °Brix by 1.5, while T4 reduced large fruit size by 27% and achieved 2.1 °Brix. In T5, where 100% water was applied straight after 2 weeks of drying, reduced large fruit by 8% with only 0.5 °Brix, which was mainly on the Troyer citrange rootstock. The April applied treatment (T7) did not reduce the fruit size but still was able to achieve 0.9 °Brix. This is a desirable result for T7 where only 4 weeks of 50% irrigation was applied. Applying 50% irrigation for 8 weeks would likely have resulted in a better outcome.

Conclusion

The increase in sugar levels with RDI was achieved in this project with a range of RDI treatments applied for 4 years the experimental program. The results clearly showed that there are some fruit size losses with RDI to enhance sugar levels in fruit. The increase in °Brix is linearly related to fewer large fruit in size class 81–87 mm; there is a penalty for each °Brix increase in navel fruit (Table 10.2, Appendix). For each 1 °Brix increase there is a loss of 10% in large fruit size (81–87 mm). There are rootstocks responses to RDI treatments, *Troyer citrange* is more affected with RDI treatments than *Poncirus trifoliata* rootstocks under sandy loam soil conditions.

Outputs

Table 2. Output summary based on the project outputs for 4 years of research work on regulated deficit irrigation.

Output	Description	Detail
Dareton Road show 19 April 2021	CAL Road show and field day at Dareton	A field day was held at the Dareton research institute on 19 April 2021 as a part of the road show. A total of 80 growers attended the field day at Dareton. Project progress for deficit irrigation was presented to the growers followed by a field session. Growers look at the trial and fruit tasting were also held from control and stressed fruit.
CAL Conference, Adelaide, Presentation session, March 2019	An oral presentation was delivered. There were a range of audience including growers, marketers, researchers, extension officers and representatives from agriculture companies	An oral presentation was delivered at Citrus Australia Technical Conference in Adelaide in February 2019. The presentation had full details about the project objectives, experiments, and the latest results.

	and overseas visitors.	
Conference presentation, Field Session, 4 March 2019	Field day to growers, fruit tasting Handouts given	CT17000 – Improving citrus quality with regulated deficit irrigation. The session was delivered by visiting the navel RDI trial at Dareton. The field session was followed by the tasting session of the fruit from control and RDI treated trees. 40 handouts were distributed among the growers attending the conference.
Field day Dareton, 10 Sep 2018	An oral presentation was delivered at Dareton Field and trial visit session was also held. Growers had the opportunity to taste the fruit harvested from the control and RDI treated trees. 26 growers attended the field day.	26 Riverina citrus growers visited Dareton. The update on the regulated deficit irrigation research work was presented and 26 handouts were given to growers.
WA Citrus Industry day, 19 Oct 2018	An oral presentation was delivered. There were a range of audience including growers, and extension officers and a few representatives from agriculture companies. 36 growers attended the field day.	An oral presentation was delivered at WA citrus industry day as a part of the by Citrus Australia Limited road show. The presentation had full details about the project objectives, experiments, and the latest results. The updated results and the progress of the Regulated Deficit Irrigation project was presented to 36 growers at the WA Industry day in Perth, WA.
Queensland Field day, 21 December, 2017	An oral presentation was delivered. There were a range of audience including growers, and extension officers and a few representatives from agriculture companies.	An oral presentation was delivered at Queensland citrus industry day at Gayndah as a part of the by Citrus Australia Limited road show. The presentation had full details about the project objectives, experiments, and the latest results.
Hort Unit Meeting (June 2022)	A group of 25 researchers and extension officers will visit Dareton during Hort. Unit workshop. Field visit is arranged to see the trial followed by fruit tasting from RDI treated trees.	
Project Reference Group meeting – 4 February 2018	The update of the project results to the PRG. The project reference group is comprised of growers, industry experts, project team and Hort Innovation representative.	The project results for 2018 were presented to the project reference group meetings. The session was followed by a detailed discussion about the RDI program. The project reference group visited the navel RDI trial at Dareton and looked at the on-ground field experiment, experimental design, and soil monitoring equipment. The project reference group was involved in the modification of next year's

		(2019) RDI treatment program.
Project Reference Group meeting – 24 February 2019	The update of the project results to the PRG. The project reference group is comprised of growers, industry experts, project team and Hort Innovation representative.	The project results for 2019 were presented to the project reference group meetings. The session was followed by a detailed discussion about the RDI program. The project reference group visited the navel RDI trial at Dareton and looked at the on-ground field experiment, experimental design, and soil monitoring equipment. The project reference group was involved in the modification of next year's (2020) RDI treatment program.
Magazine article	ACN Article Target audience were citrus growers and packers	Khurshid, T. 2019. Early results for deficit irrigation trials. Australia Citrus News. August edition, pages 30-31.
Magazine article	Citrus Connect Article Target audience were citrus growers and packers	Khurshid, T. 2020. Regulated deficit irrigation techniques enhance sweetness. CitrusConnect (March), NSW DPI.
Sunraysia daily, Feb 2019	Newspaper article Target audience were citrus growers and packers	Results are sweet (Sunraysia daily). One year data was presented in the newspaper.
International conference, Mersin, Turkey – Nov 2022	Oral presentation Target audience will be growers, marketers, researchers, extension officers and packers	This conference was supposed to be held in 2020, but due to the Covid19, face to face conference will be held in November 2022 in Mersin, Turkey. An oral presentation will be delivered on the 4 years research work on regulated deficit irrigation.
Information sheets: Information sheet will only be possible after the conclusion of project	Information sheets were given as hand out to growers at the field days.	The information sheets had the update of the ongoing Regulated Deficit irrigation project. These information sheets were given as hard copies who attended the field days or technical forums.

Outcomes

Table 3. Outcome summary based on the project outcome for 4 years of research work on regulated deficit irrigation.

Outcome	**Alignment to fund outcome, strategy and KPI**	**Description**	**Evidence**
Grower's awareness and ability to use deficit irrigation	Outcome 3: Improved product quality and increased productivity from the application of innovation. The results of this project will help enhance product quality such as sweetness,	This research work on RDI has already been conducted and the growers were aware about the project and the RDI activities. The updates were presented by different means of communication throughout the project.	Magazine articles, field days, conferences, Final Report

	flavour and juiciness (SIP, 2017-2021). Strategy 3.2: Undertake R&D and extension to enhance product quality (Sweetness, flavour and juice content).		
Improved citrus quality with enhanced sugar and acid levels	Same as above	The improved citrus quality was achieved with RDI due to enhanced sugar 1-1.5 °Brix levels in fruit. The March/or April applied RDI treatments can enhance sugar with minimal effect on fruit size at harvest. (Tables 1.3, 2.3, 3.4, 4.3 - Appendix 2)	Results and Final Report (4 years' data) – Appendix 2,
Informed decisions for growers to adopt the technique	Same as above	Worldwide literature search is more focused on mandarin. However, there is very limited work or long-term work has been reported for navel oranges. This work has provided new knowledge, which is easily adoptable by the Australian growers to enhance fruit quality. Recommendation will be provided in an electronic information sheet. Information sheet will be developed at the conclusion of the project after the acceptance of the Final Report and prior to 2022-23 growing season.	General discussion (Chapter 10) - Appendix 2
Water use efficiency due to less water use	Same as above	Potential water saving. Water saving of 0.77 ML/ha for the RDI duration is achieved.	Table 1.2 – Appendix 1

Monitoring and evaluation

Table 4. Monitoring and evaluation based on key evaluation questions.

Evaluation question	Project performance	Continuous improvement opportunities
Effectiveness	The industry has not widely adopted the technique as yet because the technique is just published in the final report. However, the industry is aware of the technique and some growers might be using it already as part of their own experimentation. Growers did pick up the technique after attending the field days at Dareton. A few growers also discussed the techniques with me in one-to-one meetings or phone calls. However, growers who do practice RDI techniques do not often share the information with other growers.	Commercial scale testing of project RDI recommendations by citrus growers in association with packing sheds.

	It was the first large scale controlled replicated trial for 4 years' duration, which was carried out at Dareton under controlled conditions. The trial involved 3 main commercial navel varieties and rootstocks, which will be of benefit to growers of Australia. Most of the trials in overseas are only 1 or 2-year studies.	In future, a large scale semi-commercial trial should be conducted involving one navel variety and on rootstock with control and recommended RDI treatments. There is a block of citrus trees available for this work at the Dareton Research Station.
	During the 4 years of experimentation, different climatic conditions (rainfall) occurred and additional information was collected (2020).	Rainfall cannot be controlled, however in future, it is possible install heavy plastic sheets between tree rows to direct the rainwater to drain out of the trial site without affecting the trees. It will also be effective for weed control within the rows.
	During the trial multiple RDI strategies were applied under the direction of t PRG. Also, different types of deficit monitoring equipment were tested, including arial drone technology.	During the current trials, the available thermal cameras failed to detect the canopy temperatures, however, now better grade cameras are available that can be fitted to the drone. The drone can now also be flown at a lower altitude of 50 m for the possible detection of canopy temperatures.
	Additional work was carried out during the trial on consumer sensory evaluation, and storage trials were also conducted in the last year of the project.	Consumer evaluation should be carried out with a single variety on a single rootstock for RDI treatments. Too many samples at the same time can confuse the assessor.
	Work on 'Afourer' mandarin was also carried out in Riverina and Sunraysia as demonstration trials at the grower's properties.	Most of the 'Afourer' work was affected with rainfall in the Riverina. Therefore, in future this work should be conducted in the Curlwaa region as that has clay soil, and it is closer to Dareton. The RDI treatment should also commence earlier than 15 April to enhance sugar levels in fruit.
Relevance	The project was quite relevant to the needs of growers. It was introduced to find ways to increase sugar levels in the fruit with regulated deficit irrigation. To provide sweeter navels for Asian markets and maintain Australia's reputation for high quality sweet navel oranges and maintain a competitive advantage for Australian fruit.	All growers need to adhere to Australian minimum industry internal quality harvest standards for navels. Industry and exporters should develop a marketing program or find niche markets where fruit can be sold by higher sugar levels and the returns are higher. RDI can have the disadvantage of fruit size reduction, therefore a market development strategy would aim at smaller, sweeter fruit with higher monetary returns.
Appropriateness	The intended beneficiaries such as growers and packers were well engaged and were aware of the	There should be a pre-harvest tasting session for growers and marketers every

	project activities and results. This was possible through field days, conference, magazine articles, phone calls and one on one trial site visits. However, due to the Covid19 group restrictions multiple fields days were not conducted as originally planned. The intended beneficiaries (growers and marketers) were also engaged by fruit tasting during sensory evaluation sessions with small group studies. Consumers (non-growers) were engaged in fruit tasting during sensory evaluation sessions. Risk management: 2020 Repeat of the same trial treatments from 2020 due to the significant rainfall during the RDI. In 2021, the same treatments were repeated to complete the trial. R&D manager was engaged via phone discussions, Milestone reports and Emails.	year. However, it is not always possible for growers and marketers to be available at specific time. The other option is to store the fruit and then have several sessions for the growers at a later date. Fruit should only be stored for 15 days. The public find it difficult to detect 1 to 2 °Brix in citrus fruit and it is not practical to conduct the sensory evaluation with them. In addition to that it also depends on the people country of origin and ethnicity. Asians have a different pallet than European, Africans or European nations. The sensory evaluation session should consider ethnicity and country of origin. Rainfall cannot be controlled, however in future, it is possible install heavy plastic sheets between tree rows to direct the rainwater to drain out of the trial site without affecting the trees. It will also be effective for weed control within the rows.
Engagement	The engagement process with levy payers through field days, one-on-one meetings, phone calls, extension material and industry magazines. The extension events such as field days, workshops and citrus conferences were fully accessible to the industry members. Field days in 2020 and 2021 were restricted due to Covid19 on entry to NSW state government facility.	Dareton Research Station always had a high industry reputation both in Australia and overseas for research and extension-based activities to impart knowledge to visitors.
Efficiency	The project was expanded with the existing budget to evaluate a range of other technologies not proposed at the beginning of the project. This is to get more value from the extensive trial work undertake at the Dareton trial site. Evaluation was conducted on fruit dendrometers, trunk psychrometers, and one model of sap flow sensors (ICT) and this was to determine the water use and growth rates in navel oranges. The project engaging with stakeholders and also through conducting the project reference group meetings.	In future work, the best RDI treatment identified in this project should be applied over an extended period and compared to a fully irrigated (non-RDI) treatment on a mature navel block at Dareton Primary Industries Institute with one navel variety grafted on one rootstock.

Recommendations

The following recommendations are based on a study conducted on 3 navel orange varieties at the Department of Primary Industries citrus research site at Dareton, NSW. The results were collected from a 2-hectare trial established on deep sandy loam soil. Therefore, care should be taken with the application of RDI practices in other soil conditions and regions. It is suggested that RDI be first tested on a small scale of approximately 2–5 rows, including a control row, before it is extended to a full block of trees. The responses might vary due to different soil types, rootstocks, tree health, crop management practices and climatic conditions. NSW Department of Primary Industries does not take responsibility for any adverse outcomes. These recommendations are general guidelines developed from 4 seasons of RDI trial results on navel oranges and provide citrus growers with new information that can assist quality management in the orchard.

Washington navel and Lane Late oranges

- Sugar levels can be enhanced in navel fruit with RDI commenced on 15 March or 1 April depending on the rootstock used, and the degree of fruit size reduction is related to the time and severity of application.
- The RDI application will involve 2 weeks of soil profile drying (water is withheld for 2 weeks), followed by 50% irrigation for 8 weeks to enhance the fruit sugar content by 1-1.5 °Brix at harvest. The end of soil profile drying will coincide with the stem water potential value of 8-10 bar and the tensiometer reading of more than -60 kPa at a soil depth of 30 cm as an indicator of desired stress levels to be achieved. The physical indicator will be leaf curling during the RDI stress period. However, the °Brix values will vary according to the rootstocks used or the climatic conditions during the growing season. The 10% reduction in large size fruit (81-78 mm) is expected for every 1 °Brix increase in sugar content.
- The responses of navel fruit to RDI are based on the rootstocks. *Troyer citrange* rootstock is more sensitive to RDI than *Poncirus trifoliata* rootstock. The fruit size reduction was higher in *Troyer citrange* rootstock, which has large canopies and requires more water than small size trees grown on *Poncirus trifoliata* rootstock.
- Macropyhylla rootstock is not recommended for Washington navel or Lane Late, because it is not compatible with those two scions. Washington navel and Lane Late trees completely failed to grow on *Citrus macrophylla* in the deep sandy loam soil at Dareton.
- Washington navel or Lane Late grown on *Citrus volkameriana* or *Swingle citrumelo* rootstock should never be stressed with RDI. *Citrus volkameriana* and *Swingle citrumelo* are extremely sensitive to imposed water stress with tree health and productivity significantly reduced.

M7 navels

- There should be no stress applied to M7 growing *on Poncirus trifoliata* or *Troyer citrange* rootstocks, because M7 navel is the earliest maturing navel in Australia and can have high sugar levels without the need to apply RDI treatments. The RDI treatments will significantly affect fruit size in M7 navels.
- M7 navel was found to have a good compatibility with *Citrus macrophylla* rootstock for trees planted at Dareton, and RDI can be recommended to enhance sugar levels without compromising the fruit size. To the author's knowledge, there is no compatibility data available for M7/*Citrus macrophylla* elsewhere in the literature. Therefore, growers could apply RDI on a small, test scale to assess the quality outcomes in a commercial orchard. The sugar content can be increased up to 1 °Brix in M7 navels grown on *Citrus macrophylla* rootstock without significant fruit size losses.
- M7 navel grown on *Citrus volkameriana* or *Swingle citrumelo* rootstock should never be stressed with RDI. *Citrus volkameriana* and *Swingle citrumelo* are extremely sensitive to imposed water stress with RDI treatments and offer no commercial advantage.
- The gradual decrease in water without a 2-week drying of the soil profile has minimal effect on increasing sugar levels for navel varieties.
- There should be no water stress imposed before 15 March for any navel varieties used in this study. Full irrigation should be applied during the active growth period (November to 15 March).

Other

- The results on 'Afourer' mandarins are not conclusive, as they were affected by regular rainfall during this study in the Riverina. Therefore, this study could be conducted in Sunraysia in the clay soil conditions typical of Curlwaa,

NSW. The time of RDI application should be by 15 March to have a significant increase in sugar levels of up to 2 °Brix. An increase of 1 °Brix may not offer any commercial market advantage for 'Afourer' mandarins.
- Current drone technology failed to detect any differences in canopy temperatures with a thermal camera in trees subjected to RDI treatments in February, March or April. The use of a multi-spectral camera also failed to produce any meaningful results with the use of normalised difference vegetation index (NDVI). NDVI is a measure of the level of green colour in the leaves.
- The sensory analysis data suggested that tasting of fruit is subjective among the general public and people find it difficult to pick up differences of 1 °Brix, whereas citrus growers and marketers were able to detect the 1 °Brix differences in fruit harvested from control and RDI treated trees.
- The storage trials conducted in 2021 on M7, Washington navel and Lane Late did not affect the internal quality of the fruit stored at 5 °C for 5 weeks, however, large scale transit trials need to be conducted in collaboration with MFC for export distance oranges.

Further Research

- The research work continues to apply and test RDI on a large-scale block with one variety and rootstock at a time.
- The use of RDI application in the month of May needs to be assessed for Washington navel and Lane Late oranges in future research.
- High-tech thermal cameras fitted to a drone should be used to detect canopy temperatures at lower altitude (50 m). One of the companies has claimed that an advanced thermal camera technology is now available. Therefore, the new technology should be tested in future work. If successful, growers will be able to assess water stress on their entire block of trees. This technique needs to be verified in future research project.
- Sensory evaluation should be conducted with growers and marketers as well as public based on ethnicity. The study should involve a trip to an Asian country(s) to understand the local public perception of taste and quality. The research project in future should collaborate with other institutes for sensory evaluation work.
- Simulated transit trials for RDI treated fruit should be conducted for export purposes in collaboration with Mildura Fruit Company (MFC).

Refereed scientific publications

- There were no refereed papers published from this project. There is a plan to publish a refereed paper in 2023 in a scientific journal.
- It is planned to present the data at the International Citrus Congress at Mersin, Turkey in November 2022. The work will be published in the conference proceedings in 2022/2023.
- A fact sheet will be produced prior to the commencement of 2023 growing season, so RDI can be applied by the growers. The fact sheet will be available at the NSW DPI website and also will be published via Citrus Australia website and the Australian Citrus News.

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Intellectual property

There is no Intellectual property attached to this project.

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Appendix 1: Detailed methodology

Trial site

A two-hectare site was established at NSW Department of Primary Industries Dareton in September 2010; this was used for the deficit irrigation research work. The trial site was 8 years old and in full commercial production at the start of the experimental program in 2018. There were 38 rows running North-South, with 27 trees per row, giving a total of 1,026 trees (Figure 2.1). Row to row distance was 5 m and the distance within the row was 2.5 m, giving a tree density of 800 trees/ha. The soil was a deep loamy sandy with all rootstocks having deep unimpeded root zones.

Figure 2.1. Aerial view of regulated deficit irrigation navel trial (2019) at the NSW DPI Dareton Research Station. Photo: Dr Tahir Khurshid.

Trees were drip-irrigated with 5 emitters per tree, each delivering 1.2 L/h, located on a double lateral with 0.6 m dripper spacing. Every winter the trees were lightly hand pruned and skirted after harvest. All other cultural activities were applied according to local practices. Readily available water (RAW) was calculated in the root zone and dripper-wetted area. Next, the irrigation was estimated for the control (T1) by measuring the evapotranspiration (ETc) using the FAO56 Penman Monteith method (ETc = ETo * Kc). Capacitance probe and water mark sensor readings were used to ensure the control continued to supply the correct amount of water. The treatments were based on reduced percentages of the control irrigation schedule. For example, in 2018, the irrigation water was switched off for T2 to the equivalent of 25 mm of the Etc from T1. The investigations of root zone for this trial indicated that the readily available water RAW indicated that the profile would completely dry out to 80 cm depth. The installed soil moisture probes confirmed this to be correct. Afterwards, 50% of the irrigation water was applied for 8 weeks in different treatments (given elsewhere in this report). Irrigation scheduling was based on the estimated ETc (ETc = ETo * Kc). ETo was calculated from weather information (Table 2.1).

Table 2.1: Annual reference evaporation (ETo) and rainfall for each experimental season.

Year	ETo (mm)	Kc	Rainfall (mm)
2018	1834	0.42	135
2019	1873	0.46	115
2020	1668	0.48	254
2021	1640	0.51	221

Experimental design

The experiment was conducted for 4 consecutive years (2018–2021) at NSW DPI, Dareton. There were 5 rootstocks (*Poncirus trifoliata*, *Troyer citrange*, *Swingle citrumelo*, *Citrus volkameriana* and *Citrus macrophylla*) and 3 navel varieties with different maturing times including M7 (early maturing), Washington navel (mid maturing) and Lane Late (late maturing). In each row, 3 varieties were randomly allocated as a single tree plot to each set of rootstocks within the row (Figure 2.2). The experimental plots were guarded with additional trees within the rows. The guard trees are shown in the trial plan as a non-coloured cell. Six regulated deficit irrigation treatments were randomly applied to the entire row within a block. There was a total of 6 blocks, therefore each irrigation treatment is replicated 6 times. This arrangement was suited well to a large scientifically designed and replicated trial. This was one of the larger replicated designed experiments in the world to the author's knowledge.

	Treat.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Block 1	T1			WN	M7	LL			LL	M7	WN			WN	M7	LL			WN	LL	M7			M7	LL	WN		
				TC	TC	TC			T	T	T			M	M	M			S	S	S			V	V	V		
	T6			WN	M7	LL			WN	M7	LL			M7	LL	WN			WN	M7	LL			WN	LL	M7		
				V	V	V			TC	TC	TC			T	T	T			M	M	M			S	S	S		
	T3			LL	M7	WN			LL	M7	WN			M7	LL	WN			WN	LL	M7			M7	LL	WN		
				T	T	T			V	V	V			S	S	S			TC	TC	TC			M	M	M		
	T2			M7	LL	WN			M7	LL	WN			M7	LL	WN			LL	WN	M7			M7	LL	WN		
				M	M	M			S	S	S			V	V	V			T	T	T			TC	TC	TC		
	T5			WN	M7	LL			LL	M7	WN			LL	M7	WN			LL	M7	WN			LL	WN	M7		
				V	V	V			M	M	M			TC	TC	TC			S	S	S			T	T	T		
	T4			M7	WN	LL			M7	WN	LL			LL	WN	M7			LL	WN	M7			M7	WN	LL		
				S	S	S			T	T	T			M	M	M			V	V	V			TC	TC	TC		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Block 2	T6			M7	LL	WN			M7	LL	WN			WN	M7	LL			WN	LL	M7			LL	WN	M7		
				V	V	V			T	T	T			M	M	M			S	S	S			TC	TC	TC		
	T5			WN	LL	M7			LL	M7	WN			WN	LL	M7			M7	WN	LL			M7	LL	WN		
				S	S	S			TC	TC	TC			V	V	V			T	T	T			M	M	M		
	T1			WN	M7	LL			WN	LL	M7			WN	M7	LL			M7	WN	LL			LL	WN	M7		
				M	M	M			S	S	S			T	T	T			V	V	V			TC	TC	TC		
	T2			WN	LL	M7			LL	M7	WN			LL	WN	M7			LL	M7	WN			WN	LL	M7		
				TC	TC	TC			M	M	M			V	V	V			T	T	T			S	S	S		
	T3			M7	WN	LL			LL	WN	M7			WN	M7	LL			M7	LL	WN			LL	M7	WN		
				T	T	T			S	S	S			TC	TC	TC			M	M	M			V	V	V		
	T4			M7	WN	LL			M7	WN	LL			M7	WN	LL			WN	M7	LL			LL	WN	M7		
				M	M	M			V	V	V			S	S	S			TC	TC	TC			T	T	T		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Block 3	T4			M7	LL	WN			M7	LL	WN			M7	WN	LL			M7	LL	WN			WN	M7	LL		
				V	V	V			S	S	S			T	T	T			TC	TC	TC			M	M	M		
	T5			M7	WN	LL			WN	LL	M7			WN	LL	M7			M7	WN	LL			M7	WN	LL		
				TC	TC	TC			T	T	T			M	M	M			S	S	S			V	V	V		
	T6			LL	M7	WN			WN	M7	LL			LL	M7	WN			LL	M7	WN			M7	WN	LL		
				M	M	M			TC	TC	TC			T	T	T			V	V	V			S	S	S		
	T1			WN	LL	M7			M7	LL	WN			M7	WN	LL			LL	M7	WN			LL	WN	M7		
				T	T	T			V	V	V			S	S	S			M	M	M			TC	TC	TC		
	T3			LL	M7	WN			WN	M7	LL			LL	WN	M7			LL	WN	M7			WN	M7	LL		
				TC	TC	TC			S	S	S			V	V	V			M	M	M			T	T	T		
	T2			WN	LL	M7			WN	LL	M7			LL	WN	M7			WN	LL	M7			M7	WN	LL		
				S	S	S			M	M	M			TC	TC	TC			T	T	T			V	V	V		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Figure 2.2. The experimental design of the trees. The plan is showing the first 3 blocks of the experiment.

Regulated deficit irrigation treatments

Six irrigation treatments were applied in each year for 2018 to 2021. The treatments varied every year and were determined by the project reference group after evaluating the results from the previous year's research work. A detailed treatment structure for each growing year is given later in the report (Chapter 1-4, Appendix 2).

Water used during the RDI period

The total amount of water used during the RDI period is given below for the control treatment for the treatments applied in early-March, mid-March and early- April. In all treatments soil profile was dried for 2 weeks, followed by 50% irrigation for 8 weeks. During this period there was a saving of 0.89 ML/ha, 0.79 and 0.75 ML/ha for early-March, mid-March and early- April respectively (Table 2.2)

Table 2.2: Water usage and water savings ML/ha during the RDI period*

	Control	1-15 March	15-20 March	1-15 April
Water used	2.42	1.53	1.64	1.67
Water saved		0.89	0.79	0.75

*This includes water usage for the 2 weeks of soil profile drying period plus 8 weeks of 50% irrigation

Plant water status

Pre-dawn water potential is said to be a more reliable indicator of plant water status since it is measured when the plant is assumed to be in equilibrium with the soil water potential (Naor 2000). Therefore, it is less subjected to temperature and sunlight variability throughout the day. The pressure required to force water out of the stem of a severed leaf equals the water potential and is measured by a pressure gauge. As soil moisture is depleted, more tension develops in the plant, requiring more pressure to force water out of the cut surface of the leaf stem. During the period of water restrictions, pre-dawn stem water potential was recorded twice weekly with a pressure chamber (Model 600 Pressure Chamber Instrument) (Figure 2.2) in 3 mature leaves following the procedure described by Turner (1981). Samples were taken from Washington navel (mid maturing) trees on 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange)* for each irrigation treatment in 2 replicates. Pressure chamber measurements were made between January and August in 4 growing seasons (Table 2.3).

Figure 2.2: Pre-dawn stem water potential was recorded in a pressure chamber on fully expanded leaves. Photo: Dr Tahir Khurshid.

Table 2.3: Pressure chamber data were collected on given dates to measure the pre-dawn* stem water potential. The number of occasions the data were recorded is given in parenthesis.

2018	2019	2020	2021
27 Feb	6 Mar–20 Jul (n = 22)	3 Jan–22 May (n = 22)	17 Feb–17 May (n = 23)

*Data were collected early in the morning while it was still dark and was completed 30 minutes before sunrise.

Tensiometers

A set of tensiometers were installed for Washington navel (mid maturing) trees at depths of 30, 60 and 90 cm for 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange)* for each irrigation treatment in 2 replicates (Figure 3.2D). Tensiometers provide the soil tension levels through a gauge. A value > 35 is considered ‘stressed’ for the soil depth in question. Data were manually collected every second day at about 10.00 am between January and August for 4 growing seasons (Table 2.4).

Table 2.4: Tensiometer data were collected at 30, 60 and 90 cm depths on given dates* to measure soil tension. The number of occasions the data were recorded is given in parenthesis.

2018	**2019**	**2020**	**2021**
13 Mar-24 Jul (n = 19)	13 Jan-1 Jul (n = 40)	14 Jan-26 Jul (n = 51)	18 Jan-24 May (n = 39)

*Data were collected each morning at 10.00 am.

Gypsum blocks

Gypsum blocks use 2 electrodes placed into a small block of gypsum to measure soil water tension. Wires connected to the electrodes are connected to either a portable hand-held reader or a data logger. The amount of water in the soil is determined by the electrical resistance between the 2 electrodes within the gypsum block; more water in the soil will reduce the resistance, while less water will increase it. A set of gypsum blocks were installed for M7, Washington navel and Lane Late trees to depths of 30, 60 and 90 cm for 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) for each irrigation treatment in one replicate (Figure 3.2B), making a total of 36 gypsum blocks for the experiment. Gypsum blocks were automated, and the data were transferred to a computer every 60 minutes.

EnviroPro soil sensors (probes)

Enviro probes (Entelechy Pty Ltd) provide an estimation of the soil moisture status for each sensor at each depth. Each Enviro probe (1 m long) has 8 sensors fixed to the probe in 10-cm increments (Figure 3.2A and C). Probes were installed for M7, Washington navel and Lane Late for 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) for each irrigation treatment in one replicate. The probes were automated and the data were transferred to a computer every 60 minutes.

			
Figure 2.3A: 1-meter-long Enviro probes (green) were installed. Each probe has 8 sensors graduated at 10 cm depths.	Figure 2.3B: Gypsum blocks (30, 60 and 90 cm depth). Sensors are attached at the bottom of a PVC pipe.	Figure 2.3C: Wi-Fi Lan system to telecast data directly to a computer for Enviro probe and gypsum blocks.	Figure 2.3D: Tensiometers installed at 30, 60 and 90 cm depths. Data were recorded manually.
Photos: Dr Tahir Khurshid.			

Fruit growth measurements

Twenty fruit around the tree canopy of selected trees were randomly selected and tagged. Fruit diameter (mm) measurements were collected with digital callipers (Mitutoyo Digimatic, Japan) weekly after fruit drop was complete in January (Table 2.5). These measurements were recorded for each variety for each rootstock, but the data will only be presented for *Poncirus trifoliata* and *Troyer citrange*. Data were collected from 2 replicates for each irrigation treatment.

Table 2.5: Fruit growth data were collected for M7, Washington navel (WN) and Lane Late navel for 4 growing seasons. The number of occasions the data were recorded is given parenthesis.

	2018	2019	2020	2021
M7	8 Jan–30 Apr (15)	7 Jan–4 May (17)	3 Jan–23 Apr (16)	4 Jan–24 Apr (17)
WN	8 Jan–29 May (18)	7 Jan–26 Jun (22)	3 Jan–4 Jun (21)	4 Jan–24 May (20)
Lane Late	8 Jan–7 Jul (24)	7 Jan–26 Jun (22)	3 Jan–11 Jul (23	4 Jan–14 Jul (24)

Fruit quality profiles throughout the growing season

Data on fruit quality profiles (°Brix and acid) were collected weekly for each variety from 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) in 6 irrigation treatments from 2 replicates. Five fruit per tree were randomly selected from around the tree canopy throughout the growing season and taken to the laboratory to assess internal fruit quality. Per cent TSS of the juice was measured as °Brix with an Atago PAL-1 refractometer (www.atago.net, Japan) and % citric acid (% acid) was estimated by titrating 10 mL of juice against standard 0.1 mol/L NaOH solutions. The juice sugar:acid ratio was calculated from this data as described by El-Zeftawi (1982). Fruit quality profile data were collected weekly for 4 years from when water stress was first applied to the trees (Table 2.6). This was done to assess how the irrigation deficits affected the fruit sugar and acid levels.

Table 2.6: Fruit quality data were recorded weekly for M7, Washington navel (WN) and Lane Late navel for 4 growing seasons. The number of occasions the data were recorded is given parenthesis.

	2018	2019	2020	2021
M7	27 Feb–16 May (13)	7 Mar–29 May (13)	24 Feb–27 Apr (9)	24 Feb–3 May (11)
WN	27 Feb–6 Jun (15)	7 Mar–26 Jun (17)	24 Feb–9 Jun (14)	24 Feb–24 May (15)
Lane Late	27 Feb–15 Jul (20)	7 Mar–16 Jul (19)	24 Feb–6 Jul (17)	24 Feb–14 Jul (22)

Fruit quality assessment at harvest

The internal fruit quality measurements were carried out at harvest. Ten fruit per tree were randomly selected from around the tree canopy. Per cent TSS of the juice was measured as °Brix with an Atago PAL-1 refractometer (www.atago.net, Japan) and % citric acid (% acid) was estimated by titrating 10 mL of juice against standard 0.1 mol/L NaOH solutions. The juice sugar:acid ratio was calculated from this data as described by El-Zeftawi *et al*. (1982). BrimA is an Australian quality standard used a maturity index and is calculated as (°Brix-(% Acid × 4)) × 16.5 (Clark 2016).

Yield determination and fruit size distribution

Fruit and tree yield for each experimental tree were recorded at harvest (Table 2.6). Fruit size (diameter) was sorted into 5 classes based on < 65 mm (> 138 fruit/carton), 65–67 mm (138–125 fruit/carton), 69–75 mm (113–100 fruit/carton), 75–81 mm (88 fruit/carton) and 81–87 mm (< 80 fruit/carton) using a commercial grader [Colour Vision Systems Pty Ltd, Australia (MAF Oceania group)]; Figure 2.4. Fruit yield was adjusted for the number of fruits harvested during weekly sugar profiles and fruit used for quality determination at the final harvest (Table 2.7).

Figure 2.4: Fruit were weighed, counted and graded into different size classes for each tree with a commercial Colour Vision grading machine at Dareton. Photo: Dr Tahir Khurshid.

Table 2.7: Fruit harvest dates for M7, Washington navel and Lane Late navel for 4 growing years.

	2018	2019	2020	2021
M7	16 May	3 June	5 May	10 May
Washington navel	6 June	2 July	17 June	15 June
Lanes Late	31 July	5 August	29 July	29 July

Appendix 2: Detailed results and discussion

This section has 10 chapters and the entire experimental program, results and discussions are given in this section.

Chapter 1: Experimental program for navel oranges – 2018

Irrigation treatments

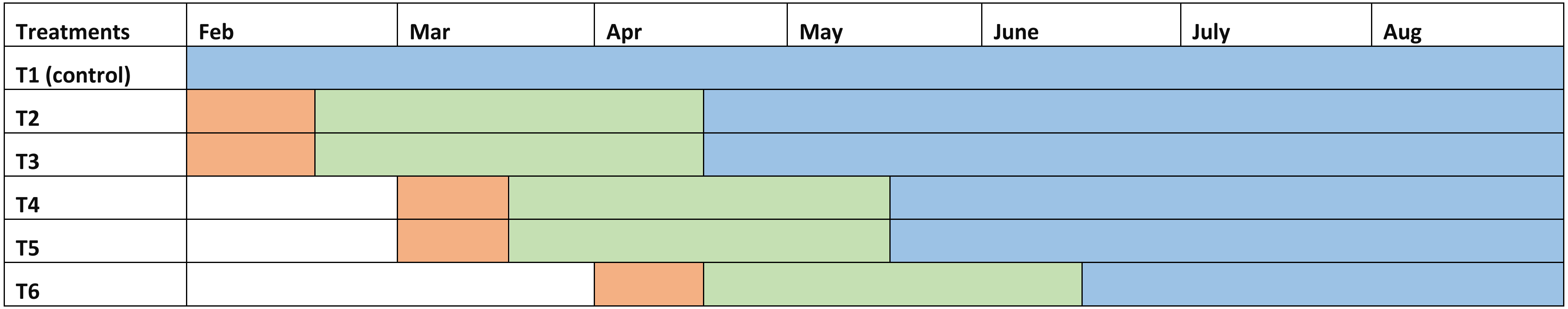
Six regulated deficit irrigation treatments were applied to experimental trees during the active fruit development stages (from late December to late March (Bevington and Khurshid 2007)). The treatments were designed to apply 2 soil stress levels (mild and severe) in Early-February, mid-March and Late-April to assess fruit quality effects, fruit yield and fruit size distribution in citrus trees. The irrigation treatment structure applied in 2018 is in Table 1.1. The orange boxes represent the drying period when irrigation water was withheld from the trees. This drying period was necessary to empty the soil profile to 30 cm so an accurate volume of water could then be applied. This drying period also imposes water stress on the trees to trigger an increase in sugar levels as early as possible. The light green boxes represent the availability of 50% irrigation water and the blue boxes represent the availability of 100% irrigation water.

Stress physiology and plant responses

The Enviro probes indicated soil moisture percentage after applying 2 different levels of water stress to citrus trees at 25 mm and 35 mm in February and March. In April, the treatment was applied only at 25 mm. Irrigation was ceased completely for 2 weeks for 25 mm and 3 weeks for 35 mm of calculated Etc.

T1 was the control, receiving 100% irrigation. In T2 (25 mm) and T3 (35 mm), the soil profiles were dried from 1–15 February, and 50% irrigation was applied for 8 weeks from 16 February, followed by 100% irrigation from 15 April until harvest. However, the effects from drying lasted until 28 February (approximately 2 weeks) in T2 (25 mm; Figure 1.1). The stem water potential was 31.7 bar for T2 on 28 February (Table 1.2). In T3 (35 mm), these effects lasted until 7 March (approximately 3 weeks; Figure 1.1) and the stem potential was 32.4 bar on 28 February (Table 1.2). T2 and T3 received 100% irrigation from 15 April, however, trees recovered after 20 days on 5 May to approximately the same level as the control trees (Figure 1.1). In the regulated deficit treatments T4 (25 mm) and T5 (35 mm), the soil profiles were dried from 1–15 March, and 50% irrigation was applied for 8 weeks from 16 March followed by 100% irrigation from 15 May until harvest (Table 1.1). In T6 (25 mm) the soil profiles were dried from 1–15 April, and 50% irrigation was applied for 8 weeks from 16 April followed by 100% irrigation from 15 June until harvest (Table 1.1).

Table 1.1: Regulated deficit irrigation treatment plan and its duration for the 2018 growing season.



Key

Dry period	50% irrigation	100% irrigation

T1 – 100% irrigation per ETc, throughout the entire growing season (control)
T2 – Profile drying down to 25 mm (1–15 February), 50% irrigation of T1 (15 February–15 April), 100% irrigation (15 April to harvest) – early mild stress (EMS)
T3 – Profile drying down to 35 mm (1–15 February), 50% irrigation (15 February–15 April), 100% irrigation (15 April to harvest) – early severe stress (ESS)
T4 – Profile drying down to 25 mm (1–15 March), 50% irrigation (15 March–15 May), 100% irrigation (15 May to harvest) – mid mild stress (MMS)
T5 – Profile drying down to 35 mm (1–15 March), 50% irrigation (15 March–15 May), 100% irrigation (15 May to harvest) – mid severe stress (MSS)
T6 – Profile drying down to 25 mm (1–15 April), 50% irrigation (15 April–15 Jun), 100% irrigation (15 June to harvest) – late mild stress (LMS)

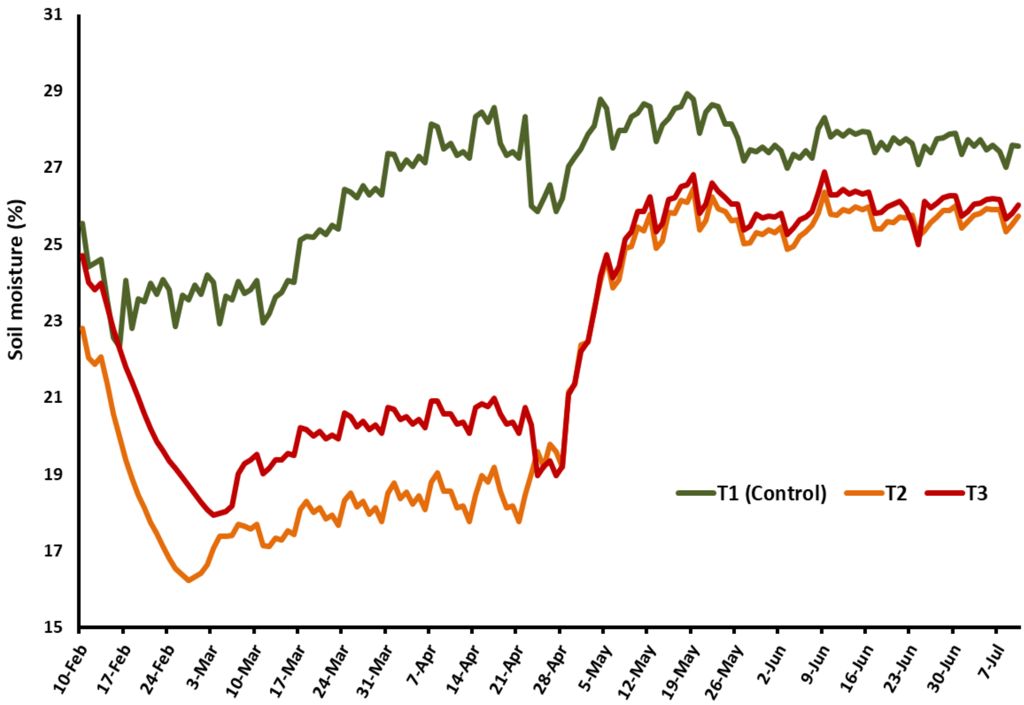


Figure 1.1: Soil moisture (%) during irrigation treatments T1 (control), T2 (applied in February at 25 mm) and T3 (applied in February at 35 mm) for the 2018 growing season.

Table 1.2: Midday stem water potential (SWP) for the 6 irrigation treatments.

Irrigation treatments	SWP (Bar*)
T1 (control)	20.4
T2	31.7
T3	32.4
T4	26.5
T5	25.5
T6	20.4

*SWP values are given in Bar. 1 Bar = 0.1 MPa (Mega pascal). T2 and T3 were under water stress, while T4 and T5 were at the beginning of water stress. T6 was not under stress. Data were recorded on 28 February 2018.

Visual depiction of water stress

Insufficient soil water is the most common cause of curling citrus leaves. This can occur at any time of year but is most common with trees that are not regularly irrigated during hot weather. In this study, stressed trees displayed curled leaves once the soil moisture was depleted from the soil (Figure 1.2). The amount of leaf curling was related to the degree of stress.

Figure 1.2: Photos taken during profile drying, Control tree with no imposed stress (left), and tree with medium to severe imposed stress (Right). Photos: Dr Tahir Khurshid.

Fruit quality components at harvest

Fruit quality data were collected at harvest from all experimental trees on 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) and 6 irrigation treatments. The main effect for irrigation treatments were significant for M7, Washington navel and Lane Late.

In M7, °Brix values were increased by 1° for treatments T2, T3 and T4 compared to the control (Table 1.3). The rootstock effect was not significant for °Brix levels. There was a significant effect of irrigation treatments on BrimA values (the Australian standard for maturity), which were increased with T2 and T3 compared to the control. The rootstock effect was not significant for BrimA values. The were no effects of irrigation treatments or rootstocks on acid levels or juice content.

The interaction between irrigation treatments and rootstocks was significant for °Brix, BrimA values and acid levels (Table 1.4). Irrigation treatments T2 and T6 had increased °Brix values compared to the control on *Poncirus trifoliata* rootstock (15.1, 15.4 and 13.8, respectively). T6 increased °Brix by 1.6, and this increase has an important commercial significance to the citrus industry. In another significant interaction, irrigation treatments T2 and T6 had increased BrimA values compared to the control (176, 181 and 159, respectively) on *Poncirus trifoliata* rootstock. The increase in T6 was up by 22 units compared to the control. The interaction effect was also significant for the acid values on *Poncirus trifoliata* rootstock with irrigation treatments T3 and T4 having increased acid levels compared to the control (1.2, 1.3 and 1.0, respectively; Table 1.4). In the interaction effects, *Troyer citrange* did not show any effect on the quality attributes.

Table 1.3: Fruit quality attributes °Brix, BrimA, acid (%) and juice (%) in M7, Washington navel and Lane Late navels for the 2018 growing season.

	M7				Washington navel				Lane Late			
Irrigation treatments (It)	°Brix	BrimA	Acid (%)	Juice (%)	°Brix	BrimA	Acid (%)	Juice (%)	°Brix	BrimA	Acid (%)	Juice (%)
T1 (control)	14.4	163	1.1	53	13.0	131	1.3	48	12.8	143	1.0	51
T2	15.5	180	1.2	46	14.6	157	1.3	46	14.6	161	1.2	50
T3	15.2	170	1.2	46	14.8	148	1.5	46	14.9	164	1.2	49
T4	15.1	168	1.2	44	14.2	147	1.3	48	14.7	165	1.2	50
T5	14.8	165	1.2	51	14.0	149	1.3	47	14.9	174	1.1	52
T6	14.8	166	1.2	47	13.7	139	1.3	48	13.7	154	1.1	51
Probability	*	*	ns	ns	***	***	*	ns	***	***	***	ns
LSD ($p < 0.05$)	0.60	6.81	1.31	–	0.53	10.20	0.12	–	0.63	11.56	0.08	–
Rootstocks (Rt)												
Poncirus trifoliata	14.8	168	1.2	47	14.0	144	1.3	47	14.1	159	1.1	50
Troyer citrange	15.1	170	1.2	49	14.1	146	1.3	47	14.4	161	1.2	51
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–	–	–	–
Interaction (It × Rt)												
Probability	***	***	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	0.95	16.68	0.19	–	–	–	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Table 1.4: The interaction between irrigation treatments and rootstock for M7 navel fruit quality attributes for the 2018 growing season.

	Poncirus trifoliata	***Troyer citrange***	***Poncirus trifoliata***	***Troyer citrange***	***Poncirus trifoliata***	***Troyer citrange***
	°Brix		BrimA		Acid (%)	
Irrigation treatments			**M7**			
T1 (control)	13.8	15.1	159	167	1.04	1.24
T2	15.1	15.9	176	183	1.10	1.21
T3	15.0	15.4	167	174	1.23	1.22
T4	14.8	15.4	156	180	1.34	1.12
T5	14.7	14.8	166	163	1.17	1.23
T6	15.4	14.1	181	152	1.11	1.24
Probability	*		**		*	
LSD ($p < 0.05$)	0.95		71		0.2	

Mean separation within the columns was tested with LSD at the same rootstock across different irrigation treatments. *$p < 0.05$, **$p < 0.01$.

In Washington navel, °Brix, BrimA and acid were increased with deficit irrigation treatments. °Brix values increased with T2, T3, T4 and T5 compared to the control (Table 1.3), with T2 and T3 values increasing by 1.6 and 1.8 degrees, respectively. Rootstock did not affect °Brix values. Irrigation treatments T2, T3, T4 and T6 increased BrimA values, with the greatest increase from T2 (Table 1.3). Rootstock had no effect on °Brix values. Fruit acid levels were only increased with T3, the severe stress (35 mm) treatment. Mild stress normally fails to enhance acid levels. Juice content was not influenced by irrigation treatments or rootstock. There was no interaction effect between irrigation treatments and rootstocks for any quality attributes (Table 1.3).

In Lane Late navels, the effect of irrigation treatments was significant on °Brix, BrimA and acid levels. °Brix values were increased by all irrigation treatments compared to the control (Table 1.3). However, the extent of this increase was highest for T3. The BrimA values were increased by T2, T3, T4 and T5 compared to the control, however, the increase with T5 was much higher compared to T6 (Table 1.3). The acid levels in the fruit were only increased with T2 and T3 compared to the control. There was no effect of rootstock on any quality attributes. The interaction effect between irrigation treatments and rootstocks was not significant for any quality attributes (Table 1.3).

Fruit yield components at harvest

Fruit yield components at harvest were recorded on all experimental trees for M7, Washington navel and Lane Late oranges. Trees were fully harvested, and yield components were recorded.

In M7 navels, there were no significant effects of irrigation treatments on fruit yield/tree, fruit number/tree or average fruit weight. Trees carried an average of 30.4 kg/tree and average fruit number/tree was 202 (Table 1.5). Fruit number/tree was lower in trees growing on *Poncirus trifoliata* rootstock than *Troyer citrange*. While it appeared that average fruit weight was decreased by deficit irrigation treatments compared to the control, it was not a statistically significant outcome, but it could be commercially important. The rootstock effect was also significant on average fruit weight, which was decreased by 21.5 g/fruit on trees growing on *T. citrange* rootstock compared to *Poncirus trifoliata* (Table 1.5).

In Washington navels, there were no significant effects of irrigation treatments on fruit yield/tree or fruit number/tree. Trees carried an average of 31.4 kg/tree and average fruit number/tree was 274 (Table 1.5). Fruit number/tree was lower in trees growing on *Poncirus trifoliata* rootstock than *Troyer citrange*. Fruit weight decreased significantly with the deficit irrigation treatments from 13.3 g to 26.4 g compared to the control (Table 1.5). The rootstock effect was also significant on average fruit weight, which decreased by 10.5 g/fruit on trees growing on *Troyer citrange* rootstock compared to *Poncirus trifoliata* (Table 1.5).

In Lane Late navels, there were significant effects of irrigation treatments on fruit yield/tree, fruit number/tree and average fruit weight. Fruit yield/tree increased from 10.5 kg/tree to 21.1 kg/tree with the different irrigation treatments compared to the control (Table 1.5). The effect on fruit number/tree was also significant, and irrigation treatments T4 and T5 had fewer fruit than the control.

In M7 navels, fruit number/tree was lower in trees growing on *Poncirus trifoliata* rootstock compared to *Troyer citrange*. Fruit weight was decreased with T2, T3, T4 and T5 compared to the control (Table 1.5). The rootstock effect was also significant on average fruit weight, which decreased by 13.7 g/fruit on trees growing on *Troyer citrange* rootstock compared to *Poncirus trifoliata* (Table 1.5).

There were no significant interaction effects found between irrigation treatments and rootstocks for M7, Washington navel or Lane Late oranges (Table 1.5).

Table 1.5: Fruit yield (kg)/tree, fruit number/tree and individual fruit weight in M7, Washington navel and Lane Late navels for the 2018 growing season.

	M7 navel			Washington navel			Lane Late navel		
Irrigation treatments (It)	Fruit yield (kg)	Fruit number	Fruit weight (g)	Fruit yield (kg)	Fruit number	Fruit weight (g)	Fruit yield (kg)	Fruit number	Fruit weight (g)
T1 (control)	33.2	207	165.7	34.6	263	130.8	51.4	261	198.0
T2	31.2	217	143.6	28.3	257	109.0	36.8	221	163.3
T3	27.2	183	152.3	30.1	293	104.4	40.9	248	163.1
T4	29.7	196	151.1	28.7	253	113.4	33.0	189	174.4
T5	27.0	183	151.5	31.8	286	109.6	29.9	181	163.9
T6	34.2	231	147.6	34.7	293	117.5	37.7	208	182.0
Probability	ns	ns	ns	ns	ns	**	**	*	**
LSD ($p < 0.05$)	–	–	–	–	–	12.3	10.2	57.7	20.9
Rootstocks (Rt)									
Poncirus trifoliata	30.2	188	162.7	30.3	255	119.5	36.5	200	181.3
Troyer citrange	30.6	217	141.2	32.4	293	108.7	40.0	236	167.6
Probability	ns	*	***	ns	*	**	ns	*	*
LSD ($p < 0.05$)	-	30.6	8.8	–	36	7.1	–	33.3	12.0
Interaction (It x Rt)									
Probability	ns	ns	*	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	21.5	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks, and the interactions. * $p < 0.05$, ** $p < 0.01$ and ns (non-significant).

Fruit size distribution

Fruit size distribution was assessed for all experimental trees for each variety and rootstock. The analysed data is shown in Table 1.6 for the main exportable size classes for main effects and interaction effects for irrigation treatments and rootstocks. The data extracted from Table 1.6 is also presented in Figures 1.3 to 1.5, so the data is visually and effectively communicated to readers.

In M7 navel, the irrigation treatments did not affect the size classes (Figure 1.3). However, compared to the control, the deficit irrigation treatments decreased the fruit in size class 81–87 mm and even though this was not statistically significant (Table 1.6), it has commercial significance, because large fruit have higher monetary returns. The extent of reduction was related to the time of irrigation application and T2 had a 15% reduction compared to the control. The percentage of fruit size reduction was significant for rootstocks in size classes 75-81 mm and 81–87 mm. On both occasions *Troyer citrange* had reduced fruit size by 8% compared to *Poncirus trifoliata* (Table 1.6). The interaction effect was significant for size class 75-81 mm, the fruit size per cent was significantly decreased with T2 (15%) and T3 (19%) compared to T1 (26) in *Troyer citrange* rootstock (data not shown).

In Washington navel, T2, T3, T4 and T5 had more fruit in the 69–75 mm size class than T1 (Table 1.6). All the irrigation treatments significantly reduced the amount of fruit in the 81–87 mm class (Table 1.6 and Figure 1.4). Rootstock influenced the amount of fruit in the large size class, with *Poncirus trifoliata* producing more large sized fruit than *Troyer citrange* and the interaction with rootstock and irrigation treatment was also significant for size class 75–81 mm (Table 1.6).

In Lane Late navel, T2 and T3 had 22% less large-sized (81–87 mm) fruit compared to the control, while T4 and T5 had 15% and 22% reduction respectively. T5 had 10% reduction compared to the control (Table 1.6 and Figure 1.5). *Poncirus trifoliata* produced added large fruit than *Troyer citrange* (Table 1.6). The interaction effect was not significant between irrigation treatments and rootstocks.

Relationship of large fruit size (81–87 mm) vs °Brix (total soluble solids)

Regression analysis was carried out between large fruit size (81–87 mm) and ^{0}Brix values. A significant relation was found for M7, Washington navel and Lane Late navel oranges. The data indicated that the relation between fruit size and sugar levels was reasonably strong (R^2 = 0.62) for M7 navels (Figure 1.6), however, this relationship was stronger for Washington navel (R^2 = 0.99), Figure 1.7, and Lane Late navel oranges (R^2 = 0.93), Figure 1.8. M7 is generally an early maturing orange and the sugar levels increase quickly with maturity compared to the mid-maturing Washington navels and late-maturing Lane Late navels. These relationships show that the increase in sugar levels induced by deficit irrigation treatments by the water volumes has a pronounced effect on large-sized fruit and the degree of stress dictates the fruit size and increased sugar levels in sweeter oranges. However, in M7, the maturity time was also a contributing factor, causing a weak relationship.

Table 1.6: Fruit size distribution (%)/tree for M7, Washington navel and Lane Late navel in different size classes per tree for the 2018 growing season.

	M7			Washington navel			Lane Late		
Irrigation treatments (It)	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm
T1 (control)	28	27	26	24	31	35	17	34	44
T2	32	25	11	32	30	16	25	31	23
T3	28	25	20	36	32	13	28	37	22
T4	29	27	16	30	31	20	28	32	29
T5	29	27	19	29	34	21	28	31	22
T6	32	25	15	26	36	25	26	27	34
Probability	ns	ns	ns	***	ns	***	*	*	**
LSD (p < 0.05)	–	–	–	4.9	–	8.9	7.4	6.1	12.3
Rootstocks (Rt)									
Poncirus trifoliata	29	30	22	27	32	26	23	32	33
Troyer citrange	30	22	14	33	33	17	27	32	25
Probability	ns	***	*	ns	ns	***	ns	ns	*
LSD (p < 0.05)	–	3.3	6.0	–	–	4.9	–	–	7.1
Interaction (It x Rt)									
Probability	ns	**	ns	ns	*	ns	ns	ns	ns
LSD (p < 0.05)	–	8.0	–	–	6.6	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *p < 0.05, **p < 0.01, ***p < 0.001 and ns (non-significant).

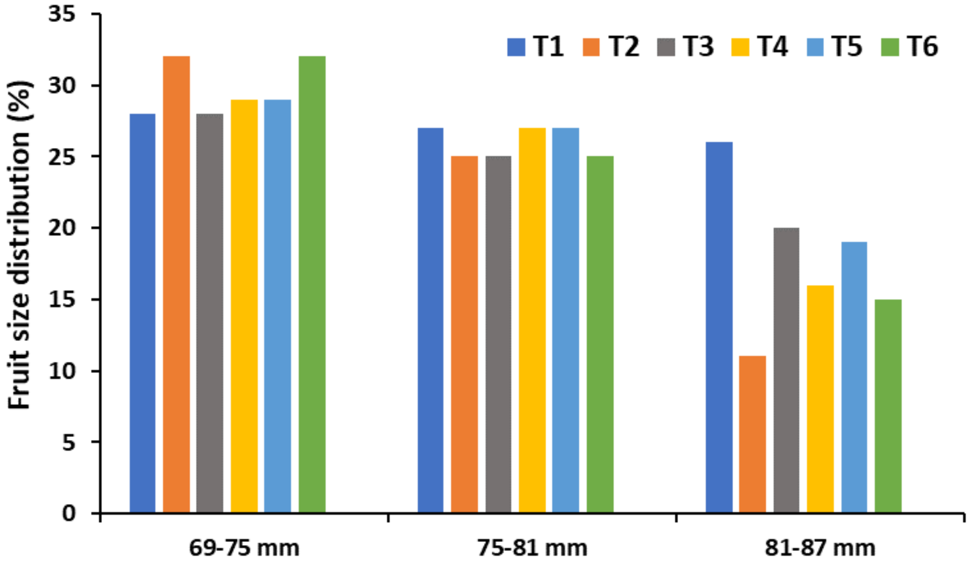


Figure 1.3: Fruit size distribution (%) of 3 export size classes for M7 navels at harvest. Six irrigation treatments were applied in the 2018 growing season. T1 is the control (100% irrigation).

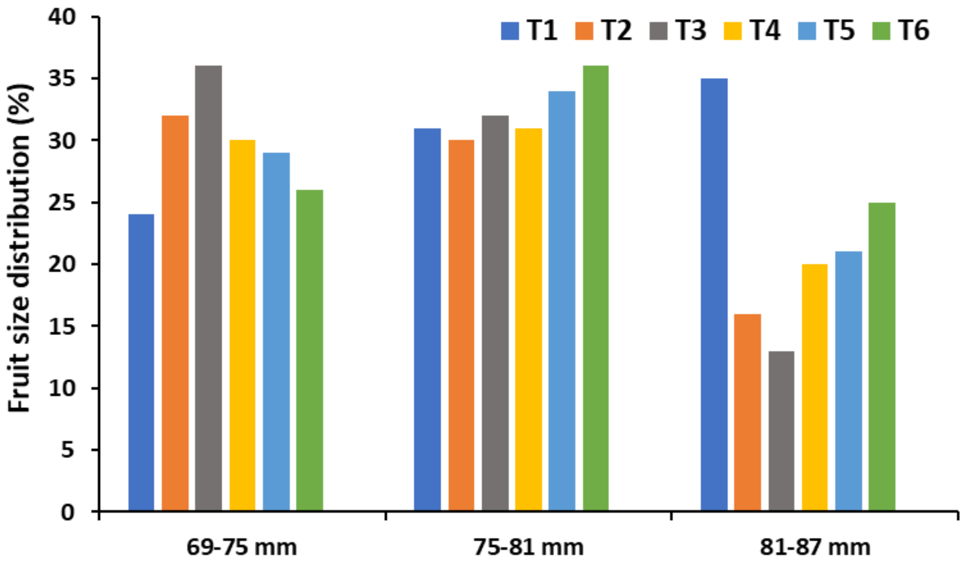


Figure 1.4: Fruit size distribution (%) of 3 export size classes for Washington navels at harvest. Six irrigation treatments were applied in the 2018 growing season. T1 is the control (100% irrigation).

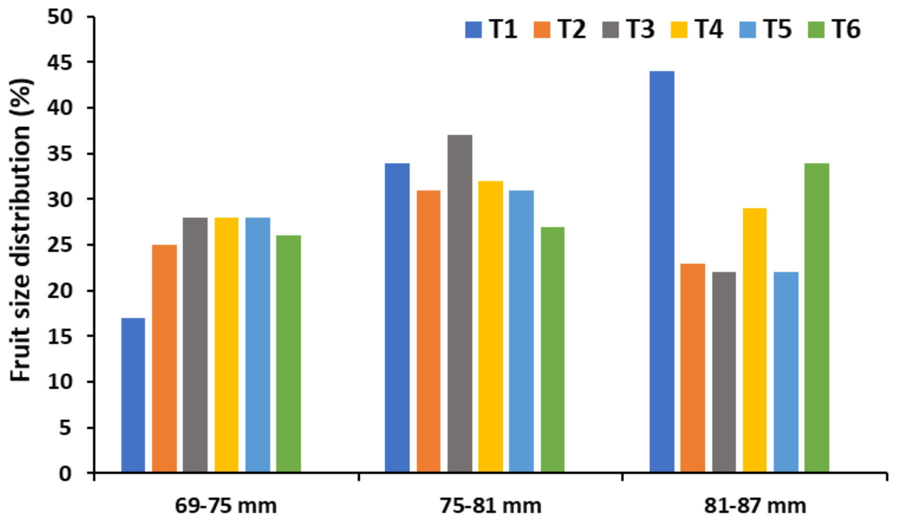


Figure 1.5: Fruit size distribution (%) of 3 export size classes for Lane Late navels at harvest. Six irrigation treatments were applied in the 2018 growing season. T1 is the control (100% irrigation).

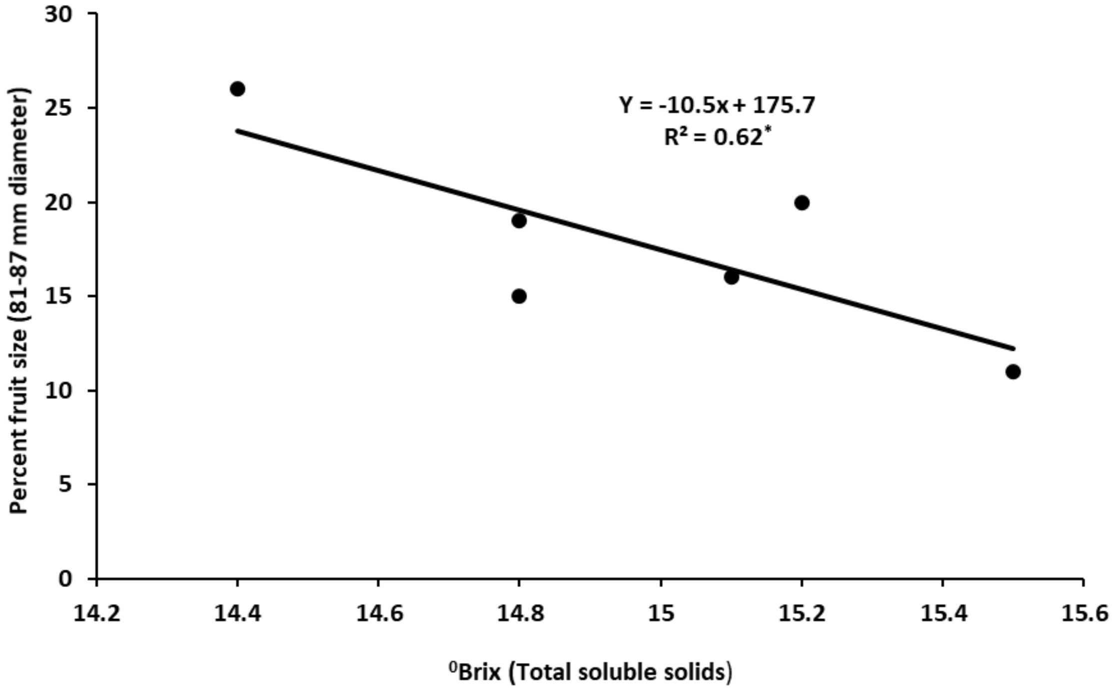


Figure 1.6: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for M7 navel in 2018. Regression coefficient $R^2 = 0.62$ is significant at $p < 0.05$ (*).

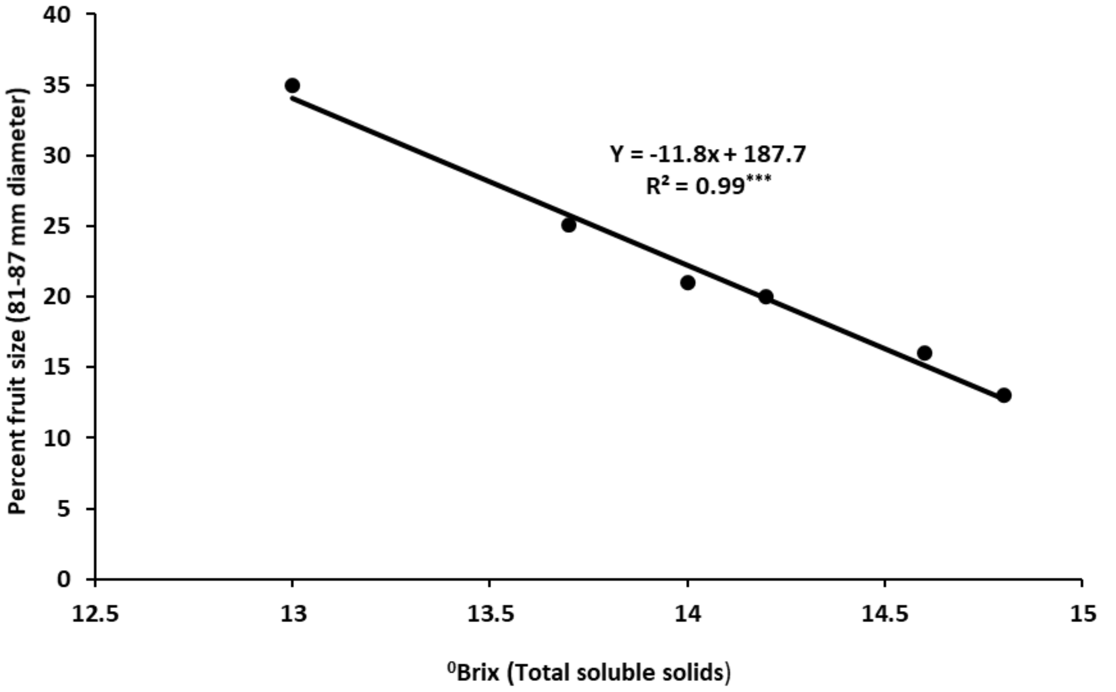


Figure 1.7: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for Washington navel in 2018. Regression coefficient $R^2 = 0.99$ is significant at $p < 0.001$ (***).

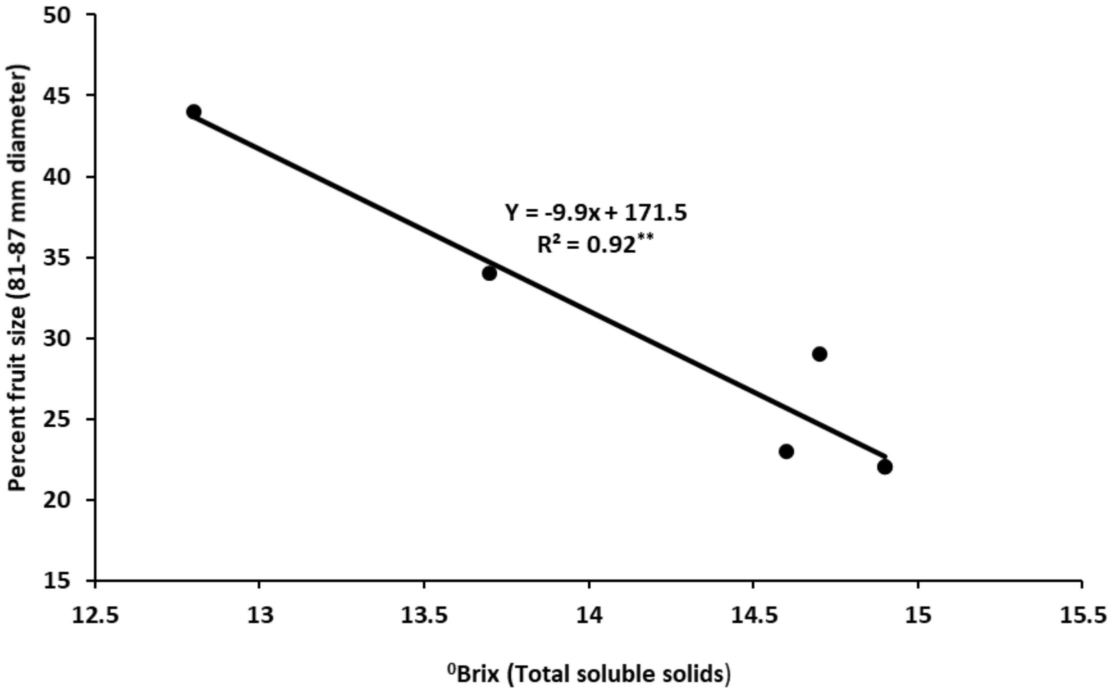


Figure 1.8: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for Lane Late navel in 2018. Regression coefficient $R^2 = 0.92$ is significant at $p < 0.01$ (**).

Chapter 2: Experimental program for navel oranges – 2019

Irrigation treatment structure

Six irrigation treatments were applied to the experimental trees at different periods during the active fruit development stages, which lasts from late December to late March (Bevington and Khurshid 2007). The treatments were applied in early-March, late-March and early-April to assess fruit quality effects, fruit yield and fruit size distribution in citrus trees. The irrigation treatment structure for 2019 is given in Table 2.1. Orange coloured boxes represent the drying period when irrigation water is withheld from the citrus trees. This is done to empty the soil profile to 30 cm depth so an accurate volume of water can be applied to the soil and to impose water stress on the trees to trigger the increase sugar levels as early as possible. Light green boxes represent the availability of 50% irrigation water and blue boxes represent the availability of 100% irrigation water.

T1 is the control, receiving 100% irrigation water. In T2, the soil profile was dried for 2 weeks (1–15 March), and then 100% irrigation water was applied to wet the profile followed by drying it again and this pattern were continued until harvest. In T3, the soil profile was dried for 2 weeks (1–15 March) and 50% irrigation was applied for 8 consecutive weeks. In T4, soil profile was dried for 2 weeks (15–30 March), and then 50% irrigation was applied for 8 consecutive weeks. In T5, the soil profile was dried for 2 weeks (1–15 April), and then 50% irrigation was applied for 8 consecutive weeks. In T6, the soil profile was dried for 2 weeks (1–15 April) and then 50% irrigation water was applied continuously, and trees were re-irrigated one week before harvest for M7, Washington navel and Lane Late navels (Table 2.1).

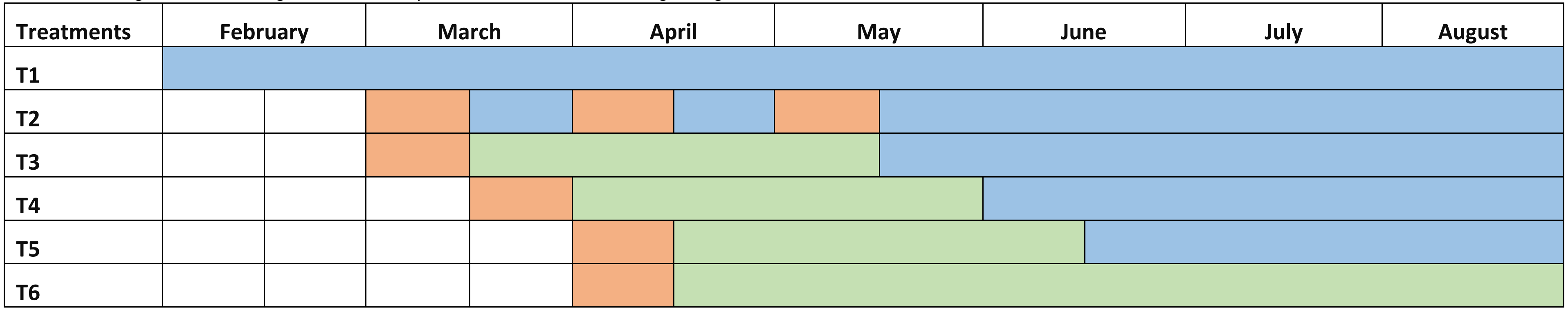
Stress physiology and plant responses

Enviro probes indicated the water levels after applying different levels of water stress to the citrus trees. The drying pattern of T2 vs T1 (control) is given in Figure 2.1.

In T2, the soil profile was dried from 1–15 March and then full irrigation of 16 hours was applied over 2 days (16 and 17 March) to fill the soil profile; this was achieved by 19 March. The profile was dried again for 7 days and was re-irrigated on 28 and 29 March with 10 hours of irrigation. The pattern of drying and wetting continued until August (Figure 2.1). Tree response was measured by the pre-dawn stem water potential (SWP), which corresponds to the values of 9.7 bar (Table 2.2) after achieving the desired stress levels.

In T3, the soil profile was dried from 1–15 March followed by 50% irrigation for 8 consecutive weeks (Figure 2.2). The stem water potential was 8.9–9.3 bar between 13–15 March (Table 2.1). In T4, the soil profile was dried from 15–30 March followed by 50% irrigation for 8 consecutive weeks (Figure 2.2). The stem water potential values reached 7.4 bar by 29 March (Table 2.2). In both T5 and T6, the soil profile was dried from 1–15 April. The stem water potential values were 6.8 and 6.5 bar on 16 April for T5 and T6 respectively. In T5, 50% irrigation was applied for 8 consecutive weeks after the drying period, while in T6, 50% irrigation was continued until harvest for each of the navel varieties (Figure 2.2). The Enviro probe data indicated the drying and irrigation treatments were achieved as planned. The water stress caused by the later treatments (T5 and T6) was not as severe as the those applied earlier, as indicated by the low stem water potential values (Table 2.2). The recovery time for T3 and T4 was 3 to 4 weeks after full irrigation commenced.

Table 2.1: Regulated deficit irrigation treatment plan and its duration for 2019 growing season.



<u>Key:</u>

Dry period	50% irrigation	100% irrigation

T1 –100% irrigation per ETo, throughout the entire growing season (control)
T2 – Profile drying down to 25 mm (1–15 March), 100% irrigation (15 March–30 March), 100% irrigation (15 May to harvest) – dry/wet treatment (DWT)
T3 – Profile drying down to 25 mm (1–15 March), 50% irrigation (15 March–15 May), 100% irrigation (15 May to harvest) – early mild stress (EMS)
T4 – Profile drying down to 25 mm (15–30 March), 50% irrigation (30 March–30 May), 100% irrigation (30 May to harvest) – mid mild stress (MMS)
T5 – Profile drying down to 25 mm (1–15 April), 50% irrigation (15 April–15 June), 100% irrigation (15 June to harvest) – late mild stress (LMS)
T6 – Profile drying down to 25 mm (1–15 April), 50% irrigation (15 April to harvest), 100% irrigation (a week prior harvest) – long late mild stress (LLMS)

The recovery time for T5 was approximately 2 weeks after the resumption of full irrigation. In T6, 50% irrigation was continued for the remainder of the growing season until harvest. During the growing season, 27.8 mm rain was received on 2 May, however, it did not interfere with the experimental trials for the 2019 growing season.

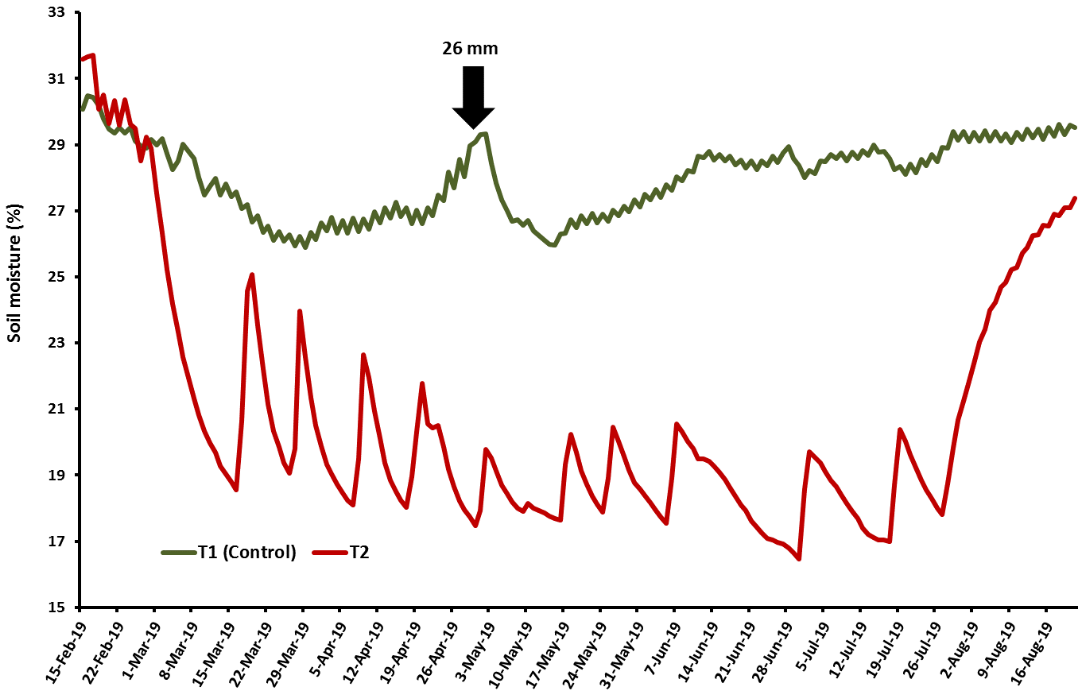


Figure 2.1: Soil moisture (%) during irrigation treatments T1 (control) and T2 for the 2019 growing season.

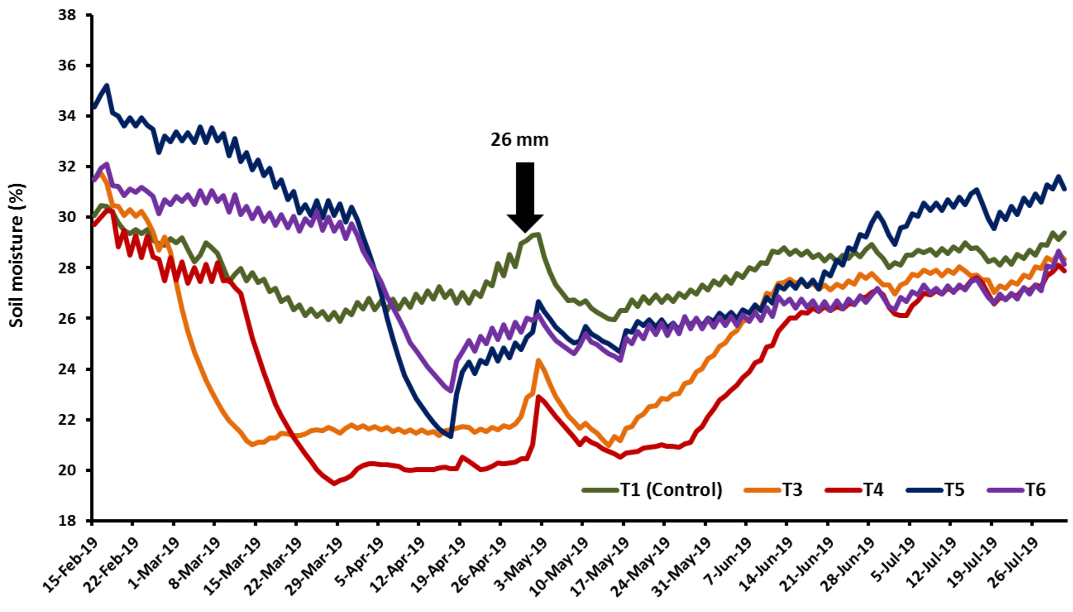


Figure 2.2: Soil moisture (%) during irrigation treatments T1 (control), T3, T4, T5 and T6 for the 2019 growing season.

Table 2.2: Pre-dawn stem water potential (SWP) values in bar for irrigation treatments in 2019. 1 bar = 0.1 MPa.

	T1	T2	T3	T4	T5	T6
6 Mar	3.3	4.5	4.7	4.6	4.6	4.5
8 Mar	3.4	4.3	4.3	4.4	4.7	4.5
13 Mar	5.9	9.7	8.9	5.1	5	4.7
15 Mar	4.8	9.7	9.3	5.7	4.9	5.3
20 Mar	4.1	4.5	5.6	4.5	4.8	4.4
22 Mar	4.1	5.6	5.6	5.3	5.4	5.5
27 Mar	4.9	5.0	4.9	4.6	4.2	4.9
29 Mar	5.3	4.2	5.1	7.4	4.1	5.2
3 Apr	4.3	4.8	4.8	4.7	6.0	4.6
5 Apr	4.8	4.9	5.1	4.9	5.8	4.9
10 Apr	4.8	5.8	5.0	4.4	6.9	5.1
12 Apr	5.1	5.4	5.1	5.2	5.0	5.2
16 Apr	4.8	5.1	4.7	5.2	6.8	6.5
18 Apr	4.1	5.1	4.6	5.3	5.5	5.4
26 Apr	4.9	4.9	4.5	5.4	6.1	5.6
14 May	4.4	4.2	4.4	4.7	4.1	4.0

Fruit quality components at harvest

Fruit quality data were collected at harvest from all experimental trees on 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) and 6 irrigation treatments.

In M7 navel, the deficit irrigation treatments did not affect °Brix values, which ranged from 14.1 to 14.6 in all treatments including the control (Table 2.3). There was also no significant effect on BrimA or acid values from the irrigation treatments and rootstocks. Irrigation treatments had significant effects on per cent juice values, but this effect was not commercially meaningful, because the reduction was only 55 or below.

In Washington navel, T2 increased the °Brix value by 1 unit while T3, T4 and T5 increased it by less than 1 unit compared to the control (Table 2.3). There was no rootstock effect on °Brix values. T2 increased BrimA values compared to the control, while the other treatments had no effect. There was also no effect on BrimA values and rootstocks. Irrigation treatments significantly increased the acid levels in all treatments. These were quite pronounced in T3, T4 and T5. There was no effect on acid values or per cent juice (Table 2.3).

In Lane Late navels, T2, T3 increased °Brix by more than 1 unit compared to the control, while T5 and T6 increased °Brix by half a unit compared to the control (Table 2.3). The higher °Brix value of 1.7 was achieved with T3, where trees were water stressed from 1 March. There were no rootstock effects found on °Brix values. BrimA values followed the same trend as °Brix values for irrigation treatments effects. The higher BrimA value of 162 was achieved with T3 compared to the control. There were no rootstock effects found on BrimA values. The irrigation treatments T2, T3 and T4 significantly increased acid levels compared to the control. The per cent juice was not affected by irrigation treatment or rootstocks (Table 2.3). In all 3 navel varieties, there were no interaction effects found between irrigation treatments and rootstocks for any quality attributes (Table 2.3).

Table 2.3: Fruit quality attributes °Brix, BrimA, acid (%) and juice (%) in M7, Washington navel and Lane Late navels for the 2019 growing season.

	M7				Washington navel				Lane Late			
Irrigation treatments (It)	°Brix	Brim A	Acid (%)	Juice (%)	°Brix	Brim A	Acid (%)	Juice (%)	°Brix	Brim A	Acid (%)	Juice (%)
T1 (control)	14.1	166	1.0	50	12.8	141	1.0	44	12.5	141	1.0	47
T2	14.6	173	1.0	46	13.9	154	1.1	43	13.8	155	1.1	49
T3	14.6	173	1.0	45	13.7	148	1.2	43	14.2	162	1.1	48
T4	14.4	173	1.0	45	13.6	149	1.2	44	13.7	156	1.1	49
T5	14.2	170	1.0	46	13.6	147	1.2	42	13.0	150	1.0	48
T6	14.6	171	1.1	48	13.1	145	1.1	44	13.0	150	1.0	48
Probability	ns	ns	ns	*	***	*	***	ns	***	***	**	ns
LSD ($p < 0.05$)	–	–	–	2.72	0.57	8.67	0.07	–	0.51	7.57	0.06	–
Rootstocks (Rt)												
Poncirus trifoliata	14.4	169	1.0	46	13.4	147	1.1	43	13.3	151	1.0	48
Troyer citrange	14.5	172	1.0	47	13.5	148	1.1	44	13.4	154	1.0	49
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–	–	–	–
Interaction (It x Rt)												
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit yield components at harvest

Fruit yield components at harvest were recorded on all experimental trees for M7, Washington navel and Lane Late oranges for the 2019 growing season.

In M7 navels, there were no significant effects of irrigation treatments on fruit yield/tree, fruit number/tree or on average fruit weight. Trees carried an average of 45.2 kg/tree, and average fruit number/tree was 288 (Table 2.4). T2 significantly decreased mean fruit weight by 27.2 g compared to the control, while the fruit weight reduction in T3 was 16.8 g. T4 had a slight reduction of 5.5 g while T5 and T6 had no reduction in fruit weight. The interaction effect suggested that T5 and T6 did not decrease the fruit weight on *Troyer citrange* rootstock. This suggests the reduction in fruit weight was not affected by the late treatments in *Troyer citrange*, but still affected the fruit weight in *Poncirus trifoliata*. In M7 navels, the effects on 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) were not significant for fruit yield/tree, fruit number/tree or on an average fruit weight (Table 2.4).

In Washington navels, there was no significant effects of irrigation treatments on fruit yield/tree and fruit number/tree. Trees carried an average of 51.7 kg/tree, and average fruit number/tree were 285 (Table 2.4). Fruit weight was decreased with T2 and T3 by 29.3 g and 36.7 g respectively compared to the control. In T4 the fruit weight reduction was 22 g, while in T5 and T6 no significant reduction was found compared to the control. This suggests the late treatments are not affecting fruit size as much as the early treatments. In Washington navels, the effects on 2 rootstocks were significant and fruit weight was decreased by 25.3 g by *Troyer citrange* compared to *Poncirus trifoliata* rootstock (Table 2.4).

In Lane Late navels, there was a significant effect of irrigation treatments on fruit yield/tree and on average fruit weight. Fruit yield/tree was decreased by 18.8 kg/tree to 14 kg/tree for T2 and T3 respectively compared to the control, and in T4, the yield reduction was 10.7 kg/tree (Table 2.4). The rootstock effect was non-significant for yield/tree. There was no significant effect of irrigation treatments on fruit number/tree. However, fruit number/tree remained higher in *Troyer citrange* rootstock compared to *Poncirus trifoliata* rootstock (Table 2.4). Average fruit weight was significantly decreased with T2 and T3 by 37.6 g and 44.8 g respectively compared to the control (Table 2.4). In T4, the fruit weight reduction was 33 g, while there was no significant reduction in T5 and T6. The rootstock effect was significant for average fruit weight, which was decreased by 41.1 g for *Troyer citrange* rootstock compared to *P. trifoliata* (Table 2.4). The interaction indicated that T3 and T4 decreased the fruit weight by 28 g and 22 g respectively compared to the control in *Troyer citrange* rootstock.

The overall results indicate that the late treatments did not affect the fruit size compared to the earlier applied treatments in Lane Late navels. There were no significant interaction effects between irrigation treatments and rootstocks for M7, Washington navel or Lane Late oranges (Table 2.4).

Table 2.4: Fruit yield (kg)/tree, fruit number/tree and individual fruit weight in M7, Washington navel and Lane Late navels for the 2019 growing season.

	M7 navel			**Washington navel**			**Lane Late navel**		
Irrigation treatments (It)	Fruit yield	Fruit	Fruit weight	Fruit yield	Fruit	Fruit weight	Fruit yield	Fruit	Fruit weight
T1 (control)	52.0	311	167.4	55.0	273	203.0	54.5	267	214.9
T2	40.9	301	140.2	46.1	275	173.7	35.7	214	177.3
T3	43.2	290	150.6	47.0	286	166.3	40.5	240	170.1
T4	42.7	277	161.9	50.9	283	181.0	43.8	245	181.9
T5	44.5	264	170.9	55.4	296	195.1	36.5	192	205.1
T6	47.6	287	168.3	55.5	298	198.1	38.5	201	216.0
Probability	ns	ns	*	ns	ns	**	*	ns	***
LSD ($p < 0.05$)	–	–	21.4	–	–	22.6	11.5	–	21.9
Rootstocks (Rt)									
Poncirus trifoliata	44.6	283	162.5	51.0	267	198.9	40.9	202	214.9
Troyer citrange	45.7	293	157.3	52.3	304	173.6	42.2	252	173.5
Probability	ns	ns	ns	ns	ns	***	ns	**	***
LSD ($p < 0.05$)	–	–	–	–	–	13.1	–	35.5	12.6
Interaction (It x Rt)									
Probability	ns	ns	*	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	30.3	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatments, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit size distribution

Fruit size distribution was assessed for all experimental trees for each variety and rootstock. The data is shown in Table 2.5 for the main exportable size classes for main effects and interaction effects for irrigation treatments and rootstocks. The data extracted from Table 2.5 is also presented in figures 2.3 to 2.5, so the data is visually and effectively communicated to readers.

In M7 navel, the irrigation treatments did not affect the 69–75 mm and 75–81 mm size classes, however, T2 resulted in 14% less fruit in the 81–87 mm size class (Table 2.5; Figure 2.3). The extent of reduction was related to the type of irrigation treatment applied. T2 was a dry and wet treatment, and it has detrimental effects on fruit size; ongoing manipulation with irrigation treatments is not recommended. T4 had a reduction of 7%, while the other treatments did not affect the fruit size in M7. One of the reasons for fruit size not being affected is that, especially in T5 and T6, trees were receiving water until 1 April and fruit size had been achieved before water stress was applied. There was no effect of rootstocks on the size classes (Table 2.5).

In Washington navel, the irrigation treatment had a significant effect on size class 69-75 mm, 75-81 and 81–87 mm (Table 2.5). In size class 81–87 mm, the reduction in T2, T3 and T4 was 19%, 21% and 13% respectively compared to the control (Figure 2.4). The reduction of 5-7% for T5 and T6 was less severe. This also indicated that late applications have no effect on fruit size. The effect of rootstock was significant for size classes 69-75 mm, 75-81 mm and 81–87 mm (Table 2.5), however, *Troyer citrange* had a reduction of 7% compared to *Poncirus trifoliata* for both 75-81 mm and 81–87 mm size classes. (Table 2.5). The interaction effect was not significant for any size classes (Table 2.5).

In Lane Late navel, the irrigation treatments had a significant effect on size classes 69–75 mm and 81–87 mm (Table 2.5). In size class 69–75 mm, there was an increase of 18 and 12% for T2 and T3 respectively compared to the control (Figure 2.5). However, in size class 81–87 mm, T2, T3 and T4 had reductions of 26%, 28% and 17% respectively compared to the control (69%). T5 and T6 did not reduce the fruit size. The data suggest that the late treatment does not reduce fruit size. The percentage of fruit size reduction was significant for rootstocks in all three fruit size classes (Table 2.5). However, it is significant to notice that in size class 81–87 mm, *Troyer citrange* had 22% reduced fruit size compared to the *Poncirus trifoliata* (Table 2.5). The interaction effect was not significant for irrigation treatments and rootstocks (Table 2.5).

Relationship of large fruit size (81–87 mm) vs °Brix (Total soluble solids)

Regression analysis revealed no significant relationship between large fruit size fruit (81–87 mm) and °Brix values in M7 navels (Figure 2.6). However, a significant relationship was found for Washington navel (Figure 2.7) and Lane Late navel (Figures 2.8). The relationship between fruit size and sugar levels was stronger for Washington navel (R^2 = 0.77) and Lane Late oranges (R^2 = 0.95) than for M7 navels. M7 is generally an early-maturing orange and the sugar levels increase rapidly towards maturity compared to the mid-maturing Washington navels and late-maturing Lane Late navels. Overall, these results show that by reducing the water volumes and imposing moisture stress has a pronounced effect on large-sized fruit and the degree of stress dictates the fruit size and increased sugar levels in sweet oranges.

Table 2.5: Fruit size distribution (%)/tree for M7, Washington navel and Lane Late navel in different size classes per tree for the 2019 growing season.

	M7 navel			Washington navel			Lane Late navel		
Irrigation treatments (It)	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm
T1 (control)	12	20	63	10	25	60	7	22	69
T2	18	25	49	18	31	41	25	24	43
T3	10	20	64	19	32	39	19	29	41
T4	15	22	56	16	25	47	15	26	52
T5	11	23	62	12	26	53	10	24	63
T6	12	21	63	12	26	55	10	24	63
Probability	*	ns	*	***	**	***	**	ns	***
LSD ($p < 0.05$)	4.9	–	10.9	4.9	5.4	10.5	9.5	–	12.4
Rootstocks (Rt)									
Poncirus trifoliata	12	22	61	12	24	55	9	21	66
Troyer citrange	14	22	58	17	31	43	20	29	44
Probability	ns	ns	ns	**	***	***	***	***	***
LSD ($p < 0.05$)	–	–	–	2.6	3.1	6.0	5.5	3.6	7.2
Interaction (It × Rt)									
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

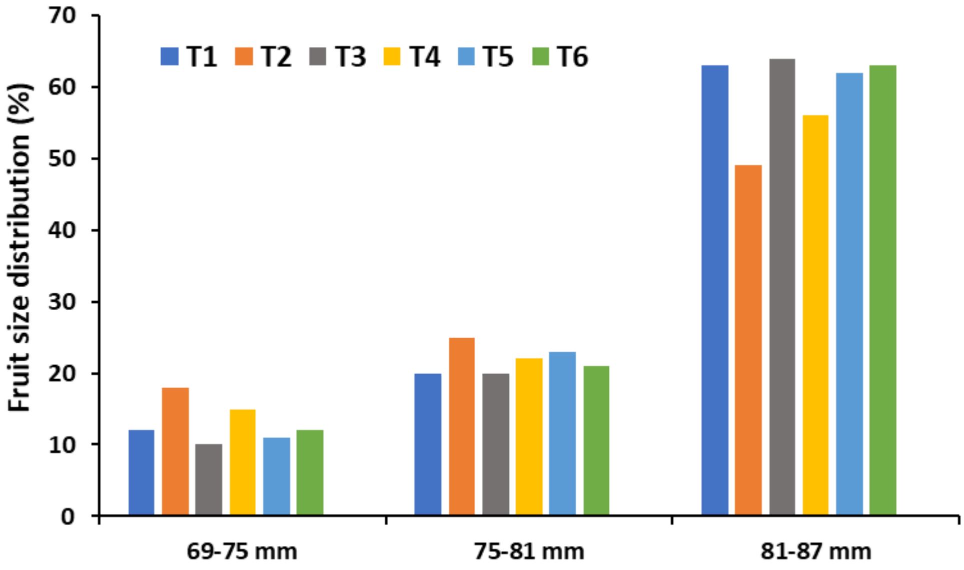


Figure 2.3 Fruit size distribution (%) of 3 export size classes for M7 navel at harvest. Six irrigation treatments were applied in the 2019 growing season. T1 is the control (100% irrigation).

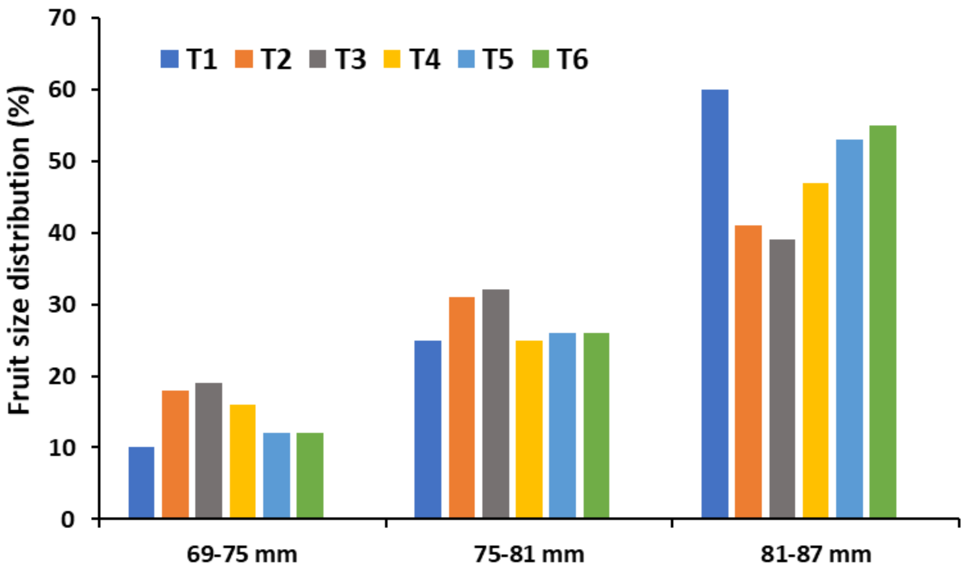


Figure 2.4: Fruit size distribution (%) of 3 export size classes for Washington navel at harvest. Six irrigation treatments were applied in the 2019 growing season. T1 is the control (100% irrigation).

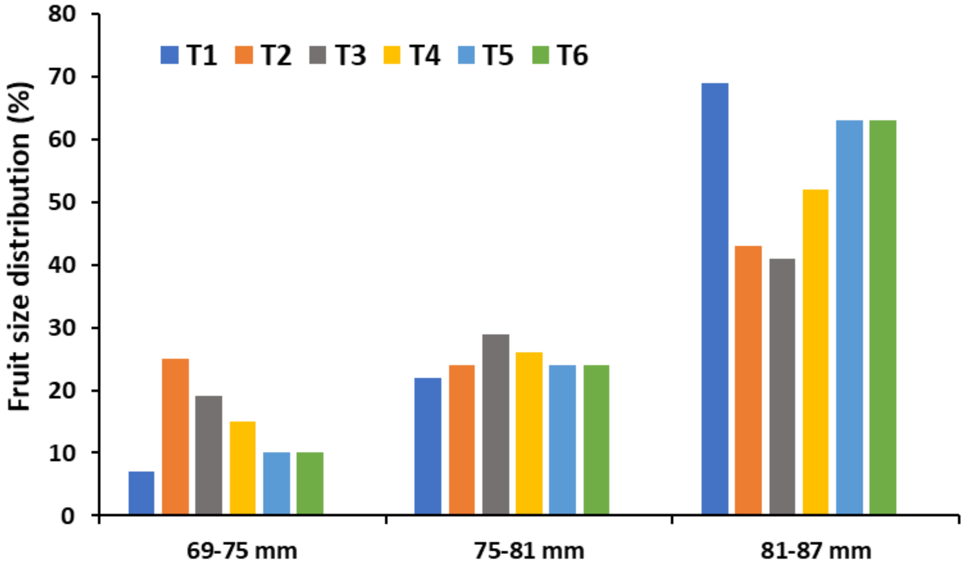


Figure 2.5: Fruit size distribution (%) of 3 export size classes for Lane Late navel at harvest. Six irrigation treatments were applied in the 2019 growing season. T1 is the control (100% irrigation).

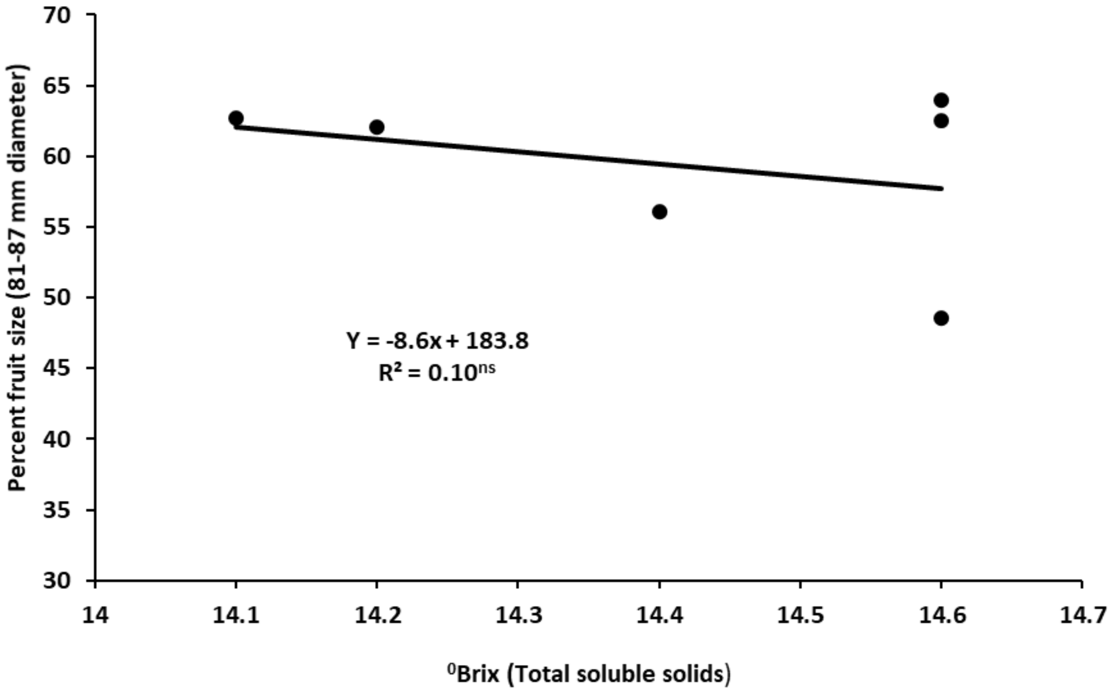


Figure 2.6: The relationship between large fruit size (81–87 mm) and °Brix values at harvest for M7 navel in 2019. Regression coefficient R^2 = 0.10 is not significant.

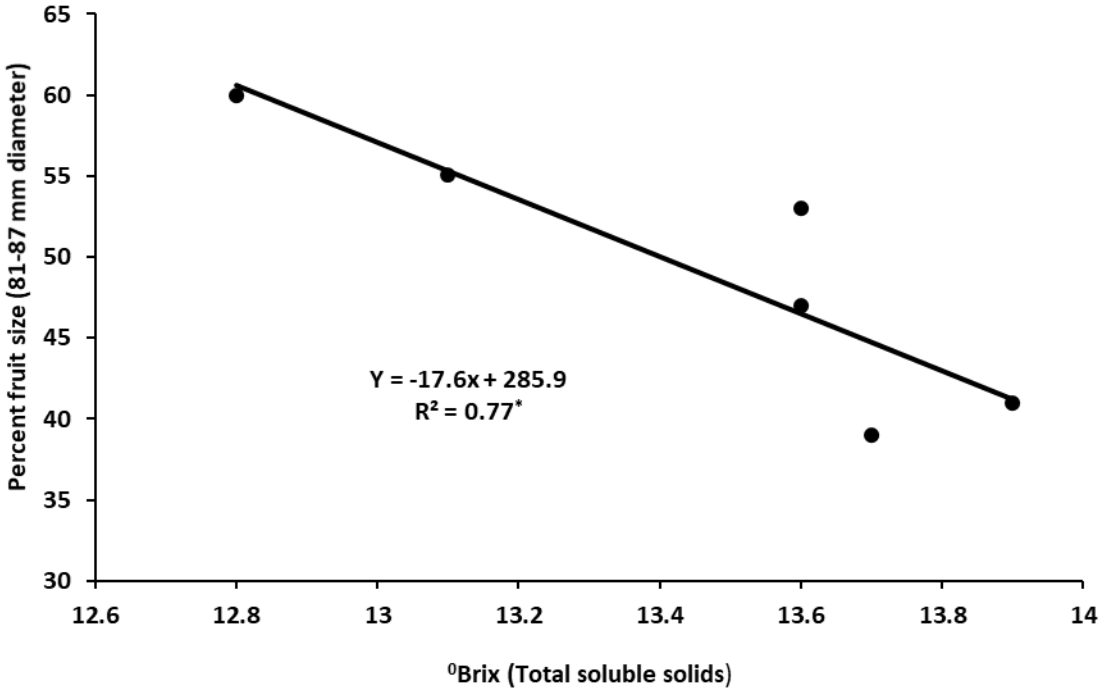


Figure 2.7: The relationship between large fruit size (81–87 mm) and °Brix values at harvest for Washington navel in 2019. Regression coefficient $R^2 = 0.77$ is significant at $p < 0.05$ (*).

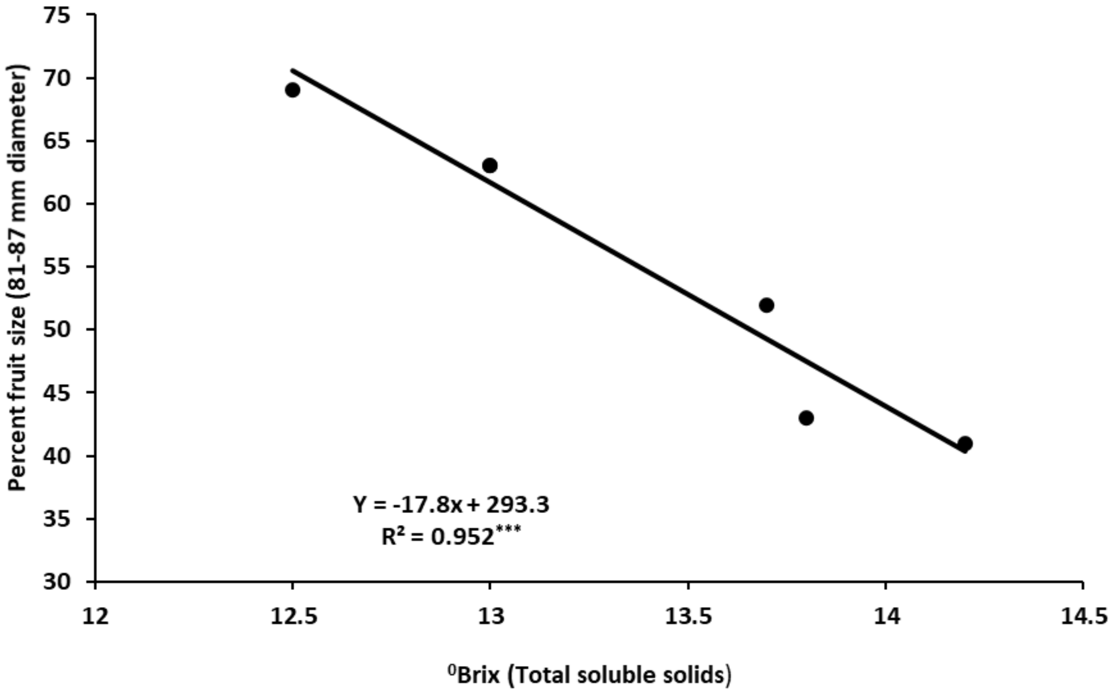


Figure 2.8: The relationship between large fruit size (81–87 mm) and °Brix values at harvest for Lane Late in 2019. Regression coefficient $R^2 = 0.95$ is significant at $p < 0.001$ (***).

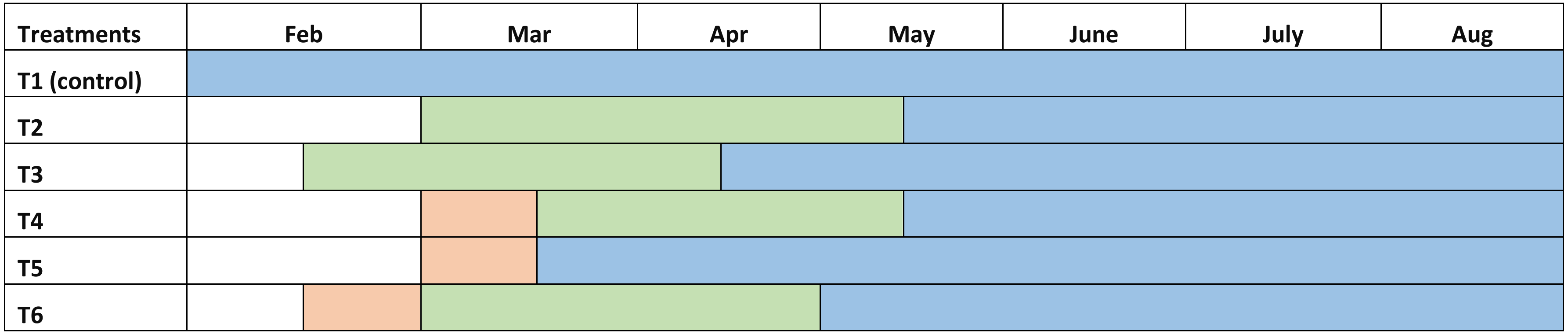
Chapter 3: Experimental program for navel oranges – 2020

Irrigation treatment structure

Six irrigation treatments were applied to the experimental trees in 2020 (Table 3.1). The orange boxes represent the drying period when irrigation water was withheld from the citrus trees. The light green boxes represent the availability of 50% irrigation water and the blue boxes represent the availability of 100% irrigation water. The treatments were designed to apply deficit irrigation in February and March to assess fruit quality effects, fruit yield and fruit size distribution in citrus trees.

T1 is the control, receiving 100% irrigation. In T2, the soil profile was not dried, and 50% irrigation was applied, however, once the fruit size fell behind the control, the profile was re-wetted by the application of full irrigation water. In T3, the soil profile was not dried, and 50% irrigation was applied for 8 consecutive weeks from 15 February to 15 April followed by 100% irrigation until harvest. In T4, the soil profile was dried for 2 weeks (1–15 March) and 50% irrigation was applied for 8 consecutive weeks followed by 100% irrigation until harvest. In T5, the soil profile was dried for 2 weeks (1–15 March) followed by 100% irrigation until harvest. In T6, the soil profile was dried for 2 weeks (15–28 February) and 50% irrigation was applied for 8 consecutive weeks followed by 100% irrigation until harvest (Table 3.2).

Table 3.1: Regulated deficit irrigation treatment plan and its duration for the 2020 growing season.



Key

Dry period | 50% irrigation | 100% irrigation

T1 –100% irrigation per ETo, throughout the entire growing season (control)
T2 – No profile drying, 50% irrigation (1 March–15 May), 70% irrigation (in case fruit size decreased) – monitored stress (MS)
T3 – No profile drying, 50% irrigation (15 Feb–15 April), 100% irrigation (15 April to harvest) – early light stress (ELS)
T4 – Profile drying down to 25 mm (1–15 March), 50% irrigation (15 March–15 May), 100% irrigation (15 May to harvest) – mid mild stress (MMS)
T5 – Profile drying down to 25 mm (1–15 March), 100% irrigation (a week prior harvest) – mid light stress (MLS)
T6 – Profile drying down to 25 mm (15–1 Mar), 50% irrigation (1 Mar to 1 May), 100% irrigation (1 May to harvest) – early mild stress (EMS)

Rainfall during 2020

The 2020 growing season was wet; significant rainfall occurred from February to June, affecting the imposed deficit irrigation treatments. Total rainfall distribution for each month is given in Table 3.2. Figure 3.1 shows one significant downpour from 1 April 2020. The total amount of rainfall in April was 72 mm.

Table 3.2: Rainfall (mm) at Dareton for the 2020 growing season (Jan–May).

	January	February	March	April	May
Rainfall (mm)	6	21	26	72	1

Figure 3.1: 23 mm rainfall was recorded on a single day (1 April 2020) at the Dareton Research Institute in the regulated deficit irrigation trial. Photo: Dr Tahir Khurshid.

Stress physiology and plant responses

The Enviro probes indicated the water levels after applying different levels of water stress to the citrus trees.

T1 was the control, and 100% irrigation was applied. In T3, 50% irrigation was applied from 15 February without drying the soil profile (Figure 3.2). The early reduction of irrigation caused very mild stress to the trees by 23 February. On the other hand, in T6 the soil profile was dried for 2 weeks (15–29 February) and trees were highly stressed by 29 February compared to T3 as shown by the per cent soil moisture levels (Figure 3.2). These stress levels were also demonstrated by the stem water potential (SWP) of 12 bar in T6 by 3 March (Table 3.3). The stress level in T3 was minor and the SWP value was 4.7 bar by 7 March (Table 3.3). However, 18 mm of rain fell 4 March, which relieved the trees from the imposed stress. Soil was saturated and the irrigation was held from 5–12 March to allow the water to drain and reimpose the stress treatments. Trees in T6 showed severe stress by 13 March as evidenced by a SWP value of 14 bar (Table 3.3). T3 had an SWP value of 6.7 at the same time. Therefore, both treatments achieved their representative stresses. Irrigation was resumed on 13 March. However, once again 23 mm of rain fell on 1 April (Figure 3.1), and trees were relieved from stress by 4 April. Irrigation was held from 4 April to reimpose the stress. According to the soil probe figures, trees achieved the desired stress, and the data suggested the SWP values on 21 April were 7.4 bar in T3 and 7.3 bar in T6. Irrigation was resumed on 21 April for these treatments.

In T2, 50% irrigation was applied from 1 March without drying the soil profile. In treatments 4 and 5, the soil profile was planned to be dried from 1–15 March. The trees had barely started their responses to the water deficit treatments and 18 mm of rain fell on 4 March, relieving the trees from any stress. This was shown by the low SWP values for these treatments by 3 March (Table 3.3). The soil was saturated, and the irrigation was held from 5–12 March to allow the water to drain and reimpose the stress treatments. T2 achieved some stress by 10 March (Figure 3.3) and the SWP value was 7.3 bar by 13 March (Table 3.3). T4 and T5 caused stress by 13 March with SWP values of

8.1 and 8.2 bar respectively (Table 3.3). T4 and T5 remained stressed by 23 March (Figure 3.2) and the SWP values were 7.0 and 8.3 bar respectively on 24 March. More rainfall (23 mm) occurred on 1 April (Figure 3.1), which relieved the trees of T2, T4 and T5 treatments by 4 April (Figure 3.2). Irrigation was held from 4–20 April to reimpose the stress. According to the soil probe figures, trees achieved the desired stress, and the SWP value of 8.1 bar on T2, 8.8 bar on T4 and 7.3 bar on T5 were recorded on 21 April (Table 3.3). Irrigation was resumed on 21 April for these treatments.

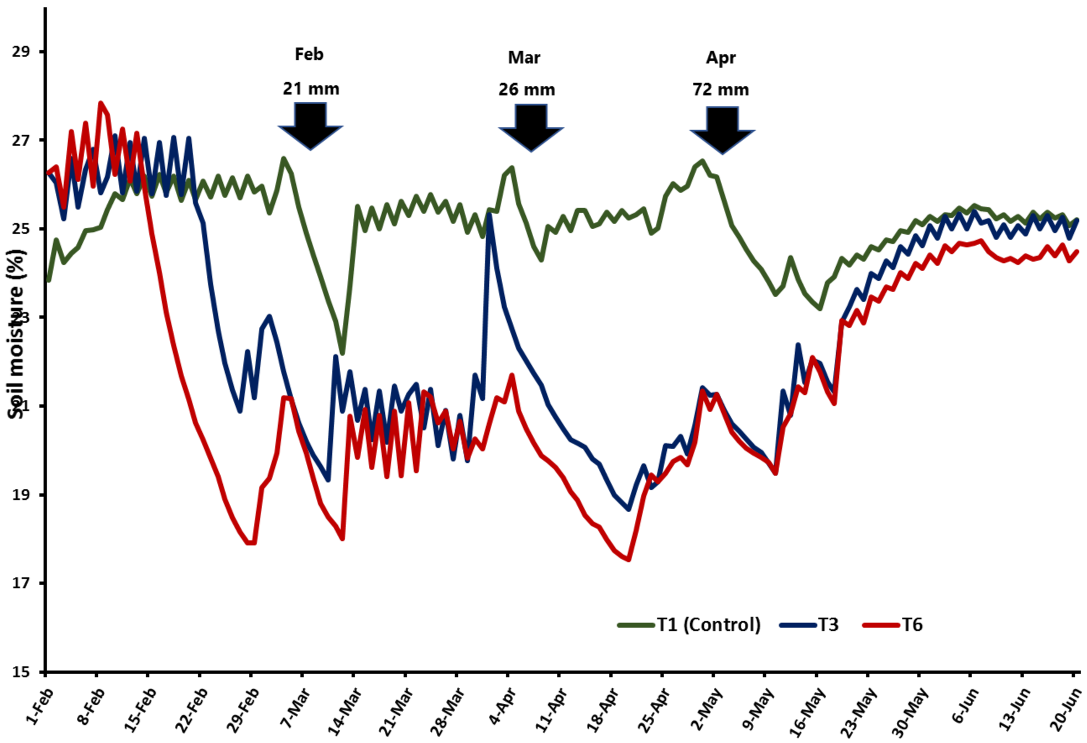


Figure 3.2: Soil moisture (%) during irrigation T1 (control), T3 and T6 for the 2020 growing season. Black arrows indicate when rainfall occurred.

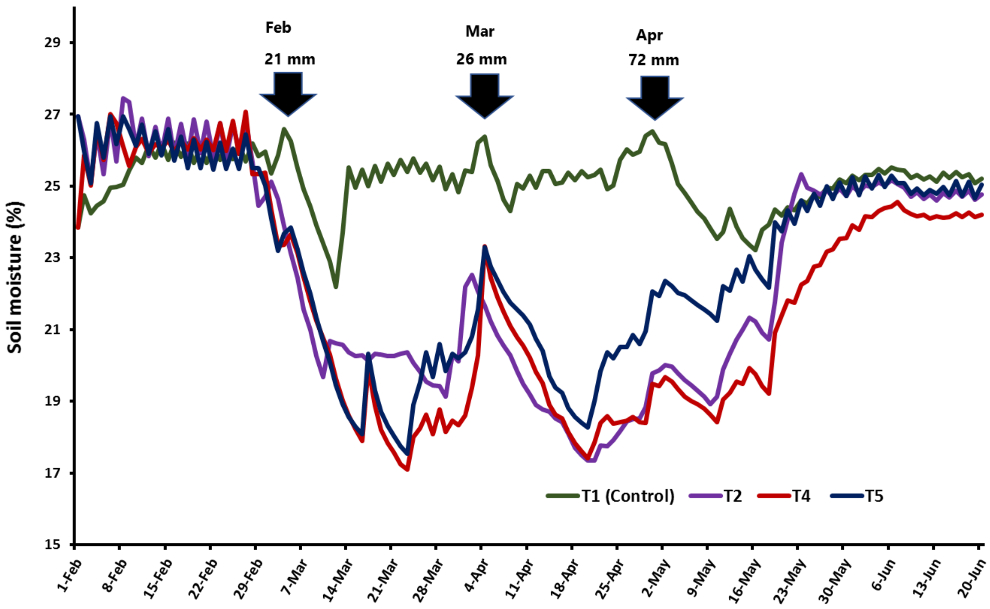


Figure 3.2: Soil moisture (%) during irrigation treatments T1 (control), T2, T4 and T5 for the 2020 growing season. Black arrows indicate when rain fell.

Table 3.3: Pre-dawn stem water potential (SWP) values in bar for irrigation treatments in 2020. 1 bar = 0.1 MPa.

	T1	T2	T3	T4	T5	T6
31 Jan	4.3	4.1	3.9	3.8	3.9	4.0
11 Feb	3.1	3.4	3.5	3.4	3.0	3.0
17 Feb	4.5	4.0	4.2	4.2	3.8	4.1
25 Feb	5.2	4.1	5.1	4.8	4.7	5.4
28 Feb	5.3	4.0	5.3	5.0	5.2	6.3
3 Mar	4.9	5.8	5.0	4.6	4.7	12.0
7 Mar	4.7	5.0	4.7	5.3	4.6	5.5
13 Mar	6.4	7.3	6.7	8.1	8.2	14.0
17 Mar	4.3	6.1	4.1	6.4	6.4	7.8
20 Mar	4.8	5.6	5.0	6.7	7.9	7.4
24 Mar	5.3	6.4	5.6	7.0	8.3	8.0
27 Mar	5.1	6.3	5.3	5.9	6.8	7.7
31 Mar	5.8	5.8	6.5	6.6	6.3	6.0
7 Apr	4.2	4.5	4.5	5.0	4.3	4.7
15 Apr	5.1	5.3	5.2	4.7	5.8	5.4
20 Apr	4.4	6.6	7.1	8.3	6.8	6.7
21 Apr	4.3	8.1	7.4	8.8	7.3	7.3
24 Apr	3.8	6.3	5.3	5.8	5.8	5.5
28 Apr	3.8	6.6	5.8	5.6	5.9	5.7
7 May	4.0	6.4	5.5	6.2	6.0	5.8
15 May	4.2	6.3	5.6	5.9	6.0	6.2

Fruit quality components at harvest

The fruit quality data were collected at harvest 2020 from all experimental trees from 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) and 6 irrigation treatments.

In M7 navel, T6 increased °Brix values (1 °Brix) and acid levels compared to the control (Table 3.4). BrimA values were not affected by treatment or rootstock. Fruit acid levels were not affected by rootstock. Percent juice values were not affected by irrigation treatments or rootstock.

In Washington navel, the T6 deficit irrigation treatment significantly increased °Brix values (by 0.9 unit) compared to the control. There was no rootstock effect on °Brix value. The effect of irrigation treatment or rootstock was not significant for BrimA values, acid values or per cent juice content (Table 3.4).

In Lane Late navels, T4 and T6 increased °Brix values compared to T1 (Table 3.4). There were no rootstock effects on °Brix values. BrimA values followed the same trend as °Brix values for irrigation treatment effects. The higher BrimA values of 144 and 141 were achieved with T4 and T6 respectively, compared to the control (126). There were no rootstock effects on BrimA values. Irrigation treatments T4 and T6 had higher acid levels compared to the control, although the rootstock effect was not significant for acid values. The per cent juice was not affected by irrigation treatment or rootstocks (Table 3.4). There were no significant interaction effects found between irrigation treatments and rootstocks in M7, Washington navel or Lane Late navels for any quality components (Table 3.4).

Table 3.4: Fruit quality attributes °Brix, BrimA, acid (%), and juice (%) in M7, Washington navel and Lane Late navels for the 2020 growing season.

	M7				**Washington navel**				**Lane Late**			
Irrigation treatments (It)	°Brix	BrimA	Acid (%)	Juice (%)	°Brix	BrimA	Acid (%)	Juice (%)	°Brix	BrimA	Acid (%)	Juice (%)
T1 (control)	13.0	137	1.2	54	11.5	117	1.1	47	11.8	126	1.0	50
T2	12.9	137	1.1	52	11.6	116	1.1	47	12.4	136	1.0	50
T3	13.2	138	1.2	54	11.6	117	1.1	47	12.4	124	1.1	49
T4	13.2	136	1.2	52	12.2	128	1.1	46	12.8	144	1.2	48
T5	13.0	139	1.1	51	12.1	125	1.1	46	12.1	129	1.0	48
T6	14.0	142	1.3	53	12.4	124	1.2	45	13.1	141	1.1	46
Probability	**	ns	***	ns	*	ns	ns	ns	***	***	***	ns
LSD ($p < 0.05$)	0.65	–	0.09	–	0.67	–	–	–	0.59	12.08	0.08	–
Rootstocks (Rt)												
Poncirus trifoliata	13.1	137	1.2	53	11.9	121	1.1	45	12.6	135	1.1	48
Troyer citrange	13.3	139	1.2	53	11.8	121	1.1	48	12.2	132	1.1	49
Probability	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	0.34	–	–	–
Interaction (It × Rt)												
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit yield components at harvest

Fruit yield components at harvest were recorded for all experimental trees for the 2020 growing season. The irrigation treatments were affected by rainfall during the growing season at critical stages of the experiments (Figures 3.2 and 3.3).

In M7 navels, there were no significant effects of irrigation treatments or rootstocks on fruit yield/tree and fruit number/tree. Trees carried an average of 38.7 kg/tree, and average fruit number/tree was 189 (Table 3.5). T6 significantly decreased fruit weight by 14.7 g compared to the control, while all other irrigation treatments had no effect on fruit weight. In M7 navels, the rootstock effect on fruit weight was significant and *Troyer citrange* fruit weighed less than fruit from *Poncirus trifoliata* rootstock (Table 3.5). Apart from T6, no other treatments had any effect on fruit size, however, the effect of rainfall at critical times will have influenced these outcomes.

In Washington navels, there was no significant effects of irrigation treatments on fruit yield/tree, fruit number/tree or on average fruit weight. Trees carried an average of 67.2 kg/tree, and average fruit number/tree was 323 (Table 3.5). Trees on *Troyer citrange* rootstock had significantly more fruit compared to *Poncirus trifoliata* rootstock. While it was interesting to note that mean fruit weight was decreased with T6 compared to the control (Table 3.5), this was not significant (Table 3.5). Fruit weight was decreased by 18.4 g on *Troyer citrange* compared to *Poncirus trifoliata* rootstock.

In Lane Late navels, there was a significant effect of irrigation treatments on fruit yield/tree, however, the effect on fruit number/tree and an average fruit weight was not significant. Trees caried an average yield of 54.2 kg/tree and average fruit number/tree was 242 (Table 3.5). Fruit yield/tree was decreased with T2 and T6 compared to the control by 14.9 kg/tree and 14 kg/tree to 14.9 kg for T2 and T6 respectively (Table 3.5). The rootstock effect was not significant for fruit yield/tree. There was no significant effect of irrigation treatments or rootstocks on fruit number/tree (Table 3.5). The effect of irrigation treatments or rootstocks on average fruit weight was not statistically significant, however, T6 decreased the fruit weight by 20.5 g compared to the control, which may have a commercial significance. Apart from T6, no other treatments had any effect on fruit size, due to rainfall.

There were no significant interaction effects between irrigation treatments and rootstocks for M7, Washington navel or Lane Late oranges (Table 3.5).

Table 3.5: Fruit yield (kg)/tree, fruit number/tree and individual fruit weight in M7, Washington navel and Lane Late navels for the 2020 growing season.

	M7 navel			**Washington navel**			**Lane Late navel**		
Irrigation treatments (It)	Fruit yield	Fruit number	Fruit weight	Fruit yield	Fruit	Fruit weight	Fruit yield (kg)	Fruit number	Fruit weight
T1 (control)	42.4	218	203.0	72.5	345	211.8	63.1	270	235.5
T2	41.3	191	221.6	65.1	313	211.6	48.2	215	225.5
T3	34.2	160	216.0	66.9	320	212.6	61.1	272	224.6
T4	39.3	184	222.5	68.7	321	215.3	53.0	238	222.3
T5	34.7	158	228.7	66.3	313	214.5	50.9	227	231.4
T6	40.2	222	188.3	63.8	327	197.6	49.1	228	215.0
Probability	ns	ns	**	ns	ns	ns	*	ns	ns
LSD ($p < 0.05$)	–	–	22.7	–	–	–	12.3	–	–
Rootstocks (Rt)									
Poncirus trifoliata	39.3	182	226.2	66.0	302	219.8	54.0	241	226.0
Troyer citrange	38.0	196	200.5	68.4	344	201.4	54.4	243	225.4
Probability	ns	ns	***	ns	*	***	ns	ns	ns
LSD ($p < 0.05$)	–	–	13.2	–	42	8.9	–	–	–
Interaction (It × Rt)									
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit size distribution at harvest

Fruit size distribution was assessed for all experimental trees in the 2020 growing season (Table 3.6). The data extracted from Table 3.6 is also presented in figures 3.3 to 3.5, so the data is visually and effectively communicated to readers.

The data indicated that in M7 navels, the irrigation treatments had significant effect on size classes 69-75 mm and 81–87 mm (Table 3.6). Figure 3.3 indicated that for the size class 81–87 mm, there was a reduction of 12% in T6 compared to the control. The rest of the treatments did not reduce the fruit in class 81–87 mm. These results indicated that the trees could not retain the water stress conditions due to rainfall, therefore trees were relieved from water stress. The rootstocks effect was significant for size classes 69-75, 75-81 and 81–87 mm (Table 3.6). In size class 81–87 mm, *Troyer citrange* has significantly reduced the fruit size compared to *Poncirus trifoliata*. (Table 3.6).

In Washington navel, the irrigation treatment had a significant effect on size class 69–75 mm, but not on size classes 75–81 and 81–87 mm (Table 3.6). However, T6 produced 12% fewer fruit in the larger size class, and while this is not a statistically significant outcome, the commercial significance of this result cannot be ignored because the result will be monetary losses to growers if they were to use this type of deficit irrigation (Figure 3.4). Fruit on *Poncirus trifoliata* rootstock had significantly more fruit in the 81–87 mm size class than those from *Troyer citrange* rootstock (Table 3.6).

In Lane Late navel, the irrigation treatment had a significant effect on size class 75–81 mm, but not on 69–75 mm and 81–87 mm (Table 3.6). As with Washington navel, T6 produced fewer fruit (13%) in the larger size class, and although not statistically significant (Figure 3.5), it certainly has commercial significance. The remaining treatments did not reduce the fruit size in class 81–87 mm. The rootstock effect was not significant for any size classes (Table 3.6).

The interaction effect was not significant for M7, Washington navel or Lane Late navels between irrigation treatments and rootstocks (Table 3.6).

Relationship of large fruit size (81–87 mm) vs °Brix (total soluble solids)

Regression analysis showed no significant relationship between large fruit size fruit (81–87 mm) and °Brix values in M7 navels, Washington navel or Lane Late (Figures 3.6 to 3.8). While not significant, there was a trend for higher sugar levels in M7 navels, otherwise the relation would have been even weaker. M7 is generally an early maturing orange and the sugar levels increase rapidly with maturity compared to the mid-maturing oranges Washington navels or late-maturing Lane Late navels. The regression analysis indicated that there were no relations between large fruit size and °Brix value for Washington navel or Lane Late oranges. These results indicated that rainfall interfered with the regulate deficit irrigation treatments at critical stages during the water stress in 2020 growing season.

Table 3.6: Fruit size distribution (%)/tree for M7, Washington navel and Lane Late navel in different size classes per tree for 2020 growing season.

	M7 navel			**Washington navel**			**Lane Late navel**		
Irrigation treatments (It)	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm
T1	17	24	47	11	25	58	8	21	68
T2	13	22	58	12	28	56	12	21	61
T3	15	26	52	10	26	61	11	22	64
T4	12	22	61	10	27	59	12	27	58
T5	13	22	60	11	25	61	9	23	66
T6	21	29	35	17	30	46	13	27	55
Probability	*	ns	**	*	ns	ns	ns	*	ns
LSD ($p < 0.05$)	5.4	–	14.1	4.7	–	–	–	5.2	–
Rootstocks (Rt)									
Poncirus trifoliata	12	22	61	9	24	64	11	23	62
Troyer citrange	18	26	45	15	30	50	11	23	61
Probability	***	*	***	***	**	***	ns	ns	ns
LSD ($p < 0.05$)	3.1	3.6	8.2	2.7	3.4	6.7	–	–	–
Interaction (It × Rt)									
Probability	ns	ns	ns	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

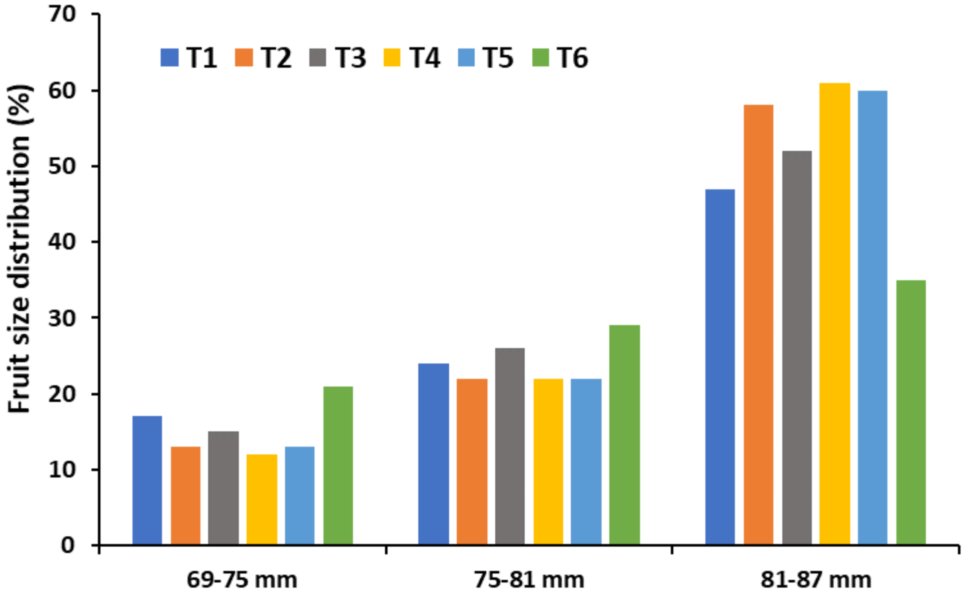


Figure 3.3: Fruit size distribution (%) of 3 export size classes for M7 navel at harvest. Six irrigation treatments were applied in the 2020 growing season. T1 is the control (100% irrigation).

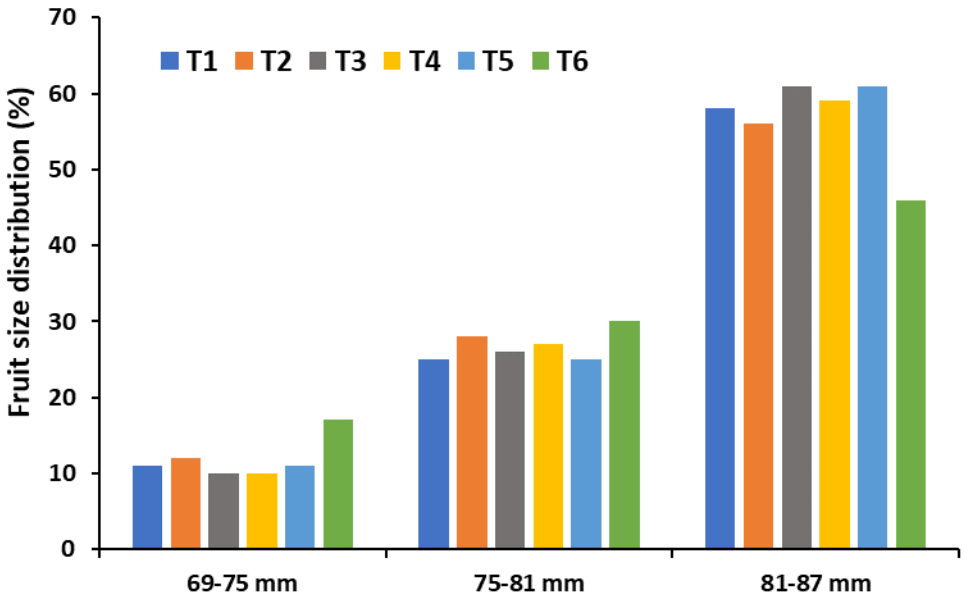


Figure 3.4: Fruit size distribution (%) of 3 export size classes for Washington navel at harvest. Six irrigation treatments were applied in the 2020 growing season. T1 is the control (100% irrigation).

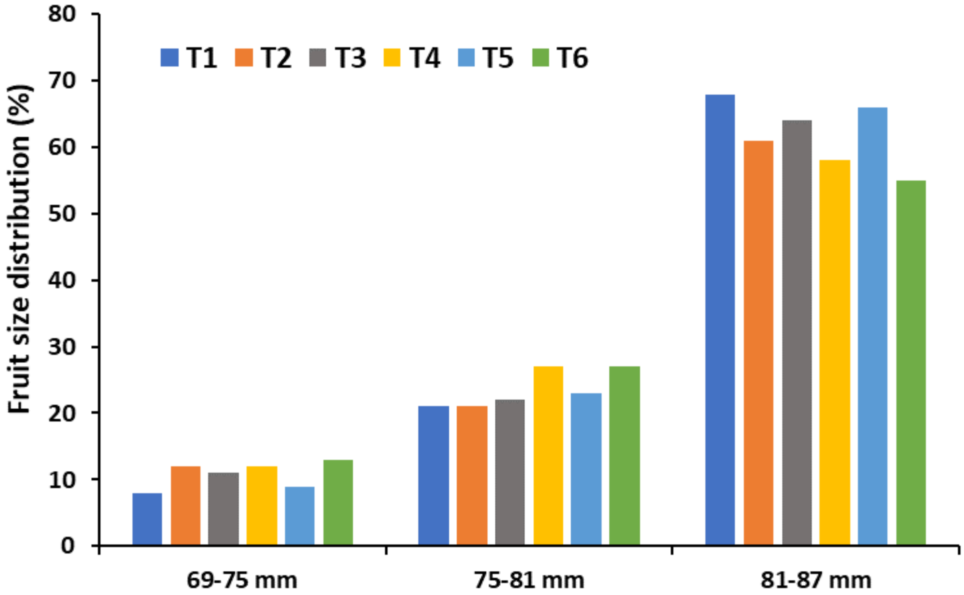


Figure 3.5: Fruit size distribution (%) of 3 export size classes for Lane Late navel at harvest. Six irrigation treatments were applied in the 2020 growing season. T1 is the control (100% irrigation).

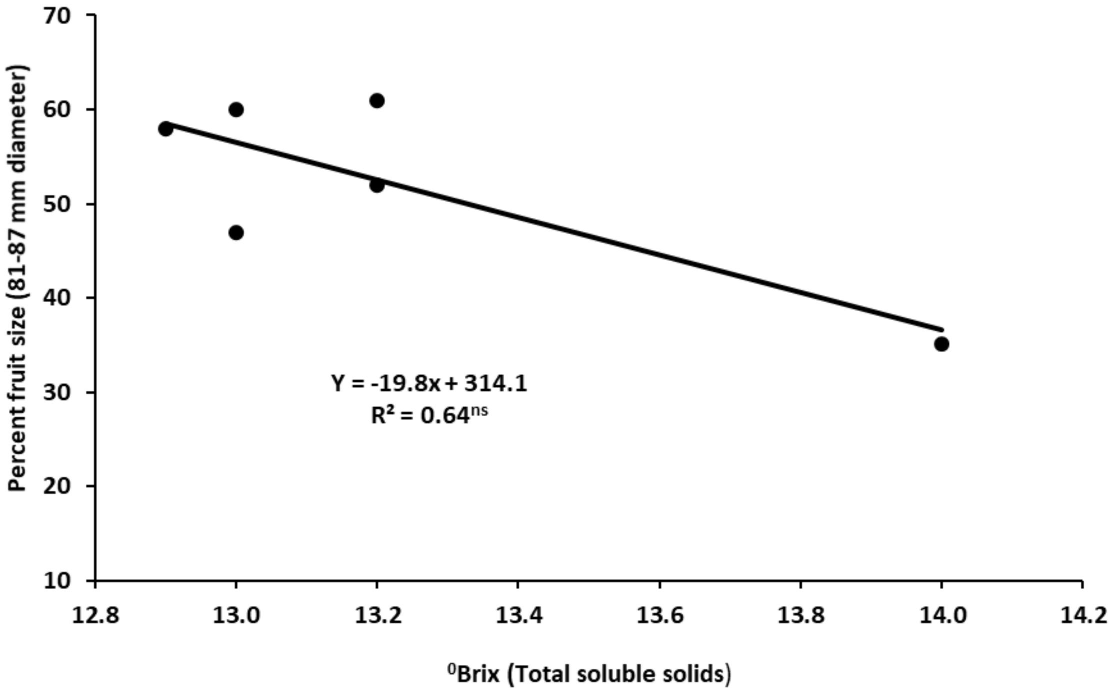


Figure 3.6: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for M7 navel in 2020. Regression coefficient R^2 = 0.64 is not significant.

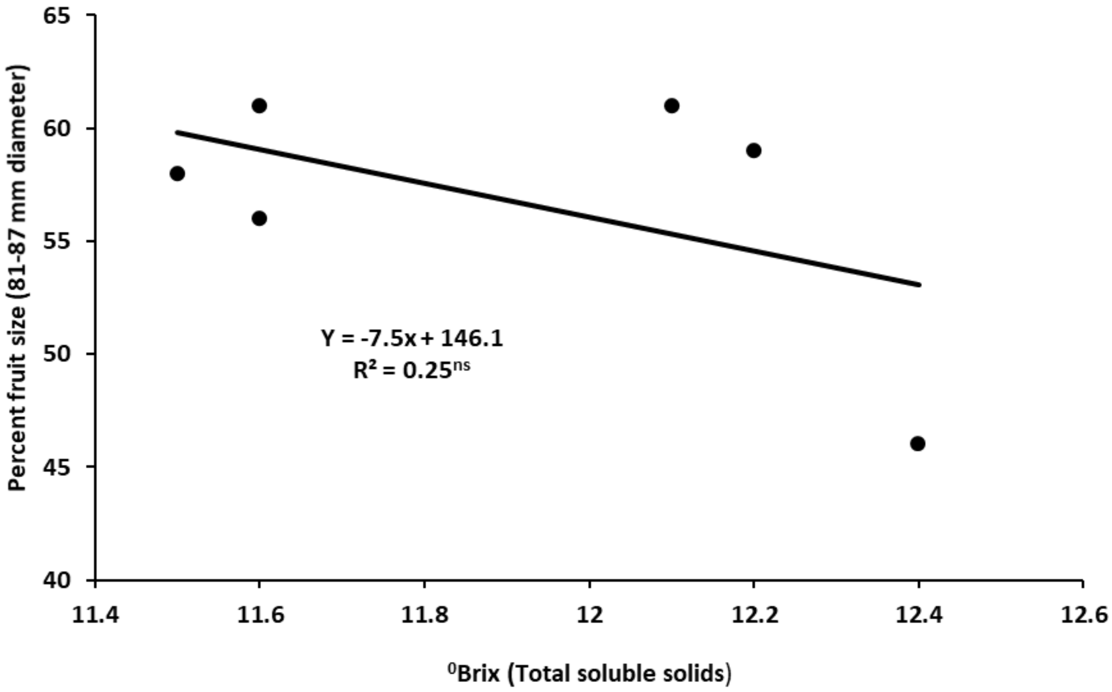


Figure 3.8: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for Washington navel in 2020. Regression coefficient R^2 = 0.25 is not significant.

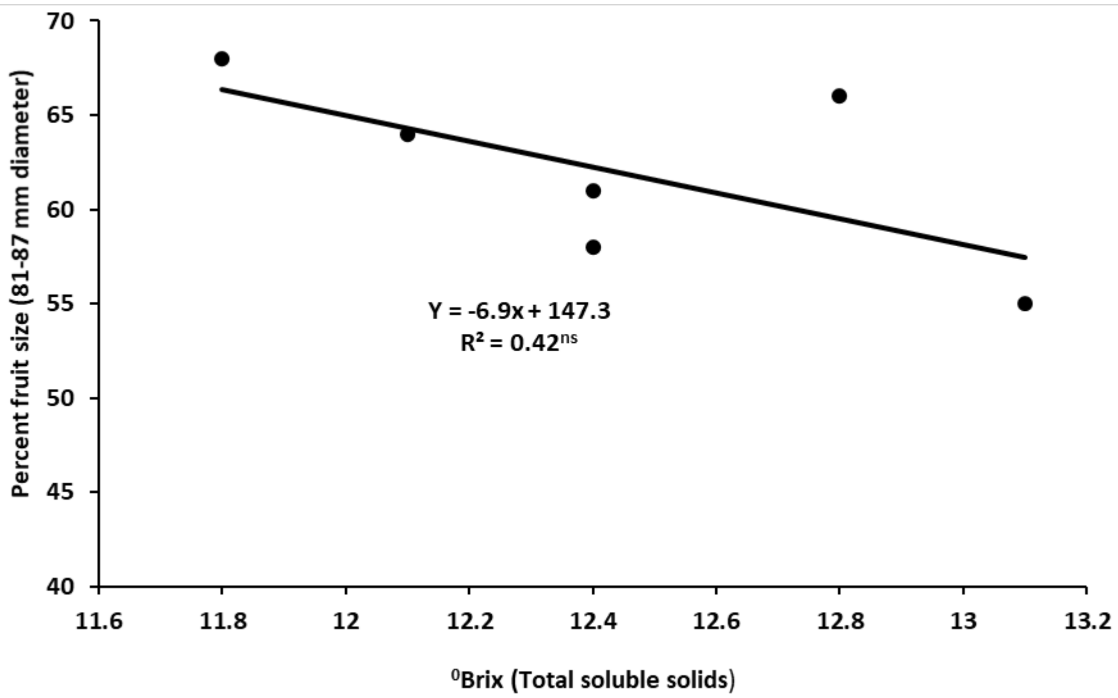


Figure 3.7: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for Lane Late navel in 2020. Regression coefficient R^2 = 0.42 is not significant.

Chapter 4: Experimental program for navel oranges – 2021

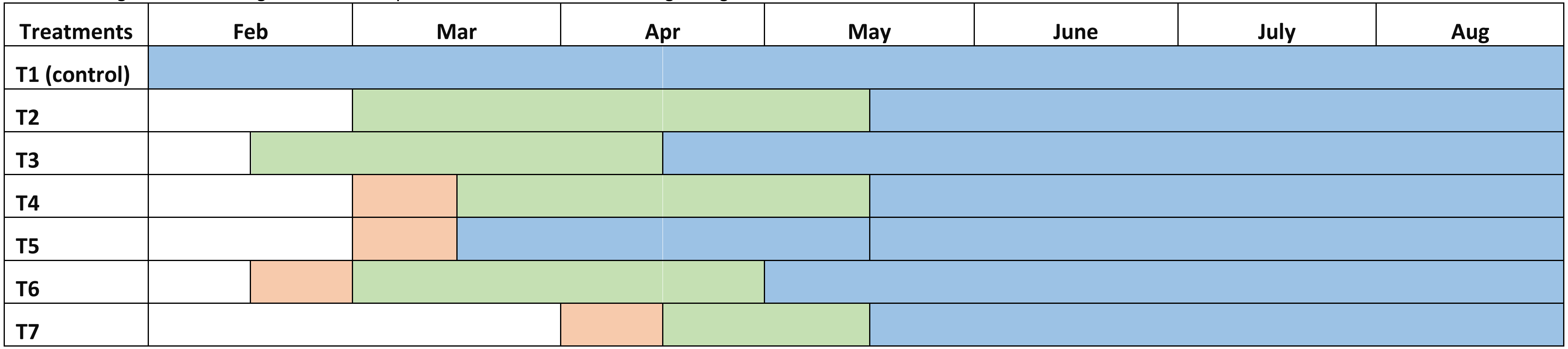
Irrigation treatment structure

Six irrigation treatments were applied to the trees at different stages during fruit development as outlined in Table 4.1. The orange boxes represent the drying period when no water was available to the soil. The light green boxes represent the availability of 50% irrigation water and the blue boxes represent the availability of 100% irrigation water. The treatments were designed to be applied early (15 February and 1–15 March) and later (from 1 April) at 25 mm to assess the fruit quality effects, fruit yield and fruit size distribution from M7, Washington and Lane Late navel citrus trees on either *Poncirus trifoliata* or *Troyer citrange* rootstock.

T1 is the control, and 100% irrigation was applied. In February, 2 treatments (T3 and T6) were applied (Figure 4.1). In T3, the soil profile was not dried, and 50% irrigation was applied for 8 consecutive weeks from 15 February to 15 April followed by 100% irrigation until harvest. In this treatment, trees displayed stress, which was indicated by the stem water potential (SWP) value of 8.9 bar on 1 March (Table 4.2). The results showed that trees with 50% irrigation as early as in February can achieve stress levels, even without pre-drying the soil profile. This stress was apparent at the early stages between late February and early March as per SWP data (Table 4.2). In T6, the soil profile was dried for 2 weeks (15–28 February) and 50% irrigation was applied for 8 consecutive weeks followed by 100% irrigation until harvest. T6 achieved maximum stress by 4 March (Figure 4.1) due to withholding water for 2 weeks in hot weather conditions during February. The SWP was already at 10 bar by 24 February and reached as high as 12.3 bar by 11 March (Table 4.2). In T3, 50% irrigation started from 1 March, but trees were showing stress until 19 March (Table 4.2).

Regulated deficit irrigation treatments T2, T4 and T5 were commenced in March. In T2, the soil profile was not dried, and 50% irrigation was applied from 1 March, however, once the fruit size fell behind the control trees, the profile was re-wetted by the application of full irrigation (Figure 4.2). Therefore, the SWP values indicated some degree of stress between 5–10 March (Figure 4.2 and Table 4.2). The soil profile was re-wetted with full irrigation as the fruit size fell below that of the control. Trees started to recover from 10 April onwards (Figure 4.2), after which, trees in T2 were not stressed and were continuously irrigated with 100% irrigation. This treatment was not easy to manage and did not provide any commercial practicality for the growers in terms of monitoring and managing the irrigation requirements.

Table 4.1: Regulated deficit irrigation treatment plan and its duration for the 2021 growing season.



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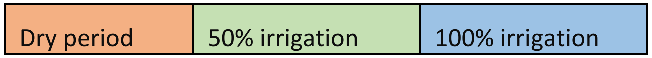

T1 –100% irrigation per ETo, throughout the entire growing season (control)
T2 – No profile drying, 50% irrigation (1 March–15 May), 70% irrigation (in case fruit size decreased) – monitored stress (MS)
T3 – No profile drying, 50% irrigation (15 Feb–15 April), 100% irrigation (15 April to harvest) – early light stress (ELS)
T4 – Profile drying down to 25 mm (1–15 March), 50% irrigation (15 March–15 May), 100% irrigation (15 May to harvest) – mid mild stress (MMS)
T5 – Profile drying down to 25 mm (1–15 March), 100% irrigation (a week prior harvest) – mid light stress (MLS)
T6 – Profile drying down to 25 mm (15–1 Mar), 50% irrigation (1 Mar–1 May), 100% irrigation (1 May to harvest) – early mild stress (EMS)
T7 – Profile drying down to 25 mm (1–15 April), 50% irrigation (15 April–15 May), 100% irrigation (a week before harvest) – late mild stress (LMS)

In T4, the soil profile was dried for 2 weeks (1–15 March) and 50% irrigation was applied for 8 consecutive weeks followed by 100% irrigation until harvest. T4 indicated its peak stress levels by 14 March (Figure 4.2) and the SPW value was 7.5 bar on 19 March (Table 4.2). This treatment exhibited stress levels until 20 April with 50% irrigation. In the Mildura region, March is still a warm period and fruits are actively growing, therefore, the stress levels were expected if pre-drying of the soil was practiced from 1–15 March.

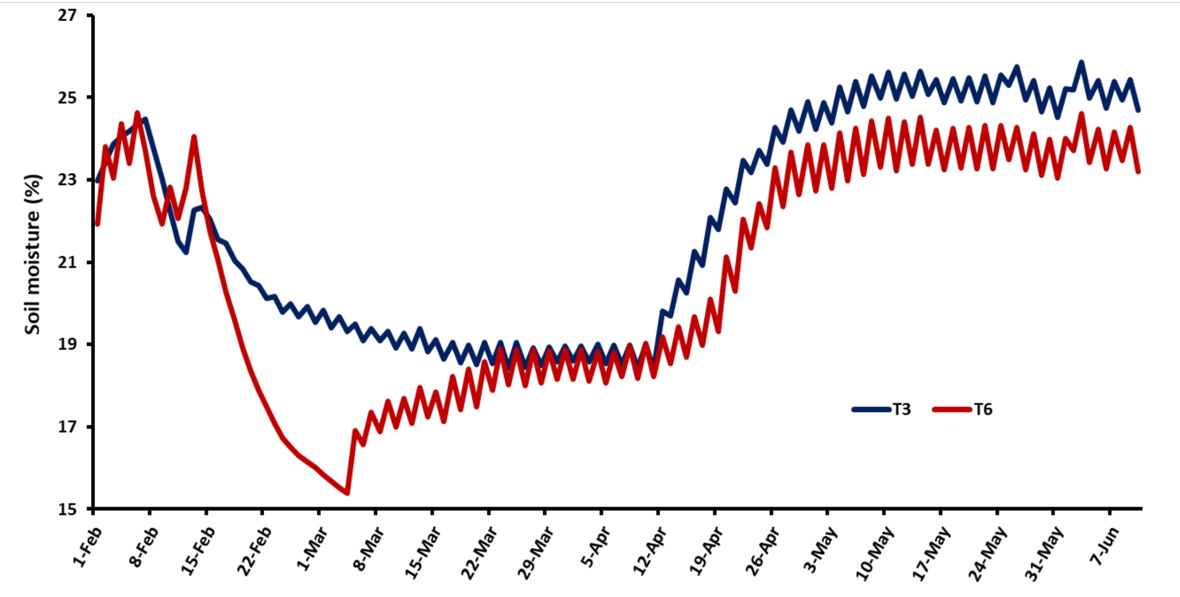

Figure 4.1: Soil moisture (%) during irrigation treatments T3 and T6 applied in February for the 2021 growing season.

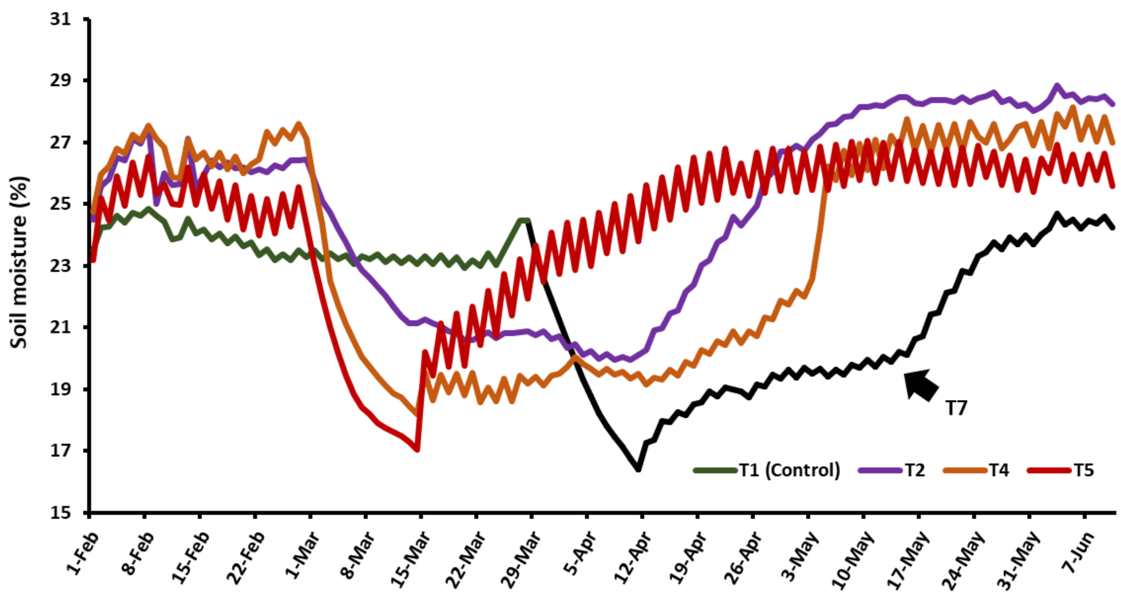

Figure 4.2: Soil moisture (%) during irrigation treatments T1 (control), T2, T4, T5 and T7 for the 2021 growing season. Treatment 7 starts from 1 April as indicated by the solid black line.

In T5, the soil profile was dried for 2 weeks (1–15 March) followed by 100% irrigation until harvest. T5 reached peak stress levels by 14 March (Figure 4.2) and the SPW values were 8.1 bar on 19 March and 7.5 on 23 March (Table 4.2). As the trees were fully irrigated at the end of the soil drying period of 2 weeks, they did not exhibit any stress for the rest of the season.

In T7 (as indicated by the black solid line in Figure 4.2), the soil profile was dried for 2 weeks (1–15 April), and 50% irrigation was applied for 4 consecutive weeks followed by 100% irrigation until harvest. This additional treatment was tested to see if the stress applied in April will be of any benefit to increase the sugar levels in the fruit. In this treatment a reasonable stress levels were achieved (Figure 4.2) and as indicated by the SWP value of 7.1 bar on 13 April (Table 4.2).

Table 4.2: Pre-dawn stem water potential (SWP) values in bar for irrigation treatments in 2021. 1 bar = 0.1 MPa.

	T1	T2	T3	T4	T5	T6	T7
17 Feb	4.0	4.7	4.7	4.4	5.2	5.2	5.3
19 Feb	4.4	5.4	5.0	4.3	5.4	6.0	5.5
24 Feb	3.7	4.9	6.6	5.0	6.8	10.0	5.5
26 Feb	3.5	4.2	7.3	5.6	6.5	8.9	5.0
1 Mar	4.4	4.8	8.9	5.9	6.1	12.3	5.6
5 Mar	4.6	6.7	7.4	5.7	5.4	11.3	5.5
10 Mar	4.3	6.3	6.4	6.7	5.3	7.6	5.6
12 Mar	4.3	6.0	5.7	6.3	5.8	9.4	5.5
17 Mar	5.1	5.8	5.8	6.3	5.8	10.7	4.5
19 Mar	4.8	6.7	6.0	7.5	8.1	7.6	4.6
23 Mar	5.0	6.0	5.7	7.6	7.5	6.6	4.8
26 Mar	5.2	5.6	5.4	7.0	5.3	5.5	4.5
30 Mar	4.5	5.6	5.7	7.3	5.8	5.6	5.1
5 Apr	3.8	5.9	5.9	7.0	5.6	6.1	5.6
13 Apr	4.7	6.2	6.5	7.9	6.5	5.6	7.1
16 Apr	4.5	6.0	6.5	7.0	6.3	5.5	6.6
20 Apr	4.6	6.8	6.5	7.5	6.5	6.1	6.6
23 Apr	4.8	6.6	6.3	6.6	6.0	6.1	6.5
27 Apr	4.8	6.8	5.9	6.6	6.1	5.8	6.6
30 Apr	4.5	6.5	6.0	6.9	6.1	6.0	6.9
4 May	4.6	6.2	6.3	7.0	6.0	6.2	6.4
7 May	4.7	6.4	6.3	6.6	6.1	6.0	6.6
17 May	5.3	6.5	6.0	6.2	6.0	5.6	6.4

Fruit quality components at harvest

The fruit quality data were collected at harvest for the 2021 growing season from all experimental trees (Table 4.3).

In M7 navel, T6 increased °Brix values by 1 compared to the control (Table 4.3). There was significant effect found for rootstocks on °Brix values, which were slightly higher in *Troyer citrange* rootstock compared to *Poncirus trifoliata* rootstock. The effect of irrigation treatments or rootstocks was not significant on BrimA values, however, T4 and T7 had higher BrimA values than the control. The effect of irrigation treatments was significant on acid values, and T4, T5 and T6 increased acid levels in fruit compared to the control (Table 4.3). The acid levels were significant across rootstocks and at this instance *Troyer citrange* had higher acid than *Poncirus trifoliata* rootstock (Table 4.3). Neither irrigation treatments nor rootstocks had an effect on percent juice values.

In Washington navel, the irrigation treatments had significant effect on °Brix values. Irrigation treatment T6 has increased °Brix value by 0.9 unit compared to the control. There was no rootstock effect for °Brix value. The acid levels were significantly increased with T6 compared to the control (Table 4.3), and *Troyer citrange* had slightly higher acid levels than *Poncirus trifoliata* rootstock. The effect of irrigation treatment or rootstocks was not significant for BrimA values or per cent juice content (Table 4.3).

In Lane Late navels, T4 and T6 increased °Brix values by > 1 unit compared to the control (Table 4.3). There were no significant rootstock effects on °Brix values. Lane Late had a significant interaction effect with irrigation treatments and rootstocks. T4 and T6 increased °Brix in *Poncirus trifoliata* and *Troyer citrange* (1.9 and 1.2 units, and 2.2 and 1.9 units respectively) compared to the control. The effect of irrigation treatments was significant on BrimA values, and BrimA values were higher in T6 (150) compared to the control (139). There were a significant rootstock effects found on BrimA values, and *Poncirus trifoliata* had higher BrimA values than *Troyer citrange* rootstock. Irrigation treatment had significant effect on acid level in the fruit. Irrigation treatments T5 and T7 had the highest acid levels compared to the control. The rootstock effect was significant for acid values where *Troyer citrange* had slightly higher acid levels compared to *Poncirus trifoliata.* The per cent juice was significantly affected by the irrigation treatments, and T4 had higher juice per cent compared to the control (Table 4.3). In significant rootstocks affect *Troyer citrange* had slightly higher juice values compared to *Poncirus trifoliata*.

There were no significant interaction effects found between irrigation treatments and rootstocks in M7, Washington or Lane Late for any quality attributes (Table 4.3).

Table 4.3: Fruit quality attributes °Brix, BrimA, acid (%), and juice (%) in M7, Washington navel and Lane Late navels for the 2021 growing season.

	M7				Washington navel				Lane Late			
Irrigation treatments (It)	°Brix	Brim A	Acid (%)	Juice (%)	°Brix	Brim A	Acid (%)	Juice (%)	°Brix	Brim A	Acid (%)	Juice (%)
T1 (control)	14.3	147	1.3	53	12.8	128	1.2	50	12.8	139	1.10	52
T2	14.6	153	1.3	52	12.8	127	1.3	52	13.5	144	1.19	52
T3	14.9	155	1.4	51	13.4	134	1.3	51	14.4	152	1.29	52
T4	14.9	152	1.4	52	13.5	134	1.3	52	14.9	157	1.35	55
T5	14.7	160	1.2	53	13.1	130	1.3	54	13.3	142	1.17	51
T6	15.5	153	1.5	53	14.2	142	1.4	53	14.4	150	1.33	50
T7	14.8	160	1.2	53	12.9	128	1.3	53	13.7	140	1.30	52
Probability	*	ns	**	ns	***	ns	*	ns	***	***	***	*
LSD ($p < 0.05$)	0.47	–	0.12	–	0.43	–	0.12	–	0.42	9.31	0.12	2.9
Rootstocks (Rt)												
Poncirus trifoliata	14.4	154	1.3	52	13.1	132	1.2	51	13.9	150	1.20	51
Troyer citrange	15.0	154	1.4	52	13.3	132	1.3	53	13.8	143	1.29	53
Probability	***	ns	***	ns	ns	ns	*	1.67	ns	***	***	*
LSD ($p < 0.05$)	0.25	–	0.06	–	–	–	0.05	–	–	4.98	0.06	1.6
Interaction (It × Rt)												
Probability	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	–	–	0.59	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit yield components at harvest

Fruit yield components were recorded at harvest for all experimental trees for M7, Washington navel and Lane Late oranges for the 2021 growing season.

In M7 navels, there were no significant effects of irrigation treatments on fruit yield/tree and fruit number/tree. Trees carried an average of 37.3 kg/tree, and average fruit number/tree was 216 (Table 4.4). The significant rootstock effect suggested that *Poncirus trifoliata* had higher fruit yield/tree and higher fruit number/tree compared to *Troyer citrange* rootstock. The effect of irrigation treatment on average fruit weight was significant. All irrigation treatments, apart from T5, significantly decreased mean fruit weight compared to the control (Table 4.4). T5 did not affect the fruit size because it involved 100% irrigation immediately after drying. In M7 navels, the rootstock effect on fruit weight was significant and fruit weight was reduced by *Troyer citrange* compared to *Poncirus trifoliata* rootstock (Table 4.4).

In Washington navels, there were no significant effects of irrigation treatments on fruit yield/tree or fruit number/tree. Trees carried an average of 58.7 kg/tree, and average fruit number/tree was 269 (Table 4.4). The *Troyer citrange* rootstock significantly increased the fruit number compared to *Poncirus trifoliata* rootstock. Average fruit weight was significantly decreased by T3, T4, T5 and T6 compared to the control (Table 4.4). Fruit weight was decreased by 48.8 g on *Troyer citrange* compared to *Poncirus trifoliata* rootstock (Table 4.4).

In Lane Late navels, there were significant effects of irrigation treatments on fruit yield/tree, fruit number/tree and on average fruit weight. Trees carried an average of 38.5 kg/tree, and average fruit number/tree was 166 (Table 4.4). Fruit yield/tree was decreased with all treatments except T7 compared to the control, and with T6, this decrease was 29 kg/tree (Table 4.4). The rootstock effect was not significant for fruit yield/tree. A significant interaction between irrigation treatments and rootstocks occurred with T6 having 48 kg/tree less on *Poncirus trifoliata* rootstock (data not tabulated).

There was a significant effect of irrigation treatments on fruit number/tree, which were reduced with T2, T4, T5, T6 and T7 compared to the control. T6 caused the greatest reduction of 100 fruit/tree, which is approximately 24 kg/tree. There is a possibility of fruit fall with this early severe treatment, as hot weather conditions in combination with reduced water can cause fruit and leaves to drop. The interaction effect between irrigation treatments and rootstock was significant for fruit number/tree. The fruit number/tree in T6 (applied in February) were 76 compared to the control (257) in *Poncirus trifoliata* rootstock, which is a very significant reduction. The lower fruit number in T6 was due to the *Poncirus trifoliata* rootstock and not due to *Troyer citrange*. *Poncirus trifoliata* rootstock has a shallow root system, and the tree cannot withstand severe water stress.

The effect of irrigation treatments or rootstocks was significant on average fruit weight. Fruit weight was decreased with T3, T4 and T6 compared to the control (Table 4.4). The significant rootstock effect indicated that fruit weight was decreased by *Troyer citrange* rootstock by 41 gm compared to *Poncirus trifoliata*, which could have a commercial significance for the citrus industry.

There were no significant interaction effects between irrigation treatments and rootstocks for M7 or Washington navel (Table 4.4).

Table 4.4: Fruit yield (kg)/tree, fruit number/tree and individual fruit weight in M7, Washington navel and Lane Late navels for the 2021 growing season.

	M7 navel			Washington navel			Lane Late navel		
Irrigation treatments (It)	Fruit yield (kg)	Fruit number	Fruit weight (g)	Fruit yield (kg)	Fruit number	Fruit weight (g)	Fruit yield (kg)	Fruit number	Fruit weight (g)
T1 (control)	39.6	205	191.3	70.0	296	238.0	53.1	214	250.5
T2	34.4	207	177.7	56.3	248	232.1	38.7	166	236.8
T3	36.3	210	171.8	57.1	274	210.8	39.4	176	223.5
T4	36.0	217	164.4	55.0	266	210.0	34.7	163	214.3
T5	35.2	194	183.8	60.1	268	226.1	36.2	152	239.2
T6	37.1	235	156.1	53.5	262	209.8	24.2	114	224.9
T7	40.9	240	170.5	54.7	239	232.1	43.5	179	251.8
Probability	ns	ns	***	ns	ns	***	***	***	***
LSD ($p < 0.05$)	–	–	12.0	–	–	10.3	10.1	46.5	18.0
Rootstocks (Rt)									
Poncirus trifoliata	43.7	233	191.0	58.1	236	247.1	40.1	159	255.0
Troyer citrange	31.0	199	156.3	58.0	293	198.3	36.9	173	213.9
Probability	***	**	***	ns	***	*	ns	ns	***
LSD ($p < 0.05$)	3.6	23.0	6.4	–	31.7	5.5	–	–	9.6
Interaction (It × Rt)									
Probability	ns	ns	ns	ns	ns	ns	**	*	ns
LSD ($p < 0.05$)	–	–	–	–	–	–	14.4	65.8	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit size distribution at harvest

Fruit size distribution was assessed for all experimental trees for each variety and rootstock in the 2021 growing season (Table 4.5). The data extracted from Table 4.5 is also presented in Figures 4.3 to 4.5, so the data is visually and effectively communicated to readers.

In M7 navels, the irrigation treatments had significant effect on size classes 69-75 mm, 75-81 mm and 81–87 mm (Table 4.5). For the size class 81–87 mm, there was a reduction of 16% with T4 and 22% with T6 compared to the control (Figure 4.1). The rootstocks effect was significant for size classes 69-75, 75-81 and 81–87 mm (Table 4.5). In size class 81–87 mm, *Troyer citrange* significantly reduced the fruit size compared to *Poncirus trifoliata* rootstock (Table 4.5). There was a significant interaction between the irrigation treatments and rootstocks for 3 size classes. In size class 81–87 mm, the fruit size was 25% for T4 and 17% for T6 compared to the control (56%) in *Poncirus trifoliata* rootstock. However, the average percent of fruit size class 81–87 mm for *Troyer citrange* rootstock was 10%.

In Washington navel, the irrigation treatment had a significant effect on size class 69-75 mm, 75-81 and 81–87 mm (Table 4.5). In size class 81–87 mm, fruit size was decreased with T3, T4, T5 and T6, however, the reduction was more prominent with T4 and T6 compared to the control (Figure 4.4). T7 has a positive effect and did not reduce fruit size suggesting that late application of water stress may be beneficial for fruit size. The rootstocks effect was significant for size classes 69-75, 75-81 and 81–87 mm (Table 4.5). In size class 81–87 mm, *Troyer citrange* has significantly reduced the fruit size compared to *Poncirus trifoliata* (Table 4.5).

In Lane Late navel, the irrigation treatment had a significant effect on size class 69-75 mm, 75-81 mm and 81–87 mm (Table 4.5). In size class 81–87 mm, the irrigation treatments T3, T4 and T6 has reduce the fruit size compared to the control (Figure 4.5). T7 has no reduction in fruit size compared to the control. The rootstocks effect was significant for all 3 size classes (Table 4.5). In size class 81–87 mm, *Troyer citrange* has significantly reduced the fruit size compared to *Poncirus trifoliata*. The interaction effect was not significant for Washington navel or Lane Late navels between irrigation treatments and rootstocks (Table 4.5).

Relationship of large fruit size (81–87 mm) vs °Brix (total soluble solids)

Regression analysis showed a significant relationship between large fruit size fruit (81–87 mm) and °Brix values There was significant relation found for M7 navels, Washington navel or Lane Late (Figures 4.6 to 4.8). In figure 4.6, the data suggested that the relation between fruit size and sugar levels was reasonably strong (R^2 = 0.64) for M7 navels. M7 is generally an early maturing orange and the sugar levels increase rapidly with maturity compared to the mid-maturing Washington navels and late-maturing Lane Late navels. The relationship between large fruit size and °Brix was also quite strong for Washington navel (R^2 = 0.73; Figure 4.7). In Lane Late navels, the relation between fruit size and sugar levels was also stronger (R^2 = 0.78) as given in figure 4.8. These relationships significantly indicated that the increase in sugar levels by imposed water stress treatment caused by the reduction in water has a pronounced effect on large sized fruit and the degree of stress dictates the fruit size and an increased sugar levels in sweeter oranges.

Table 4.5: Fruit size distribution (%)/tree for M7, Washington navel and Lane Late navel in different size classes per tree for the 2021 growing season.

	M7 navel			Washington navel			Lane Late navel		
Irrigation treatments (It)	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm	69–75 mm	75–81 mm	81–87 mm
T1 (control)	22	23	34	7	18	71	9	19	69
T2	29	26	22	11	22	63	16	22	57
T3	26	25	22	15	27	51	15	30	52
T4	29	22	16	17	25	49	24	27	42
T5	25	28	26	10	25	61	12	24	61
T6	30	20	12	17	26	49	20	24	49
T7	26	25	20	9	20	66	9	20	69
Probability	**	*	***	***	**	***	***	*	**
LSD (p < 0.05)	4.2	4.8	7.2	4.0	4.7	8.3	6.8	6.4	13.6
Rootstocks (Rt)									
Poncirus trifoliata	24	28	33	6	15	77	9	18	70
Troyer citrange	30	20	11	19	31	40	20	29	43
Probability	***	***	***	***	***	***	***	***	***
LSD (p < 0.05)	2.2	2.6	3.9	2.2	2.5	4.4	3.7	3.4	7.3
Interaction (It × Rt)									
Probability	***	*	***	ns	ns	ns	ns	ns	ns
LSD (p < 0.05)	6.0	6.8	10.3	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *p < 0.05, **p < 0.01, ***p < 0.001 and ns (non-significant).

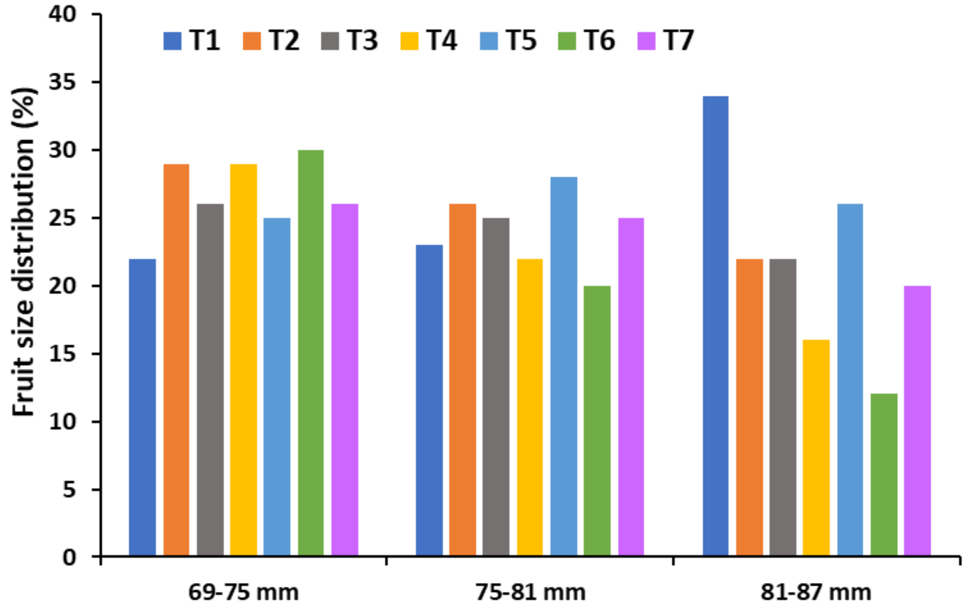

Figure 4.3: Fruit size distribution (%) of 3 export size classes for M7 navel at harvest. Six irrigation treatments were applied in the 2021 growing season. T1 is the control (100% irrigation).

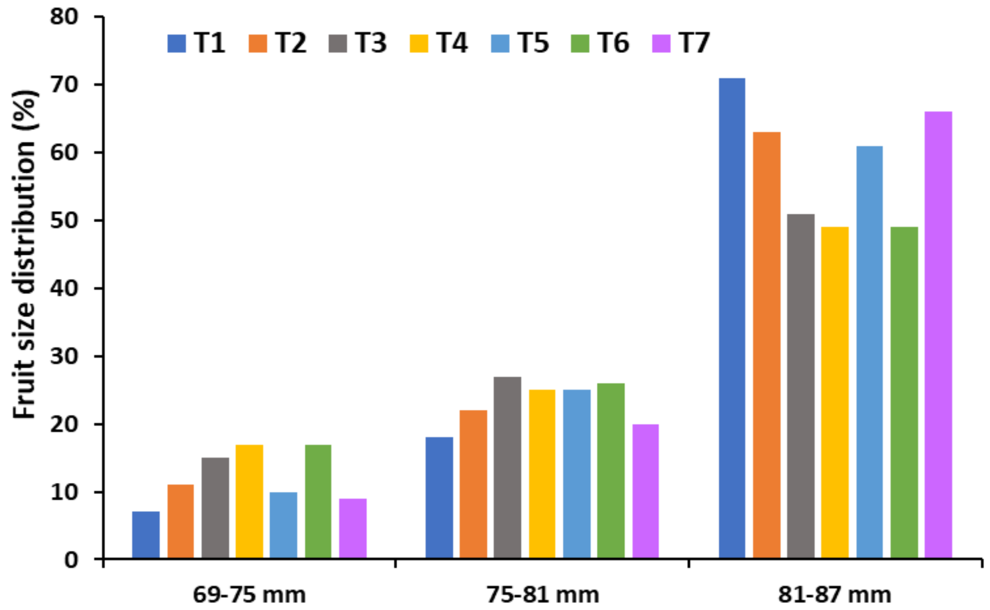

Figure 4.4: Fruit size distribution (%) of 3 export size classes for Washington navel at harvest. Six irrigation treatments were applied in the 2021 growing season. T1 is the control (100% irrigation).

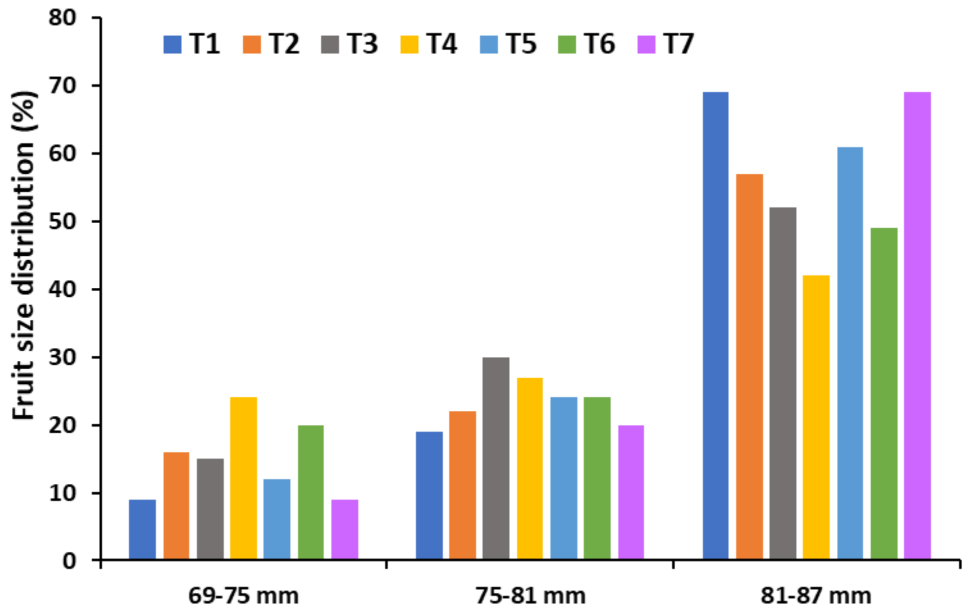

Figure 4.5: Fruit size distribution (%) of 3 export size classes for Lane Late navel at harvest. Six irrigation treatments were applied in the 2021 growing season. T1 is the control (100% irrigation).

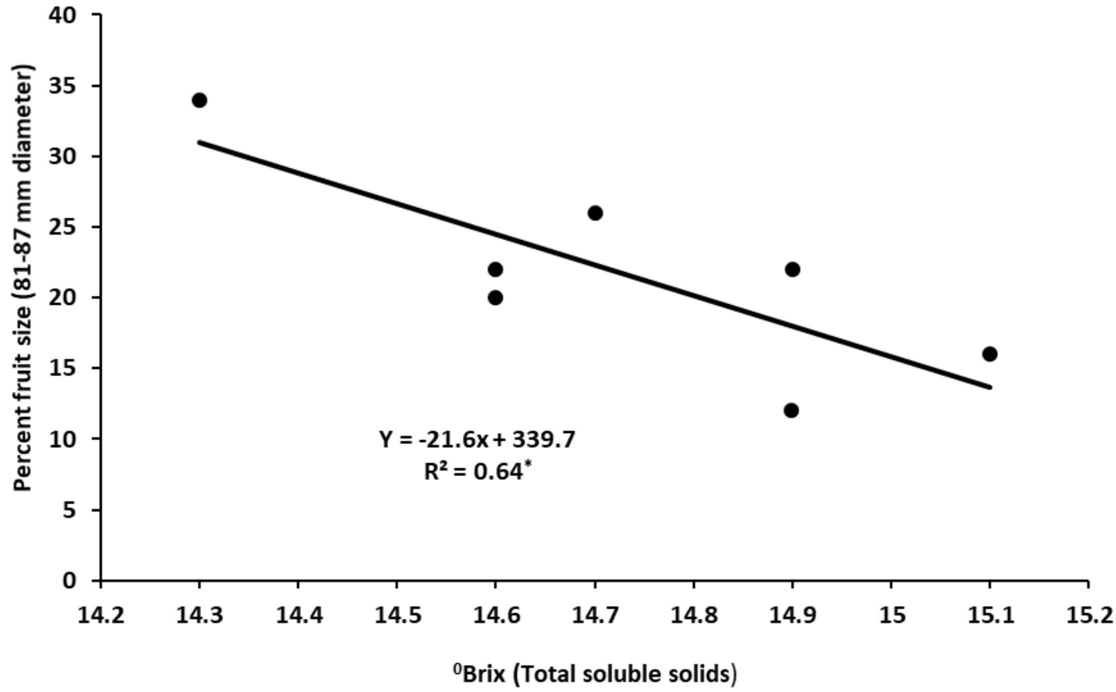

Figure 4.6: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for M7 navel in 2021. Regression coefficient $R^2 = 0.64$ is significant at $p < 0.05$ (*).

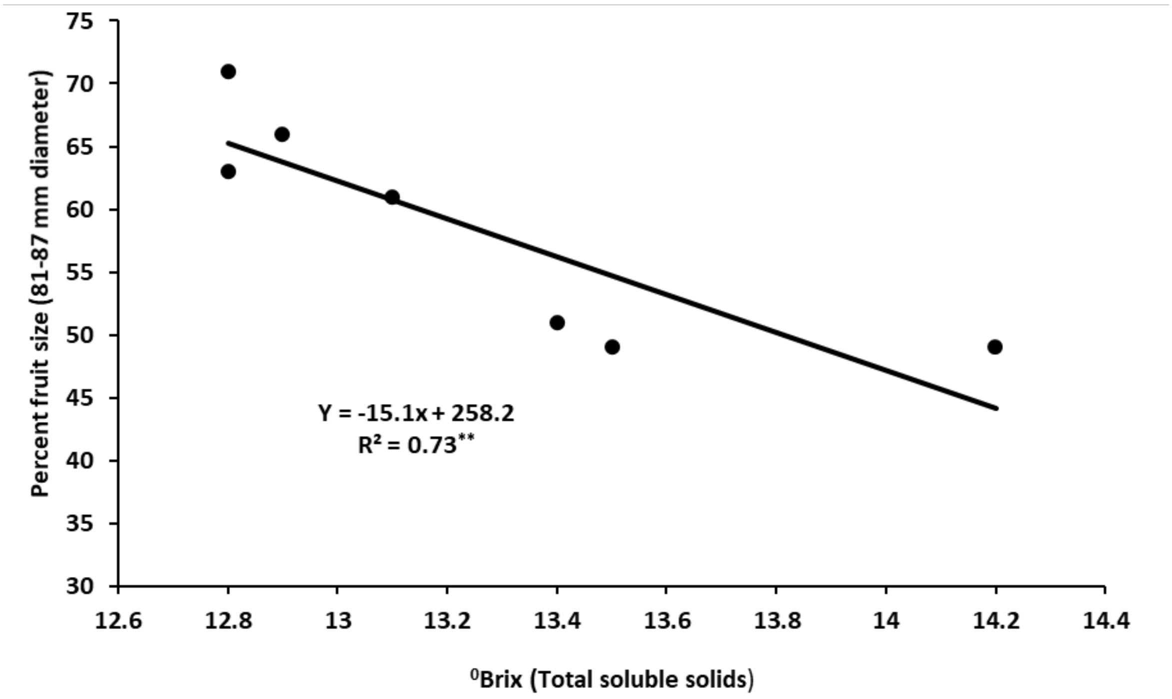

Figure 4.7: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for Washington navel in 2021. Regression coefficient R^2 = 0.73 is significant at $p < 0.01$ (**).

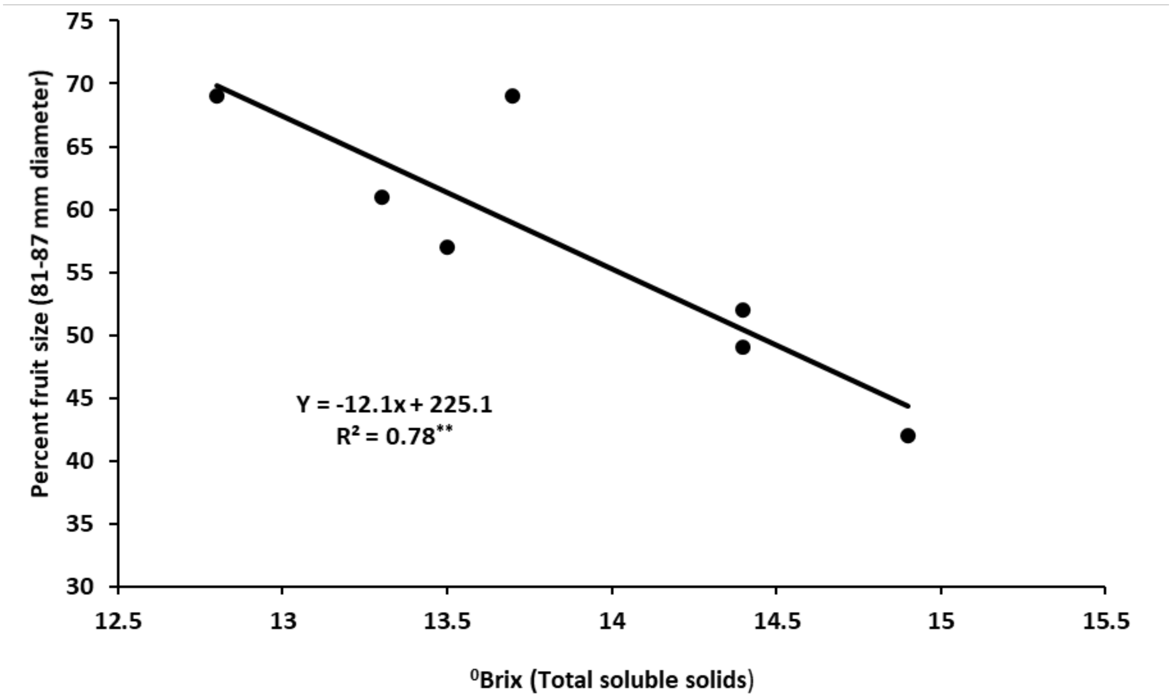

Figure 4.8: Relationship between large fruit size (81–87 mm) and °Brix values at harvest for Lane Late navel in 2021. Regression coefficient R^2 = 0.78 is significant at $p < 0.01$ (**).

Chapter 5: Sensory evaluation trials for navel oranges

Sensory evaluation for navel oranges in 2019

Sensory evaluation was designed and discussed with a biometrician and program was drawn to conduct the evaluation at harvest for M7 (early maturing) and Lane Late navel (late maturing) navel oranges. The sensory evaluation was carried out at SuniTAFE Mildura. Staff and students were involved in assessing the sensory evaluation of the fruit harvested from the regulated deficit irrigation trial at Dareton. Fruit was harvested for three regulated deficit treatments and two rootstocks *Poncirus trifoliata* and *Troyer citrange* from 4 replicates of the trial.

Fruit harvest and sample preparation

Fruit were harvested from M7 on 22 May 2019 and Lane Late on 13 August 2019. A total of 768 samples were collected. Half of the fruit was used to assess the °Brix and acid levels for each treatment at the Dareton Primary Industries Institute's laboratory before sensory evaluation, while the rest of the fruit was used for sensory evaluation and given to the assessors. Therefore, each fruit result could be related to the data obtained from the assessor after the sensory evaluation.

Samples for sensory evaluation

Each assessor was provided with a plate containing 6 fruit samples and a pre-written questionnaire (form) to be completed. A few plain biscuits and water were provided to the assessor for palate cleansing between the test samples (Figure 5.1).

Sensory evaluation room

All care was taken to segregate the assessors from each other (Figure 5.1). Each assessor was provided with an individual table and chair and instructed not to talk to other assessors. The sensory evaluation sessions were supervised to ensure correct procedures were followed throughout the sensory evaluation session.

Data analysis

Pre- and post-sensory data were subjected to analysis of variance with GenStat for Windows 21st edition (VSNI, 2021), and treatment mean separations were tested with least significant difference (LSD) at 5%.

Fruit quality (pre-sensory evaluation)

In M7 navel, the irrigation treatments T2 and T3 significantly increased sugar and BrimA values compared to the control (Table 5.1). The acid levels were not affected by irrigation treatments. There were no effects of rootstock on °Brix value, acid levels or BrimA values.

In Lane Late navel, the irrigation treatments T2 and T3 has significantly increased the sugar levels compared to the control by more than 2 degrees (Table 5.1). The acid levels were slightly increased with irrigation treatments, with T2 and T3 compared to the control. However, this increase is commercially significant, and it contributes to enhanced fruit taste. BrimA values were also significantly increased with T2 and T3 compared to the control. There were no effects of rootstocks treatments on ^{0}Brix value, acid levels or BrimA values.

Figure 5.1: Sample preparation and room set up for the sensory evaluation in 2019. Photo: Dr Tahir Khurshid.

Table 5.1: The effect of irrigation treatments and rootstocks on fruit quality components before sensory evaluation for M7 and Lane Late navel in 2019.

	M7			Lane Late		
Irrigation treatments	°Brix	Acid (%)	BrimA	°Brix	Acid (%)	BrimA
T1 (control)	13.9	0.96	166	12.9	0.86	156
T2	14.4	0.97	173	15.1	1.05	179
T3	14.4	0.95	175	15.4	1.03	186
Probability	***	ns	***	***	***	***
LSD ($p < 0.05$)	0.24	–	3.7	0.41	0.02	6.7
Rootstocks						
Poncirus trifoliata	14.1	0.96	170	14.5	1.0	174
Troyer citrange	14.3	0.96	173	14.4	1.0	173
Probability	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment and rootstocks, ***$p < 0.001$ and ns (non-significant).

In M7, the interaction between irrigation treatments and rootstocks was significant for °Brix and BrimA values (Table

5.2). In *Troyer citrange*, the °Brix values were higher for T2 and T3 compared to *Poncirus trifoliata* rootstock. The BrimA values followed the same trend with T3 having the highest BrimA value in *Troyer citrange* rootstock (Table 5.2).

In Lane Late navels, the interaction between irrigation treatments and rootstocks was significant for °Brix values, acid levels and BrimA values (Table 5.2). In *Poncirus trifoliata,* T3 increased °Brix values compared to the control, while in *Troyer citrange* the °Brix values were higher with T2 compared to the control. The acid values were higher with T2 and T3 compared to the control in *Troyer citrange*. The BrimA values were highest (193) with T3 compared to the control in *Poncirus trifoliata* rootstock, while BrimA were higher (186) than *Troyer citrange* rootstock (Table 5.2). The data indicated that the response of fruit to irrigation treatments was were slightly different across the two rootstocks.

Table 5.2: The interaction between irrigation treatments and rootstocks on quality components in 2019.

	Poncirus trifoliata	***Troyer citrange***	***Poncirus trifoliata***	***Troyer citrange***	***Poncirus trifoliata***	***Troyer citrange***
	°Brix		Acid (%)		BrimA	
	M7					
Irrigation treatments						
T1 (control)	14.0	13.8	0.97	0.94	167	165
T2	14.2	14.5	0.98	0.96	170	176
T3	14.2	14.6	0.94	0.96	172	177
Probability	*		ns		*	
LSD ($p < 0.05$)	0.34		–		5.3	
	Lane Late					
Irrigation treatments						
T1 (control)	13.0	12.7	0.89	0.82	156	155
T2	14.7	15.5	1.05	1.05	173	186
T3	15.7	15.0	1.00	1.05	193	179
Probability	***		***		***	
LSD ($p < 0.05$)	0.58		0.02		9.5	

Mean separation within the columns was tested with LSD for irrigation treatment. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Fruit quality components (post-sensory evaluation)

The scored data collected during the sensory evaluation was converted to percentages to reveal clear indication of the quality component responses to the applied deficit irrigation treatments. A 4 indicated 'Good' and a 5 indicated 'Best' for the quality attributes.

The data presented is for score 4 and 5 was combined which means that fruit quality percent presented in Table 5.3 is the independent opinions of assessors and is from overall good quality fruit. The data were averaged for the 2 rootstocks because there were no differences between them.

In M7, the data suggested that T2 has increased significantly increased the scores for sweetness (86%) tasted by the assessors compared to the control (77%) as indicated in Table 5.3. The acid levels in the fruit were regarded higher with T3 (87%) compared to the control (77%). The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. T2 had better tasting fruit than the control (87% and 78%, respectively). Generally, an adequate juice quantity was found in fruit from T1 (78%) compared to T2 or T3, however, this result was not significant. This result is interesting because fruit is actively growing in February and water stress can cause reduced juice content and reduced fruit size, however, the deficit irrigation treatments applied in this trial did not affect the juice quantity in the fruit.

Table 5.3: The effect of irrigation treatments on fruit quality components during a post-sensory evaluation for M7 and Lane Late navel in 2019.

	Sweetness	**Acidity**	**Taste**	**Juiciness**
Irrigation treatments		**M7**		
T1 (control)	77%	77%	78%	78%
T2	86%	80%	87%	70%
T3	83%	87%	84%	68%
Probability	**	**	*	ns
LSD ($p < 0.05$)	2.9	3.9	4.0	–
Irrigation treatments		**Lane Late**		
T1 (control)	77%	80%	79%	84%
T2	80%	81%	79%	79%
T3	87%	82%	87%	75%
Probability	*	ns	***	***
LSD ($p < 0.05$)	5.3	–	5.1	3.0

Mean separation within the columns was tested with LSD for irrigation treatment.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

In Lane Late navels, the data indicated that T3 had higher scores for sweetness (87%) than the control (77%). The acid levels were not different between the treatments. The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. The fruit taste in T3 scored 87%, which was higher than control (79%). Generally, an adequate juice quantity was found in fruit with T1 (84%) compared to T2 (79%) or T3 (75%).

Sensory evaluation of navel oranges in 2020

Due to Covid19 restrictions, it was not possible to conduct sensory evaluation at the SuniTAFE Institute or any other organisation. Grower gatherings were also quite restricted; therefore, sensory evaluation was carried out at Mildura Fruit Cooperative (MFC) with marketers, packers and fruit quality experts under strict Covid19 guidelines. Fruit was harvested from early-maturing M7 navels and mid-maturing Washington navels for 2 regulated deficit treatments from 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*). T1 was the control (100% irrigation) and T6 was the treatment where deficit irrigation was applied in February 2020. Additional treatments were planned, however, substantial rain fell from March through to May, which meant that the water stress planned for T3, T4 and T5, could not be applied.

Fruit harvest and sample preparation

The M7 navel crop was harvested on 5 May 2020, while Lane Late navel was harvested on 17 June 2020. Half of the fruit was used to assess the °Brix and acid levels for each treatment at the Dareton Research Institute laboratory before sensory evaluation, while the rest of the fruit was used for sensory evaluation. In this way each fruit can be related to data obtained by the assessor after the completion of sensory evaluation data. A total of 90 samples were used for the sensory evaluation for both M7 and Lane Late navels.

Samples for sensory evaluation

Each assessor was provided with a plate containing 6 fruit samples and a pre-written questionnaire (form) to be completed. A few plain biscuits and water were provided to the assessor for palate cleansing between the test samples (Figure 5.1).

Data analysis

Pre-and post-sensory data were subjected to analysis of variance with GenStat for Windows 21st edition (VSNI, 2021) and, treatment mean separations were tested with least significant difference (LSD) at 5%.

Fruit quality components (pre-sensory evaluation)

In M7 navel, the irrigation treatment T6 significantly increased sugar levels compared to the control (Table 5.4). The acid levels were also affected with irrigation treatments and acid was higher for T6 treatment. BrimA values were higher for T6 treatment compared to the control. Rootstock did not affect the quality attributes. However, the interaction between irrigation treatments and rootstock was significant for BrimA values, which were increased with T6 (143) compared to T1 (166) in *Poncirus trifoliata* rootstock, but *Troyer citrange* was not affected (data not shown).

Table 5.4: The effect of irrigation treatments and rootstocks on fruit quality components before sensory evaluation for M7 and Washington navel in 2020.

	M7			**Washington navel**		
Irrigation treatments (It)	°Brix	Acid (%)	BrimA	°Brix	Acid (%)	BrimA
T1 (control)	11.5	0.99	124	12.6	1.04	140
T6	13.5	1.22	142	13.2	1.28	134
Probability	***	***	**	***	**	*
LSD ($p < 0.05$)	0.66	0.08	8.27	0.36	0.07	6.47
Rootstock (Rt)						
Poncirus trifoliata	12.5	1.13	130	13.2	1.20	139
Troyer citrange	12.6	1.08	136	12.6	1.12	135
Probability	ns	ns	ns	**	*	ns
LSD ($p < 0.05$)	–	–	–	0.36	0.07	–
Interaction (**It × Rt**)						
Probability	ns	ns	*	ns	ns	ns
LSD ($p < 0.05$)	–	–	12.0	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

In Washington navel, the irrigation treatment T6 significantly increased sugar and acid levels compared to T1 (Table 5.4). °Brix levels and acid levels were also higher for *Poncirus trifoliata* rootstock compared to *Troyer citrange*. The acid levels were also affected with irrigation treatments and acid was higher for T6 treatment compared to the control. BrimA values were slightly lower in T6. There was no rootstock effect for BrimA values. The interaction between irrigation treatments and rootstocks were not significant for any quality attributes (Table 5.4).

Fruit quality components (post-sensory evaluation)

The data of scores collected during the sensory evaluation was converted to percentages to reveal clear indication of the quality attributes responses to the applied deficit irrigation treatments. Score 4 indicated 'Good', and score 5 indicated 'Very good' for the quality attributes. The data presented is for score 4 and 5 combined which means that the overall good fruit quality percent is presented in Table 5.4. The data was averaged over two rootstocks since there were no differences Between them.

In M7, the results indicated that T6 has increased scores for sweetness (85%) tasted by the assessors compared to the control (50%). The acid levels in the fruit were regarded higher with T6 (71%) compared to the control (51%). The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. T6 had better tasting fruit than the control (82% and 49%, respectively). Generally, T1 had an adequate juice quantity (68%) compared to T6 (42%). This indicates that the deficit irrigation techniques applied in February for T6 did reduce the juice content. In February, fruit is actively growing, and water stress can cause reduce juice content and reduced fruit size.

In Washington navels, T6 has increased scores for sweetness (93%) tasted by the assessors compared to the control (66%). The acid levels in the fruit were regarded higher with T6 (80%) compared to the control (54%). The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. At this occasion, the fruit taste in T6 treatment was (82%) compared to the control (53%). Generally, T1 had an adequate juice quantity (72%) compared to T6 (61%), however, this effect was not significant.

Table 5.4: The effect of irrigation treatments on fruit quality components post-sensory evaluation for M7 and Washington navel in 2020.

	Sweetness	Acidity	Taste	Juiciness
Irrigation treatments		**M7**		
T1 (control)	50	51	49	68
T6	85	71	82	42
Probability	***	**	*	*
LSD ($p < 0.05$)	4.7	6.7	21	2.2
		Washington navel		
Irrigation treatments				
T1 (control)	66	54	53	72
T6	93	80	82	61
Probability	*	**	*	ns
LSD ($p < 0.05$)	17.9	114	28	–

Mean separation within the columns was tested with LSD for irrigation treatment.

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Chapter 6: Drone flights to assess stress in navel orange trees

2018 growing season

A drone flight was conducted by Hort-Eye Pty Ltd. over the entire irrigation trial on 28 February 2018 to estimate crop water stress Index (CWS), and canopy temperatures. The drone (Unmanned Aerial Vehicle (UAV) was fitted with multispectral and thermal infrared (TIR) sensors. The data on canopy temperature was collected for each tree by Hort-Eye Ltd. Data was provided in an Excel sheet and the data was further analysed by me to work out treatment differences across the entire irrigation trial (Figure 6.1).

Figure 6.1: An image from the drone flight conducted on 28 February 2018 on navel trial at Dareton and the drone. Photo: Dr Tahir Khurshid.

Canopy temperature (°C)

The possibility of using plant temperature as an indicator of soil water availability for plants is not new (Gate, 1964). Plants with a soil water deficit often have decreased stomatal conductance, thus have reduced transpiration and increased leaf temperature. Measuring the infrared radiation emitted by the canopy can therefore be used as an indicator of plant water stress (Jones et al. 2002). However, it is important to note that stomatal conductance can be affected not only by soil water deficit, but also by other environmental and endogenous tree factors and climatic conditions (Jones et al. 2009). Furthermore, plant morphological aspects such as canopy shape and leaf size, as well as plant mechanisms controlling transpiration, have a direct influence on canopy temperature (Scherrer et al. 2011). Therefore, an attempt was made to measure the canopy temperature using a drone flight over the irrigation trial.

There were no differences detected in the canopy temperatures for any of the regulated deficit irrigation treatments compared to the control. In M7, there were no differences in canopy temperatures for rootstock or the interaction between irrigation treatments and rootstocks (Table 6.1).

In Washington navel and Lane Late navel, there were no differences in canopy temperature values for any applied deficit irrigation treatments, rootstock, or its interaction. It is possible that the altitude used in this trial (100 m) might have been too far from the canopies to detect any changes. Previous measures have had the camera 30 cm from the target (Stagno et., 2011) and in grape vines, the distance between the detection window and fully expanded leaves was kept at 5–10 cm (Chen et al. 2020). Therefore, on this instance there were no difference in canopy temperature detected by the drone flight at an elevation of 100 meters (Table 6.1). The thermal camera attached to the drone conducted its flight at 100-meter altitude and was not able to detect the treatment differences across the trial in terms of the canopy temperatures. I believe that the higher altitude could be the problem. In past canopy temperature was measure by pointing the infrared thermometer to the canopy at 30 cm from the target (Stagno et., 2011). However, in grapevine study, the distance between the detection window and fully expanded leaves was kept 5-10 cm (Chen et al., 2020).

Crop water stress index (CWSI)

The CWSI was developed as a standardised indicator to diagnose stress and overcome the effects of other environmental factors that affect the relationship between stress and plant temperature (Koksal et al. 2010; Jackson et al. 1981). It is the most used indicator to diagnose crop water deficits based on leaf temperature.

The CWSI is usually determined by empirical methods based on relating the leaf-air temperature difference of leaf temperature (Tc) and air temperature (Ta) to the air vapour pressure deficit of a non-water-stressed baseline. The CWSI has been successfully applied to develop irrigation plans for different crops in different regions over the past 20–25 years.

In M7, T5 and T6 had slightly lower CWSI values than the other treatments, but this result was meaningless as these treatments did not have any water stress applied until March–April. There were no differences in CWSI value for rootstock or the interaction between irrigation treatments and rootstocks (Table 6.1).

In Washington navel and Lane Late navel, there were no differences in CWSI value for any applied deficit irrigation treatments, rootstock, or their interaction. There was no crop stress detected by the drone flight at an elevation of 100 metres (Table 6.1).

Table 6.1: Canopy temperature (°C) and crop water stress index (CWSI) data for the deficit irrigation trial at Dareton as recorded by drone flights in 2018.

	M7		Washington navel		Lane Late	
	Canopy temperature (°C)	Crop water stress index	Canopy temperature (°C)	Crop water stress index	Canopy temperature (°C)	Crop water stress index
Irrigation treatments (It)						
T1 (control)	29.6	0.49	0.48	29.3	0.47	29.3
T2	30.0	0.54	0.52	29.8	0.53	30.0
T3	29.9	0.51	0.52	30.0	0.49	29.5
T4	29.5	0.51	0.49	29.5	0.51	30.1
T5	30.3	0.46	0.47	29.6	0.45	29.4
T6	29.1	0.40	0.43	29.2	0.43	29.5
Probability	ns	*	ns	ns	ns	ns
LSD ($p < 0.05$)	–	0.08	–	–	–	–
Rootstock (Rt)						
Poncirus trifoliata	30.0	0.50	0.50	29.8	0.50	30.0
Troyer citrange	29.4	0.47	0.47	29.3	0.46	29.3
Probability	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–
Interaction (It × Rt)						
Probability	ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)	–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment. *$p < 0.05$ and ns (non-significant).

2019 growing season

In 2019 several drone flights were conducted to detect canopy temperatures and provide information about how the trees were responding to the deficit irrigation trial on 3 navel varieties and 2 rootstocks. Dr Mark Skewes from SARDI, Loxton conducted 9 flights between 27 February and 16 May. Every flight was conducted at mid-day to avoid variation between the flying time. Canopy temperature data were recorded for all flights and crop water stress index was assessed from 1 April onwards. It was believed that crop stress index will provide a better indicator of crop stress status.

Figure 6.2: Drone with thermal camera operated from 27 February to 16 May by SARDI, Loxton in 2019. Photo: Dr Tahir Khurshid.

Canopy temperature (°C)

In M7 navel, there were no differences measured between the treatments and the control during the 3 flights conducted on 27 February, 13 March and 21 March. On 1 April, T4 had a slightly higher canopy temperature, but this result has no commercial importance. On April 8 and 16, there were minor differences (< 1 °C) among the treatments, but the results were meaningless. There were also no canopy temperature differences detected from 29 April and onwards (Table 6.2).

In Washington navel, there were no differences between the treatments and the control during the 3 flights conducted on 27 February, 13 March, and 21 March. On 1 April, the canopy temperature was slightly higher in T3 compared to the control, but the result has no commercial importance because the difference was only 0.5 °C. On April 8, there were no differences detected in canopy temperatures. On 16 April, there were minor differences (< 1 °C) detected in the treatments compared to the control, but the results were meaningless. There were no differences found in canopy temperatures on 29 April (Table 6.2).

In Lane Late navel, there were no differences between the treatments and the control during the 3 flights conducted on 27 February, 13 March, and 21 March. On 1 April, 8 April and 6 May, there were minor differences on canopy temperatures compared to T1, however these differences were only from 0.5 °C to 1.3 °C and do not warrant any commercial importance nor recommendation to growers for its use. On 16 April, 29 April and 16 May, there were no differences detected in canopy temperatures (Table 6.2).

Table 6.2: Canopy temperature (°C) and crop water stress index (CWSI) data for deficit irrigation trial at Dareton as recorded by drone flights in 2019.

	Irrigation treatments	27-Feb		13-Mar		21-Mar		1-Apr		8-Apr		16-Apr		29-Apr		6-May		16-May	
		Temp	CWSI	Temp	CWSI	Temp	CWSI	Temp	CWSI	Temp	CWSI	Temp	CWSI	Temp	CWSI	Temp	CWSI	Temp	CWSI
M7	**T1**	37.4	-	24.8	-	33.5	-	23.9	0.19	26.2	0.16	31.8	0.56	18.9	0.17	16.8	0.11	14.8	0.11
	T2	37.5	-	25.8	-	33.5	-	24.1	0.24	28.0	0.31	32.9	0.66	20.0	0.28	17.5	0.12	15.3	0.16
	T3	37.1	-	25.3	-	33.9	-	24.1	0.25	26.9	0.22	32.1	0.59	19.2	0.21	16.8	0.12	14.9	0.12
	T4	37.8	-	25.8	-	34.2	-	24.4	0.30	27.2	0.24	32.6	0.63	19.5	0.23	17.0	0.11	15.1	0.14
	T5	37.5	-	25.3	-	33.5	-	24.0	0.21	26.8	0.21	32.6	0.63	19.0	0.19	17.4	0.16	15.1	0.15
	T6	37.4	-	25.2	-	33.6	-	23.9	0.19	26.9	0.21	32.8	0.65	18.9	0.18	17.1	0.16	15.2	0.15
Probability		ns		ns		ns		*	*	***	***	***	***	ns	ns	ns	**	ns	ns
LSD (*P* < 0.05)		-		-		-		0.3	0.08	0.64	0.05	0.48	0.04	-	-	-	0.034	-	-
Washington navel	**T1**	37.3	-	25.3	-	33.6	-	23.9	0.20	26.7	0.20	31.9	0.57	19.0	0.18	17.1	0.12	15.2	0.16
	T2	37.6	-	26.5	-	33.4	-	24.1	0.24	27.5	0.27	32.8	0.65	19.8	0.25	17.5	0.14	15.6	0.19
	T3	37.1	-	26.3	-	34.3	-	24.4	0.31	26.9	0.22	32.2	0.60	19.1	0.19	17.0	0.11	15.0	0.13
	T4	37.6	-	26.0	-	34.3	-	24.3	0.28	27.0	0.23	32.5	0.63	19.0	0.18	17.2	0.12	15.4	0.17
	T5	37.6	-	25.8	-	33.9	-	24.1	0.24	26.9	0.23	32.8	0.65	19.4	0.23	17.7	0.15	15.6	0.19
	T6	37.4	-	25.8	-	33.9	-	23.9	0.20	26.8	0.21	32.8	0.65	19.2	0.21	17.3	0.13	15.5	0.18
Probability		ns		ns		ns		*	*	ns	ns	**	***	ns	ns	ns	ns	ns	ns
LSD (*P* < 0.05)		-		-		-		0.3	0.08	-	-	0.49	0.04	-	-	-	-	-	-
Lane Late	**T1**	37.1	-	26.0	-	33.7	-	24.0	0.22	26.5	0.18	31.6	0.54	19.2	0.21	16.8	0.10	15.1	0.15
	T2	37.4	-	25.8	-	33.7	-	24.2	0.27	27.8	0.29	33.0	0.67	19.4	0.22	17.6	0.15	15.6	0.19
	T3	36.9	-	24.9	-	34.2	-	24.2	0.28	26.8	0.21	32.2	0.60	18.9	0.17	16.7	0.09	14.9	0.13
	T4	37.4	-	25.5	-	34.1	-	24.5	0.31	27.0	0.23	32.6	0.63	19.1	0.19	17.0	0.10	15.2	0.16
	T5	37.4	-	25.0	-	33.8	-	24.1	0.24	26.8	0.21	32.8	0.65	19.1	0.19	17.6	0.15	15.9	0.21
	T6	37.5	-	24.9	-	34.2	-	24.1	0.24	27.2	0.24	32.9	0.66	19.5	0.23	17.7	0.15	15.9	0.22
Probability		ns		ns		ns		*	ns	**	**	ns	ns	ns	ns	*	*	ns	ns
LSD (*P* < 0.05)		-		-		-		0.3	-	0.6	0.05	-	-	-	-	0.8	0.06	-	-

Mean separation within the columns was tested with LSD for irrigation treatment, *p < 0.05, ***p* < 0.01, ****p* < 0.001 and ns (non-significant).

Canopy water stress index (CWSI)

In M7 navel, there were no differences detected between the treatments and the control during 3 flights conducted on 27 February, 13 March and 21 March. On 1 April, the CSI was higher in T4 than the control, but the result has no commercial importance. On April 8 and 16 April, the crop index was higher for T2 compared to the control. There were no canopy differences detected from 29 April onwards (Table 6.2).

In Washington navel, there were no differences detected between the treatments and the control during 3 flights conducted on 27 February, 13 March, and 21 March. On 1 April, there were minor differences on crop stress index across the regulated deficit treatment T3 as compare to T1 (control), however this difference does not warrant any commercial importance which can be recommended to the growers for its use. On 16 April, T2 had a slightly higher CWSI compared to the control (Table 6.2). There were no differences in CSI in the treatments on 8 April, 29 April, 6 May and 16 May (Table 6.2). In Lane Late, there were no differences detected between the treatments and control on flights conducted on 27 February, 13 March, 21 March, 1 April, 16 April, 29 April and 16 May. On April 8, there were a detected in canopy temperatures in T2 compared to T1 (control). There was also a minor increase in T2 compared to the control on 6 May (Table 6.2).

Generally, there were no differences detected with the use of drone technology, therefore a recommendation cannot be made at this stage for its use. It was suspected that having the thermal camera at an elevation of 100 metres was recording the air temperature and not the canopy temperature. A regression analysis was carried out for the mean temperature of each flight over the irrigation trial with the maximum air temperature at the time the flight was conducted. The relation clearly demonstrated a significantly strong relationship (R^2 = 0.95) between the air temperature and the so-called canopy temperature recorded by the thermal camera Figure 6.2). This relation indicated that the drone was recording the air temperatures and not the canopy temperatures.

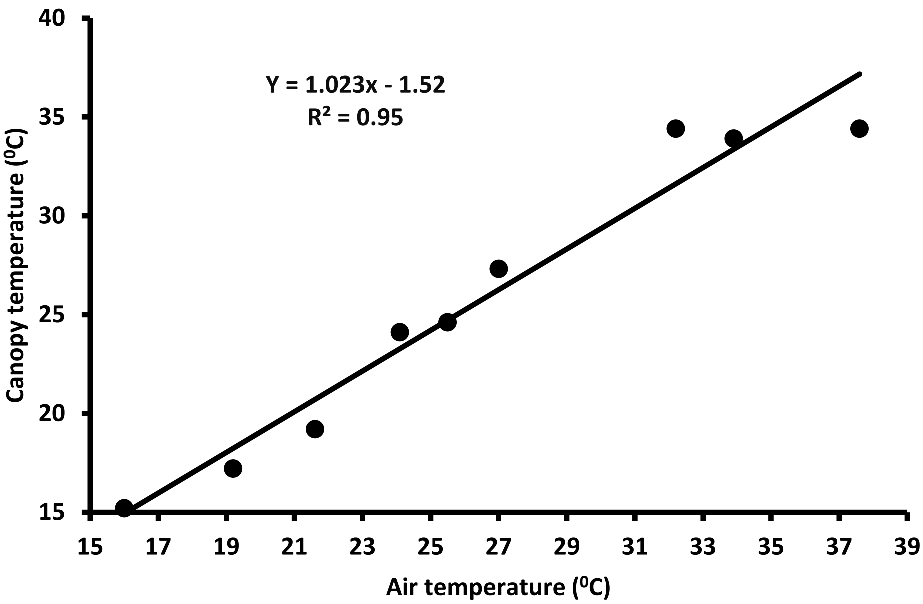

Figure 6.3: Relationship between air temperature and the canopy temperature for 9 drone flights between 27 February and 16 May 2019 in navel trial at Dareton. Each dot represents a single flight. Regression coefficient R^2 = 0.95 is significant at p < 0.001 (***).

2020 growing season

StevTech Pty Ltd conducted a drone flight over the trial area on 21 April 2020 to collect crop Normalised Digital Vegetation Index (NDVI) data. NDVI has been used in field crop such as culture beans (Guilherme-Fernando et al. 2016) and apples (David et al. 2017). In response to a suggestion from the reference committee, the drone was fitted with a multi-spectral camera (Figure 6.4). Therefor the NDVI data was collocated with a help of a drone flight.

Figure 6.4: Drone used with multi-spectral camera operated by StevTech in 2020. Photo: Dr Tahir Khurshid.

NDVI is basically an index to measure healthy green vegetation. It is calculated as the difference between near-infrared (NIR) and red (RED) reflectance divided by their sum:

$$NDVI = NIR - RED \div NIR + RED$$

However, there are reports that NDVI has been used in field crop such as culture beans Guilherme-Fernando et al., 2016). There is also a report that NDVI has been used in water deficit apple crop (David et al., 2017).

The data provide by SteveTech was further analysed to work out treatment differences across the irrigation trial. Data sets were subjected to analysis of variance with GenStat for windows 21st edition (VSNI, 2021) and treatment means separations were test with Least Significant Difference (LSD) a 5%.

In M7, T6 had the lowest NDVI values (Table 6.3). Fruit from *Troyer citrange* had higher NDVI values than fruit from *Poncirus trifoliata*. However, these differences have no commercial importance as the values are showing the trees have green leaves. Deficit regulated irrigation treatments do not change the chlorophyll content or leaf colour. Highly stressed trees have curly leaves, but the colour is still green. Therefore, using a multi-spectral camera at 100 m elevation is not recommended to evaluate water stress in citrus crops (Table 6.3).

Summary

Using a multi-spectral camera attached to a drone flown at 100 m elevation failed to assess water stress in citrus trees in the deficit irrigation trial conducted on 3 navel varieties.

Table 6.3: NDVI data for the deficit irrigation trial at the Dareton Primary Industries Institute was recorded by drone flights in the 2020 growing season.

Irrigation treatments (It)	**M7**	**Washington navel**	**Lane Late**
T1 (control)	0.844	0.847	0.853
T2	0.849	0.848	0.850
T3	0.850	0.843	0.850
T4	0.849	0.850	0.848
T5	0.842	0.847	0.845
T6	0.836	0.842	0.841
Probability	*	ns	ns
LSD ($p < 0.05$)	0.01	–	–
Rootstock (Rt)			
Poncirus trifoliata	0.841	0.840	0.842
Troyer citrange	0.850	0.853	0.854
Probability	*	***	**
LSD ($p < 0.05$)	0.006	0.005	0.006
Interaction (It × Rt)			
Probability	ns	ns	ns
LSD ($p < 0.05$)	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment, rootstocks and their interactions. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Chapter 7: Storage trials

Fruit was harvested from M7, Washington and Lane Late navel varieties in the 2021 growing season and stored to determine how well fruit from RDI treatments lasts in storage compared with fruit from trees that were fully irrigated. Fruit from 2 RDI treatments T1 (control) and T6 (stressed in February) was used in the storage trial.

Six-hundred fruit (100 fruit/tree) were harvested from 6 replicates for T1 or T6. Fruit was gently washed, dried and sorted to remove any with skin marks, blemishes or sunburn damage. Suitable fruit (n=250) were then stored in small bins at 4 °C in a cool room. Each week, 20 fruit were randomly selected and assessed for any storage disorders and fruit quality components including °Brix, BrimA, acid per cent, per cent juice were assessed and individual fruit weight was recorded.

In M7, °Brix values from fruit in T6 were higher at day 0 (harvest), 7, 14 and 28 (Table 7.1). At Day 35, there was no different in °Brix between T6 and T1 (Table 7.1). This suggests that fruit from the regulated deficit irrigation trial could be stored up to 35 days without change in total soluble solids values. BrimA values were higher in fruit from T6 than T1 from harvest to day 14 in storage, after which there were no differences (Table 7.1). The acid per cent did not differ between the groups during storage, which could explain the absence of differences in BrimA values beyond day 14 in storage. There was no difference in juice per cent for T1 or T6 at harvest or during storage up to 35 days. While there appeared to be differences in fruit weight, these were not significant.

There were no storage disorders detected. Therefore, sweeter fruit can be stored up to 35 days without any storage disorders or changes to internal quality.

In Washington navel, °Brix values were higher in T6 than T1 on day 0, 7, 14 and 28 in storage (Table 7.2). This suggests that fruit from the regulated deficit irrigation trial could be stored up to 28 days without change in total soluble solids values. BrimA values were higher in fruit from T6 than T1 from day 0 to day 14, after which there were no differences (Table 7.2). There were no differences between the groups for acid per cent, juice per cent or fruit weight (Table 7.2). These are promising results showing that sweeter fruit can last in storage.

There were no storage disorders detected, indicating that sweeter fruit can be stored up to 35 days without changes in internal quality.

In Lane Late, °Brix values were higher in T6 than T1 from day 0 to day 21 (Table 7.3), indicating that fruit from the regulated deficit irrigation treated trees can be stored up to 21 days without change in total soluble solids values. BrimA values were higher in T6 than T1 at harvest (day 0) and day 21, but not different at day 14 (Table 7.3). Acid values were not different between T6 and T1 at harvest but were higher in T6 on days 14 and 21. There was a gradual (but not significant) decrease in acid level during storage for fruit harvested from the control trees. These results suggest sweeter fruit can store well if they have high acid levels. There was no difference in juice per cent. While fruit from the control trees was heavier at harvest, this difference did not continue during storage (Table 7.3).

Although there were no storage disorders detected, some fruit discolouration and pitting were found in both T1 and T6. The current data suggest that sweet fruit can be stored up to 35 days however, extended storage trials are recommended in collaboration with Mildura fruit company (MFC).

Table 7.1: The effect of storage duration on fruit quality for M7 navels in 2021.

	Irrigation treatments	Day 0	Day 7	Day 14	Day 21	Day 28	Day 35
°Brix	T1 (control)	12.9	13.0	13.2	13.3	13.1	13.4
	T6	14.6	14.7	14.8	14.8	14.9	14.9
Probability		*	*	*	ns	*	ns
LSD (p < 0.05)		1.38	2.13	1.10	–	1.91	–
BrimA	T1 (control)	130	135	138	146	134	135
	T6	153	157	160	163	159	157
Probability		*	*	**	ns	ns	ns
LSD (p < 0.05)		16.1	23.9	11.2	–	–	–
Acid (%)	T1 (control)	1.2	1.2	1.2	1.1	1.3	1.3
	T6	1.3	1.3	1.3	1.2	1.3	1.3
Probability		ns	ns	ns	ns	ns	ns
LSD (p < 0.05)		–	–	–	–	–	–
Juice (%)	T1 (control)	49	47	47	46	49	45
	T6	46	45	45	42	48	44
Probability		ns	ns	ns	ns	ns	ns
LSD (p < 0.05)		–	–	–	–	–	–
Fruit weight (g)	T1 (control)	224	220	229	242	228	212
	T6	190	184	198	203	200	187
Probability		ns	ns	ns	ns	ns	ns
LSD (p < 0.05)		–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment. *p < 0.05, **p < 0.01, ***p < 0.001 and ns (non-significant).

Table 7.2: The effect of storage duration on fruit quality for Washington navels in 2021.

	Irrigation treatments	Day 0	Day 7	Day 14	Day 21	Day 28	Day 35
°Brix	T1 (control)	11.4	12.0	11.9	11.7	12.3	12.3
	T6	13.1	13.3	14.0	13.6	14.4	13.6
Probability		*	*	*	ns	*	ns
LSD ($p < 0.05$)		1.38	2.13	1.10	–	1.91	–
BrimA	T1 (control)	118	121	128	124	135	141
	T6	129	133	146	141	160	149
Probability		*	*	**	ns	ns	ns
LSD ($p < 0.05$)		16.1	23.9	11.2	–	–	–
Acid (%)	T1 (control)	1.1	1.2	1.0	1.0	1.0	0.9
	T6	1.3	1.3	1.3	1.3	1.2	1.2
Probability		ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)		–	–	–	–	–	–
Juice (%)	T1 (control)	51	53	51	49	50	50
	T6	51	51	48	50	51	49
Probability		ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)		–	–	–	–	–	–
Fruit weight (g)	T1 (control)	258	256	241	244	253	255
	T6	223	243	213	228	229	214
Probability		ns	ns	ns	ns	ns	ns
LSD ($p < 0.05$)		–	–	–	–	–	–

Mean separation within the columns was tested with LSD for irrigation treatment. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Table 7.3: The effect of storage duration on fruit quality for Lane Late navels in 2021.

	Irrigation treatments	Day 0	Day 14	Day 21
°Brix	T1 (control)	12.3	12.6	12.5
	T6	14.6	14.2	14.7
Probability		***	**	***
LSD ($p < 0.05$)		0.7	0.8	0.8
BrimA	T1 (control)	133	143	142
	T6	157	150	162
Probability		**	ns	**
LSD ($p < 0.05$)		17.9	–	7.8
Acid (%)	T1 (control)	1.06	0.99	0.98
	T6	1.26	1.28	1.22
Probability		ns	**	*
LSD ($p < 0.05$)		–	0.12	0.24
Juice (%)	T1 (control)	54	55	53
	T6	52	54	53
Probability		ns	ns	ns
LSD ($p < 0.05$)		–	–	–
Fruit weight (g)	T1 (control)	212	248	248
	T6	187	221	228
Probability		*	ns	ns
LSD ($p < 0.05$)		24.5	–	–

Mean separation within the columns was tested with LSD for irrigation treatment. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Chapter 8: Regulated deficit irrigation demonstration trials for 'Afourer' mandarins

Regulated deficit irrigation trial on 'Afourer' mandarin in the Riverina

A demonstration trial was established at Southern Cross Farms, a grower's property in Leeton, NSW (Figure 8.1). Four rows (12 trees/row) were selected, and 2 regulated deficit irrigation (RDI) treatments were applied. The control (2 rows) received 100% irrigation water as per Ec and the water stress was applied to the remaining 2 rows. In RDI treatment soil profile was dried for 2 weeks and no irrigation was applied. After the end of drying period, 50% of full irrigation applied for 8 weeks (15 April to 15 June) followed by 100% irrigation every second day. Data on fruit size was collected from represented trees at harvest for 4 growing seasons from 2018 to 2021. Fruit quality components were recorded for each treatment at harvest for each growing season.

Statistical analysis

Experimental data for fruit quality components were subjected to analysis of variance with GenStat for Windows 21st edition (VSNI, 2021) and treatment mean separations were tested with the least significant difference (LSD) at 5%. Some data were subjected to paired T-tests to compare treatments for fruit size, distribution, and yield.

Figure 8.1: The trial site for the regulated deficit irrigation (RDI), Leeton Riverina, and some fruit in the trial. Photo: Dr Tahir Khurshid.

Table 8.1: Rainfall (mm) at Leeton (Riverina) for the 4 growing seasons.

	2018	2019	2020	2021	2022
Jan	19	9	12	73	168
Feb	2	16	78	14	2
Mar	2	31	49	71	54
Apr	0	44	111	0	70
May	21	65	12	18	–
Jun	33	34	17	76	–
Jul	9	20	25	27	–
Aug	6	11	40	14	–

In 2018, the °Brix value was increased with RDI compared to the control (Table 8.2). BrimA value followed the same trend as °Brix values. There was slight increase in acid levels with RDI treatment, but the effect was not significant. RDI treatment significantly decreased the fruit size at harvest by 1.6 mm (Table 8.2). The 2018 growing season was a dry season and no significant rainfall was experienced during the stress duration (Table 8.1).

In 2019, there were no significant differences between the °Brix value for RDI treatment compared to the control. However, there was an increase in BrimA value was found with RDI treatment compared to the control, but the results were not significant. Acid values were slightly higher with the control although non-significant. The fruit size was not different at harvest for Control or RDI treatments (Table 8.2). The rainfall data in Table 8.1 clearly suggested that there was significant rainfall experienced throughout the growing season and trees did not experience the required stress levels. Therefore, the results were not conclusive.

Table 8.2. Fruit quality components for 4 growing seasons from the trial at Leeton, Riverina.

	Brix (%)	BrimA	Acid (%)	Fruit size (mm)
2018				
Control	14.6	160	1.23	63.9
RDI	15.8	168	1.40	61.6
Probability	**	*	ns	*
LSD ($p < 0.05$)	0.65	7	-	1.6
2019				
Control	15.9	135	1.9	50.8
RDI	15.8	147	1.7	51.2
Probability	ns	ns	ns	ns
LSD ($p < 0.05$)	-	-	-	-
2020				
Control	15.2	141	1.67	58.0
RDI	15.3	141	1.70	60.0
Probability	ns	ns	ns	*
LSD ($p < 0.05$)	-	-	-	1.2
2021				
Control	15.4	130	1.89	55.7
RDI	15.7	141	1.78	55.9
Probability	ns	*	ns	ns
LSD ($p < 0.05$)	-	14	-	-

Mean separation within the columns was tested with LSD for RDI. *$p < 0.05$, and ns (non-significant).

In 2020, there were absolutely no differences in °Brix values for RDI treatment compared to the control. BrimA value followed the same trend as °Brix values. There was also no difference in acid levels across both treatments. Fruit size at harvest was 2 mm higher for the RDI treatment compared to the control rather an unusual result (Table 8.2). The rainfall data in Table 8.1 clearly suggested that there was significant rainfall experienced throughout the growing season. In April there was a total rainfall of 111 mm. Therefore, trees did not experience the required stress levels at all, and these the results were not conclusive.

In 2021, there were no differences in °Brix values for RDI treatment compared to the control. BrimA values were significantly increased with RDI treatment compared to the control. There was also no difference in acid levels across both treatments. Fruit size at harvest was similar for the RDI treatment compared to the control (Table 8.1). The rainfall data in Table 8.1 suggested that there was significant rainfall experienced in May and June periods. A significant rainfall in March could also have prevented the trees from going into stress. In April there was a total rainfall of 111 mm. Therefore, trees did not experience the required stress levels at all, and these the results were not conclusive. It is important to notice in in 3 rainy seasons the acid levels were quite higher in general compared to 2018.

Fruit size distribution at harvest

Trees were harvested and fruit were graded for size and yield. Fruit was classed as small, medium, or large based on fruit diameter (mm) and fruit/carton for the 2018 and 2019 growing seasons (Table 8.3).

In 2018, 19 cartons were harvested from the control trees compared to 13 cartons from the RDI trees. While this was a reduction of 6 cartons, the difference was not significant. Total fruit yield was also higher for the control trees (182.7 kg) compared to RDI trees (128.7 kg). While this result was not statistically significant, it has a commercial significance because RDI reduced the yield by 54 kg (10.2 kg/tree; Table 8.3).

In 2019, 39 cartons were harvested from the control trees compared to 43 cartons from the RDI trees; however, this was not a statistically significant difference (Table 8.3). Total fruit yield was higher from the RDI trees (354.2 kg) compared to RDI trees (320.9 kg), but this was not significant. However, these results were not conclusive because the trees were not stressed as planned due to the amount of rain that fell during the trial (Table 8.3).

Table 8.3: Fruit size distribution and total yield at harvest for the 2018 and 2018 growing seasons.

	Fruit size (mm)	Fruit no./carton	No. of cartons	Yield (kg)
2018				
Control				
Small	40–60	113–180	8	75.1
Medium	60–70	88–88	9	83.4
Large	70–84	40–72	3	24.2
Total			**19**	**182.7**
RDI				
Small	40–60	113–180	5	48.5
Medium	60–70	88–88	7	70.1
Large	70–84	40–72	1	9.8
Total			**13**	**128.3**
Probability (t-value)			ns (0.82)	ns (0.71)
2019				
Control				
Small	40–60	113–180	37	300.3
Medium	60–70	88–88	2	19.1
Large	70–84	40–72	0.3	1.5
Total			**39**	**320.9**
RDI				
Small	40–60	113–180	40	332.3
Medium	60–70	88–88	2	20.1
Large	70–84	40–72	0.3	1.8
Total			**43**	**354.2**
Probability (t-value)			ns (-0.07)	ns (-0.08)

Regulated deficit irrigation trial on 'Afourer' mandarin in Sunraysia

A demonstration trial was established at Southern Cross Farms, a grower's property in Ellerslie, NSW. Four rows (12 trees/row) were selected, and 2 regulated deficit irrigation (RDI) treatments were applied. The control (2 rows) received 100% irrigation water as per Ec and the water stress was applied to the remaining 2 rows. In RDI treatment soil profile was dried for 2 weeks and no irrigation was applied. After the end of drying period, 50% of full irrigation applied for 8 weeks (15 April to 15 June) followed by 100% irrigation every second day. Data on fruit size was collected from represented trees at harvest for 4 growing seasons from 2018 to 2021. Fruit quality components were recorded for each treatment at harvest for each growing season.

Figure 8.2: The trial site for the regulated deficit irrigation (RDI) trial at Ellerslie, NSW and some fruit in the trial. (Photo: Dr Tahir Khurshid.

In 2018, the °Brix values were increased with RDI compared to the control. There was an increase of 1.2 °Brix with RDI treatment. BrimA values were not affected and were the same for both control and RDI treatment. There was an increase in acid levels with RDI treatment by 0.3 and this effect was statistically significant. RDI treatment significantly decreased the fruit size at harvest by 2.3 mm (Table 8.4). The 2018 growing season was a dry season and no significant rainfall was experienced during the stress duration (Table 8.5).

In 2019, there were no significant differences between the °Brix values for RDI treatment compared to the control. However, there was an increase of 1 °Brix, which could be important for the mandarins. The BrimA values were slightly increased with RDI treatments compared to the control, but the results were not significant. Acid values were non-significant for RDI treatments. One of the reasons for the results is the rainfall (26 mm) experienced during the month (Table 8.5). This could have contributed to the low sugar and acid levels in RDI treated fruits. Fruit size at harvest was similar for the RDI treatment compared to the control (Table 8.4).

In 2020, there were absolutely no differences in °Brix values for RDI treatment compared to the control. BrimA value followed the same trend as °Brix values. There was also no difference in acid levels across both treatments. Fruit size at harvest was similar for the RDI treatment compared to the control (Table 8.4). The rainfall data in Table 8.5 clearly suggested that there was significant rainfall experienced throughout the growing season. In March there was 26 mm rainfall and in April 72 mm (Table 8.5). Therefore, trees did not experience the required stress levels at all, and these results were not conclusive.

In 2021, there were significant differences in °Brix values for RDI treatment compared to the control. The values were increased by 0.9 degrees with RDI treatment. BrimA values were significantly increased with RDI treatment compared to the control. There was an increase of 26 units with RDI treatment. There was a significant effect of acid levels. RDI treatment increased the acid levels compared to the control. Fruit size at harvest was similar for the RDI treatment as compared to the control (Table 8.4). The rainfall data in Table 8.5 suggested that there was no significant rainfall experienced during stress periods. Therefore, there were differences observed for sugar and acid levels for both treatments. Trees were able to achieve the required stress levels in this season. Therefore, these results are more likely to be a true reflection of RDI than in the wet seasons.

Table 8.4: Fruit quality components for 4 growing seasons from the trial at Ellerslie, NSW.

	Brix (%)	BrimA	Acid (%)	Fruit size (mm)
2018				
Control	12.7	132	1.2	63.6
RDI	13.9	134	1.4	61.6
Probability	***	ns	***	**
LSD ($p < 0.05$)	0.31	–	0.05	1.6
2019				
Control	12.7	134	1.1	68.8
RDI	13.7	140	1.3	68.3
Probability	ns	ns	ns	ns
LSD ($p < 0.05$)				
2020				
Control	12.9	123	1.4	69.1
RDI	12.6	120	1.3	69.7
Probability	ns	ns	ns	ns
LSD ($p < 0.05$)				
2021				
Control	12.7	114	1.3	72.1
RDI	13.6	139	1.5	70.3
Probability	**	*	**	ns
LSD ($p < 0.05$)	0.61	23	0.09	–

Mean separation within the columns was tested with LSD for RDI treatment. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ and ns (non-significant).

Table 8.5: Rainfall (mm) at Mildura for 4 growing seasons.

	2018	2019	2020	2021	2022
Jan	7	2	6	16	12
Feb	0	3	21	0	0
Mar	0	4	26	6	13
Apr	0	0	72	0	78
May	14	26	1	7	–
Jun	22	10	9	28	–
Jul	0	10	3	29	–
Aug	18	4	41	8	–

Chapter 9: Present and historical rainfall data analysis for 61 years

Rainfall during the experimental trial

The rainfall data for 6 years are given in Table 9.1. During the project duration the rainfall varied every year. Year 2017 and 2020 were the wettest years with an annual rainfall of 270 mm and 254 mm respectively. However, the most significant months for this project are February to April, as this is when the moisture stress was applied to the citrus trees to enhance sugar levels. The desired stress was achieved in 2018, 2019 and 2021, but in 2020, 88 mm of rain fell from February through April, which interfered with the stress induced treatments. However, any rainfall from November to January is beneficial to the trees for fruit size enhancement. For example, the rain during November–December 2017 would have contributed to a fruit size increase for 2018, while the November–December 2018 rainfall would have contributed to the fruit size increase for 2019. There was only 17 mm rainfall recorded for November–December 2019, and that would have affected the fruit size for 2020. In 2020, 45 mm of rain occurred in January and it would have been beneficial for the fruit size increase for 2021 growing season.

The experimental treatments designed for 2020 are being repeated for 2021 with the hope that no unexpected rainfall will occur during March and April. So far, the season progressed successfully.

Table 9.1: Rainfall (mm) data for the last 6 years at NSW DPI Dareton*

	2017	2018	2019	2020	2021	2022
January	31	7	2	6	16	12
February	6	0	3	**21**	0	0
March	3	0	4	**26**	6	**13**
April	**46**	0	0	**72**	0	**78**
May	17	14	26	1	7	1
June	4	22	10	9	28	0
July	9	0	10	3	29	-
August	34	18	4	41	8	-
September	4	2	5	27	17	-
October	41	13	0	53	20	-
November	53	33	6	8	48	-
December	71	42	1	10	1	
Total rainfall (mm)	319	151	71	277	180	104

*Bureau of Meteorology (BOM) data - https://www.longpaddock.qld.gov.au/silo/point-data/

Historical rainfall data analysis (61 years):

The historical data for the last 61 years are summarised in Table 9.2. The data were divided into decades to reveal any rainfall patterns. I focused on March and April, as this is when most of the RDI treatments were applied. The number of times > 15 mm of rain fell were counted, and percentages were calculated for each decade and for the entire 61 years. Rainfall is effective when it exceeds 15 mm. Although, the trials were conducted from 2018–2021, it is worth looking at the rainfall patterns from the previous years. The weather data, including temperature and rainfall, vary every year. The growing seasons in 1960–1971 and 2001–2011 were the wettest in March–April and the rainfall percentage was 40–60% for March–April. On the other hand, the 1991–2000 season was dry, with 10–20% of rainfall exceeding 15 mm. For the last 61 years, the percentage of rainfall was 41-43% for March–April. Therefore, it is safer to apply deficit irrigation treatments in those months. During the current experimental program, rainfall exceeded 15 mm (effective rainfall) in March–April only for the 2020 growing season, however, seasons for 2018, 2019, and 2012 were dry in March–April.

Table 9.2: The percentage occurrence of rainfall (mm) at Dareton for 6 decades (61 years). The percentages are calculated from the number of times > 15 mm of rain fell.

	1960 – 1971	**1971 – 1981**	**1981 – 1991**	**1991 – 2001**	**2001 – 2011**	**2011 – 2021**	**61 Years records**
Jan	45	60	40	60	40	40	48
Feb	27	60	0	60	30	20	33
Mar	**55**	**40**	**50**	**10**	**60**	**30**	**41**
Apr	**64**	**50**	**40**	**20**	**40**	**40**	**43**
May	55	70	60	50	40	60	56
Jun	55	60	50	50	40	40	49
Jul	**82**	**60**	**80**	**70**	**70**	**30**	66
Aug	**82**	**80**	**80**	**60**	**60**	**60**	70
Sep	**73**	**70**	**70**	**90**	**40**	**40**	64
Oct	36	70	50	60	40	40	49
Nov	55	70	60	50	80	40	59
Dec	64	40	60	30	60	40	49

The historical data also revealed that July, August and September are the wettest and the chances of occurrence was approximately 64-70%. These months are not relevant to the RDI work, as the trees should not be stressed then. Rain from November through to February is important to enhance fruit size in citrus. Fruit growth is actively underway from December after the completion of cell division. Fruit is actively growing through February, and no water stress should be imposed during those months for any reason.

The overall rainfall data suggests rain is less likely in March and April and RDI can be carried out successfully. If any significant rainfall did occur during March–April, it is less likely that the desired stress levels will be achieved, but fruit size will not be compromised. At this stage fruit is sold based on fruit size not on °Brix levels. Therefore, every measure must be taken not to compromise fruit size until certain levels.

Chapter 10: General Discussion

Sweet orange is economically one of the most important crops in Australia, with a major part of production destined for fresh consumption. Sweet oranges are sold on domestic markets and exported to 22 countries around the world, of which 15 countries are in in Asia. Asian consumers prefer to buy sweeter fruit with high °Brix values. In Japan it is a common practice for the fruit to be sold based on sugar levels (Steven Falivene NSW Industry Development Officer - *Personnel communications*), which gives higher monetary return to the growers. Therefore, Asian consumers like sweeter fruit and they are prepared to pay for best fruit quality based on sweetness and desirable flavour.

However, in Australia, fruit is not sold on quality (sugar levels), but on size. Large fruit return higher profits to the growers. Small fruit has no export value and gives poor returns to growers. This project was initiated to enhance fruit quality with regulated deficit irrigation (RDI).

The experimental program for the RDI treatments was conducted over 4 years from 2018 to 2021. This program involved 5 rootstocks (*Poncirus trifoliata*, *Troyer citrange*, *Citrus macrophylla*, *Citrus volkameriana* and *Swingle citrumelo*. Data were collected for each rootstock, but the focus of this study was *Poncirus trifoliata* and *Troyer citrange*. Therefore, the results from these 2 extensively used rootstocks are presented in this final report. These two rootstocks are used in the major citrus growing regions of Australia. *Troyer citrange* is used in light or deep sandy loam soils of Sunraysia, while *Poncirus trifoliata* is used in heavy or clay soils of the Riverina. All other parts of Australia use these two rootstocks accordingly as per their soil conditions. The RDI program was applied to 3 navel varieties. These varieties are harvested from May to August due to the different maturity dates. M7 navel is an early-maturing variety and usually harvested in May, Washington navel is mid-maturing variety and harvested in June, and the late-maturing Lane Late navels are harvested in July–August. The different maturity times of these 3 varieties provided a better understanding about their responses to RDI and its interaction with rootstocks.

Six RDI treatments were used every year, however, these irrigation treatments were modified every year after the presentation of the project results to the project reference group (PRG) committee. The objective was to test a range of treatments better suited to enhance sugar levels and with minimum effect on fruit size. Therefore, the treatments were proposed and consulted with the PRG committee before being applied to the experimental trees every year.

Irrigation treatments were applied in February, March and April during the program (details are given in Chapters 1 to 4 for each year). There was a control where 100% irrigation was applied. In most RDI treatments, the soil profile was dried for 2 weeks to impose stress and this was monitored by tensiometers and pre-dawn stem water potential readings throughout the growing season. The trees were regarded to have achieved the desired stress levels when stem water potential values were between 8-10 bar. The stem water potential measurements with a pressure chamber are the most commonly employed methods to determine the plant water status in citrus trees (Goldhamer et al., 2012). At the same time, the tensiometer reading for 30 cm depth was above -60 kPa, which indicates negative soil tension. After 2 weeks of drying, 50% irrigation was applied for 8 weeks followed by 100% irrigation until harvest. For some treatments the soil profile was not dried, however, 50% irrigation was applied for 8 weeks followed by 100% irrigation until harvest. Every year had different treatments and timing. How these treatments affected the fruit quality, yield and fruit size is discussed below.

Fruit quality, yield and fruit size distribution (2018–2021) for navel oranges

M7 navel

M7 navel is an early maturing variety and is ready for harvest in early May to mid-May in the Sunraysia district. In 2018, fruit were harvested on 16 May. The sugar levels were increased by 1 °Brix in fruit that had RDI applied in February 2018. Although the April applied RDI (T6) did not increase °Brix levels generally, it did increase °Brix by 1.6 in fruit from *Poncirus trifoliata* rootstock.

In 2019, RDI treatments were not applied in February. The RDI treatments applied in March or April applied treatments had no effect in increasing °Brix values.

One of the reasons for the this could be the absence of a February treatment in 2019. Generally, the warm conditions in February are suitable for imposing moisture stress and sugar levels do increase in those conditions. The second reason could be the late harvest (3 June) of M7 in 2019. If you harvest M7 late, then the differences in sugar levels become minimal. The growing season generally remained dry, which is well suited to RDI, however, 26 mm of rain was received on 2 May, which meant that T2 and T6 could not complete their 50% RDI duration. In the 2020 growing season, fruit were harvested on 5 May. The °Brix value was increased in T6 (February applied treatment), although other treatments were affected due to significant rainfall in March (26 mm) and April (72 mm) during the RDI period. There were no °Brix differences for the RDI treatments at harvest apart from the February applied treatment (T6); evidently T6 carried the sugar levels to harvest. This could be because it was stressed twice due to stopping and starting irrigation in March and April, as shown by the enviro probe measurements (Figure 3.2). In 2021, T6 (February applied treatment) increased sugar levels by 1.2 °Brix. On this instance, the T3 applied in February and T2 in March without the 2 weeks drying of profile increased sugar levels by 0.6 and 0.3 °Brix respectively. This shows the significance of drying the soil profile before applying 50% irrigation. T7, which was applied in April, increased °Brix by 0.5 in M7 navels. This treatment only received 50% irrigation for less than 4 weeks, as fruit were harvested on 10 May. The result confirms that at least 8 weeks of 50% irrigation is needed to enhance at least 1 °Brix in M7 navels. Generally, there were no differences in °Brix value for the 2 rootstocks, apart from in 2021, and most of the interaction effects were not significant. However, in both 2018 and 2021, Poncirus trifoliata rootstock had 1 °Brix increase with April applied treatments. This shows that the late application of RDI can increase °Brix in Poncirus trifoliata rootstock, but not in Troyer citrange. To increase sugar levels in Troyer citrange rootstock, probably 3 weeks of soil profile drying is needed with the stem water potential values of 9-10 bar before any sugar increase is expected.

Fruit yield varies year to year. Generally, fruit yield is the product of fruit number and fruit weight per tree. The average fruit size was 152, 160, 213 and 174 g for 2018, 2019, 2020 and 2021, respectively. The fruit size was large in 2020, as the treatments did not achieve the desired stress levels due to rainfall in March–April. The emphasis was given to the fruit size distribution data that showed how the RDI treatments affected the final fruit size at harvest for size class 81–87 mm. This size class returns $400/tonne (second grade) to citrus growers. Although, in 2018 this size class was not statistically significant, however, the treatments which increased °Brix levels had reduced percentage of fruit in size class 81–87 mm.

In 2019, T2 was the worst treatment for reducing fruit size. In this treatment, the soil profile was dried and then fully irrigated once desired stress levels were reached and this dry and wet pattern continued until harvest. Clearly fruit growth of navel oranges is sensitive to this wet and dry pattern. Once fruit growth stopped due to water stress, it took at least 2 weeks before growth started after full irrigation was applied. In T2, fruit received 8 occasions of dry and wet patterns and they never attained their full growth. Therefore, T2 will not be recommended for further use as an RDI treatment. The other treatment, T4, which was applied in early March, also reduced fruit size. The April treatments did not reduce the fruit size, however, at the same time it did not increase the sugar levels either.

The growing season of 2020 was affected by rainfall, so the fruit was not reduced by any treatments apart for T6, which was applied in February. This produced high sugar levels but at a cost of 12% reduction in large fruit size. In growing season 2021, the reduction of fruit size was 12% when no soil profile was dried in February–March (T2 and T3). The reduction was 18% when the soil profile was dried in early March (T4) and the reduction was 22% when the soil profile was dried in February (T6). There was a 14% reduction with the April treatment (T7) with an increase of 1 °Brix for *Poncirus trifoliata* rootstock. This finding confirms the data for 2018 for the same treatment.

Washington navel

Washington navel is a mid-maturing variety and is ready for harvest in early June in the Sunraysia district. In 2018, fruit were harvested on 6 June. The sugar levels increased by 1.6-1.8 °Brix with T2 and T3 (February applied irrigation treatments) and by 1 with T4 (March applied treatment) in 2018. Although T6 (April applied treatment) increased °Brix levels by 0.7, this increase was 1.1 on *Poncirus trifoliata* rootstock.

Although, there were no treatments applied in February 2019, °Brix values were increased by T2 and T5 (March and April applied treatments). 2019 was a dry year, which was well suited to RDI experiments. Even though 26 mm of rain fell on 2 May, it did not affect the RDI treatments because Washington navel was harvested on 2 July and the RDI duration for all treatments was completed without any rainfall interruptions.

In 2020, fruit were harvested on 17 June. The °Brix value was increased by 1 with T6 (February applied treatment) and the increase was 1.1 on *Poncirus trifoliata* rootstock. All other treatments were affected due to significant rainfall during the RDI period and no °Brix differences were found. The February applied treatment (T6) still carried its sugar levels to harvest.

In 2021, T6 increased sugar levels by 1.4 °Brix. In this instance, T3 was applied in February without 2 weeks drying of the soil profile, and °Brix increased by 0.6. T2 and T7 did not influence °Brix, but the latter only received 50% irrigation for less than 4 weeks, as fruit were harvested on 15 June. This result confirms that at least 8 weeks of 50% irrigation is needed to achieve 1 °Brix in general. Generally, there were no differences for °Brix found for 2 rootstocks. In all RDI treatments per cent acid levels were slightly higher than the control.

Fruit yield varies year to year. Generally, fruit yield is the product of fruit number and fruit weight per tree (Lombard et al., 1985) The average fruit size was 114, 186, 211 and 221 g for 2018, 2019, 2020 and 2021, respectively. Fruit size was large in 2021. The emphasis was given to the fruit size distribution data that show how the RDI treatments affected the final fruit size at harvest for size class 81–87 mm. This size class returns $400/tonne (Second grade) to the citrus growers.

In 2018, the amount of fruit in the 81–87 mm class was significantly reduced by 20–23% with T2 and T3 (February applied treatments), 15% with T4 and T6 (RDI in March) and 10% with T6 (RDI in April). T6 also had an increase of 0.7 °Brix, suggesting that the reduced size came with increased sugar levels.

In the 2019 growing season, T2 (the wet and dry treatment applied in early March) reduced the amount of fruit in the 81–87 mm class by 19%, while T3 (also applied in early March) reduce the fruit size by 21%. T4, applied in mid-March, reduced the fruit size by 13%. T4 had only 4% reduction in *Poncirus trifoliata* rootstock and an increase of 1 °Brix, suggesting that RDI in mid-March will be desirable for this rootstock. Applying RDI early has a profound effect on reducing large fruit size. While the April applied treatments (T5 and T6) reduced fruit size by only 5%, this would be more acceptable to citrus growers. T5 and T6 were able to achieve up to 0.8 °Brix without compromising the fruit size.

The 2020 growing season was affected by rainfall, so fruit size was not reduced by any treatments apart from T6. T6 was applied in February and produced 1 °Brix, but this was coupled with a 12% reduction in large fruit size. In the 2021 growing season, the reduction in fruit size was 20% with T3 (no soil profile drying was carried out in February). When the soil profile was dried in February (T6), the reduction was 22% with an increase of 1.5 °Brix. T4, the early March treatment, also reduced the fruit size by 22%. In T5 where 100% water was applied straight after 2 weeks of drying, fruit size was reduced by 10%. The April applied treatment (T7) reduced the fruit size by 5%, but no gain in sugar. Most of the fruit size reduction was observed in *Troyer citrange* rootstock with 33% for T6.

Lane Late

Lane Late is a late-maturing variety and is ready for harvest in early late July to early August in the Sunraysia district. In 2018, fruit were harvested on 31 July. The sugar levels were increased by 1.8-2.1 °Brix with T2 and T3 (February applied irrigation treatments) and by 1.8 and 2.0 with T4 and T5 (March applied treatment) in 2018. T6 (April applied treatment) increased °Brix levels by 0.8. It was interesting to notice that the sugar increase was 2.2 °Brix in *Troyer citrange* rootstock for all RDI treatments apart from T6, which increased °Brix by 1.0.

In 2019 fruit were harvested on 5 August. T2 and T3 (RDI in March) increased °Brix by 1.3 and 1.7 respectively. T3 was more effective because the profile was dried in early March. 26 mm of rain fell on 2 May, but it did not affect the treatments because Lane Late navels were harvested on 5 August, and the RDI duration for all treatments was completed without any rainfall interruptions.

In 2020, the °Brix value was increased by 1.3 in T6 (February applied treatment), and the increase in °Brix was 1.5 for *Poncirus trifoliata* rootstock. All other treatments were affected due to a heavy rainfall during the RDI period, and there were no °Brix differences found. It appeared that the February applied treatment (T6) still carried its sugar levels to harvest, which is excellent for a late maturing variety. However, the stopping and starting of irrigation could have also contributed to T6, which was stressed 3 times (Figure 3.2).

In 2021, T6 (February applied treatment) increased sugar levels by 1.6 °Brix. T3 was applied in February without 2 weeks drying of the soil profile and increased °Brix by 1.6. T2 did not influence °Brix levels. T4 (applied in early March) increased °Brix by 2.1 and this was due to drying the profile for 2 weeks followed by 50% reduction in irrigation for 8 weeks.

T7 generally increased °Brix by 0.9. This treatment only received 50% irrigation for 4 weeks and fruit were harvested on 29 July. The result confirms that at least 8 weeks of 50% irrigation is needed to achieve 1 °Brix in general. There was 1 °Brix increase for *Troyer citrange*. In all RDI treatments, per cent acid levels were slightly higher than the control.

Fruit yield varies year to year. Generally, fruit yield is the product of fruit number and fruit weight per tree. The average fruit size was 175, 194, 226 and 234 g for 2018, 2019, 2020 and 2021, respectively. The fruit size was large in 2021 and this was also observed for Washington navel oranges. This year was well suited to the Lane Late oranges in terms of fruit size. Apart from 2020, the fruit yield was higher in *Poncirus trifoliata* rootstock compared to *Troyer citrange* in the other 3 years. Emphasis was given to the fruit size distribution data rather than how the RDI treatments affected the final fruit size at harvest for size class 81–87 mm.

In 2018, the amount of fruit in the 81–87 mm size class was reduced by 21% with T2 and T3 (RDI in February), and 15% and 22% with T4 and T5 (RDI in March). T5 was quite a severe treatment, with the soil profiles dried for almost 3 weeks. T6 (RDI in April) had a 10% reduction in large fruit size, and this was coupled with an increase of 1 °Brix.

In 2019, the amount of fruit in the 81–87 mm size class was reduced by 26% with T2, 28% with T3 and 17% with T4. These reductions were observed in both rootstocks and shows that the applying RDI early has a profound effect on reducing large fruit size but also increases °Brix levels. While T5 and T6 reduced fruit size by only 5%, which is likely to be more acceptable to growers, the °Brix was only 0.5, therefore these treatments failed to achieve the desired sugar levels.

In 2020, fruit were harvested on 29 July. The 2020 growing season was affected by rainfall, so the fruit size was not reduced by any treatments apart from T4 and T6. T4 increased °Brix by 1 and had 11% fewer large size fruit. T6, which was applied in February, produced 1.3 °Brix at the cost of 14% reduction in large fruit size.

In 2021, fruit were harvested on 29 July. T3 reduced the amount of large fruit by 16% and increased °Brix by 1.5, while T4 reduced large fruit size by 27% and achieved 2.1 °Brix. In T5, where 100% water was applied straight after 2 weeks of drying, reduced large fruit by 8% with only 0.5 °Brix, which was mainly on the *Troyer citrange* rootstock. The April applied treatment (T7) did not reduce the fruit size but still was able to achieve 0.9 °Brix. This is a desirable result for T7 where only 4 weeks of 50% irrigation was applied. Applying 50% irrigation for 8 weeks would likely have resulted in a better outcome.

The general sugar levels at harvest for three navel varieties are given for 4 growing seasons in Table 10.1. It is interesting to note that M7 is an early-maturing and sweeter variety than mid-maturing Washington navel and late-maturing Lane Late navels. The fruit size losses are also greater with M7 when trees are water stressed. In an 'on-season' crop with high crop load, the fruit size will be further affected. The poor correlations between fruit size and °Brix values for M7 navel are evidence of this. The results also suggested that heavy rainfall (2020) interfered with °Brix levels for all three navel varieties (Table 10.1). In control trees, there was a decrease of 1 °Brix in 2020 in all 3 navel varieties compared to the remaining three years.

Table 10.1: Total soluble solids (°Brix) for the control trees for 4 growing years for 3 navel varieties.

	M7	Washington navel	Lane Late
2018	14.4	13.0	12.8
2019	14.1	12.8	12.5
2020	13.0	11.5	11.8
2021	14.3	12.8	12.8

The increase in sugar levels with RDI was achieved in this project with a range of RDI treatments applied for 4 years the experimental program. The results clearly showed that there are some fruit size losses with RDI to enhance sugar levels in fruit. The increase in °Brix is linearly related to fewer large fruit in size class 81–87 mm; there is a penalty for each °Brix increase in navel fruit.

Table 10.2: Per cent fruit size decrease (81–87 mm) with an increase in °Brix levels.

°Brix	Per cent fruit size decrease (81–87 mm)
0.5	5
1.0	10
1.5	15
2.0	20
2.5	25

Economics of RDI

Fruit yield for each tree was graded into 5 size classes using a colour vision grading machine and prices were allocated for each size class as per the Mildura Fruit Company (MFC) price structure. The price is calculated from the payment structure of the MFC for different size distribution. Using navel oranges as a guideline, the costs of using several RDI treatments to enhance sugar levels were calculated for two growing seasons (2019 and 2021), where no significant rainfall was recorded. The cost is calculated on the basis of full tree harvest and each size and their relative $ value is considered for each experimental tree.

In each treatment, the soil profile was dried for two weeks, then 50% irrigation was applied for 8. Early application of RDI caused some losses for both varieties grafted to *Poncirus trifoliata* and *Troyer citrange*. These losses were more severe in *Troyer citrange* rootstock, possibly because trees on this rootstock are larger and require more water to function and survive compared to *Poncirus trifoliata*, which is a shallow-rooted variety with a small canopy structure. Generally, trees on *Troyer citrange* can have a medium to large fruit load of smaller sized fruit, therefore, water stress imposed could negatively affect fruit growth. Furthermore, applying RDI in February can cause severe losses to fruit size. As fruit is actively growing from December to March, no water stress is recommended in normal situations. To enhance sugar levels in navel oranges, RDI can be commenced from 15 March onwards.

The following price was calculated for the production of 40 t/ha. It is assumed that 1 hectare will produce 40 tonnes. For example, Washington navel trees given RDI commenced from 15 to 30 March will cost a grower $170/40 tonnes if trees were grown on *Poncirus trifoliata* rootstock (Table 10.3). However, at the same time it will cost the growers $350/40 tonnes if trees for Washington navel were grown on *Troyer citrange* rootstock. The RDI commenced in early April will cost the growers $242/40 tonnes on *Poncirus trifoliata* rootstock and $286/40 tonnes on *Troyer citrange rootstock* for Washington navel oranges. In Lane Late, the cost to the growers will be $87/40 tonnes on *Poncirus trifoliata* rootstock and $240/40 tonnes on *Troyer citrange* rootstock. The RDI commenced in mid-March seems to be suitable for *Poncirus trifoliata* rootstock, while the RDI commenced in early-April will suit *Troyer citrange* trees.

Table 10.3: The economic cost of RDI when applied at different times of the year for Washington navel and Lane Late trees grafted to *Poncirus trifoliata* and *Troyer citrange* rootstock. These figures are calculated from the 2019 and 2021 growing seasons. $ values are presented for the $ loss per 40 tonnes.

	Washington navel		Lane Late	
	Poncirus trifoliata	*Troyer citrange*	*Poncirus trifoliata*	*Troyer citrange*
1–15 Feb	437	1736	456	1645
1–15 Mar	753	1198	791	1187
15–30 Mar	170	886	350	750
1–15 Apr	242	286	87	240

RDI commenced from 15 March or 1 April will be suitable if no rainfall occurs but this will also be influenced by air temperatures. In some years, 2 weeks of soil profile drying might not be enough to attain certain stress levels in *Troyer citrange* rootstock if started on 1 April. The pre-dawn stem water potential values have to be between 8–10 bar before the desired stress levels are achieved. Sugar levels should also be monitored weekly. Therefore, growers need to decide when they would like to apply RDI treatment.

Sensory evaluation

Sensory evaluation of M7 (early maturing) and Lane Late (late maturing) navel oranges was performed in 2019 at SuniTAFE Mildura. Staff and students were involved in sensory evaluation of the fruit harvested from the regulated deficit irrigation trial at Dareton. Fruit was harvested for 3 regulated deficit treatments and 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*) from 4 replicates. In M7 navel, the irrigation treatments T2 and T3 significantly increased sugar and BrimA values compared to the control but did not the affect the acid levels. In Lane Late navel, T2 and T3 significantly increased the sugar levels compared to the control by more than 2 degrees. The acid levels were slightly increased with irrigation treatments, with T2 and T3 compared to the control. This increase is commercially significant, and it contributes to enhanced fruit taste. There were no effects of rootstock treatments on °Brix value, acid levels or BrimA values.

The sensory evaluation data were collected as scores, which were converted into percentages. The percentages were from the fruit classed as good quality. In M7, T2 had increased scores for sweetness (86%) compared to the control (77%). T3 had higher scores for acid levels (87%) compared to the control (77%). The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. T2 had better tasting fruit than the control (87% and 78%, respectively).

Generally, an adequate juice quantity was found in fruit from T1 (78%) compared to T2 or T3, however, this result was not significant. This result is interesting because fruit is actively growing in February and water stress can reduce the juice content and fruit size, however, the results from this trial did not replicate this. In Lane Late navels, T3 had higher scores for sweetness (87%) than the control (77%). The acid levels were not different between the treatments. The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. The fruit taste in T3 scored 87%, which was higher than control (79%). Generally, an adequate juice quantity was found in fruit with T1 (84%) compared to T2 (79%) or T3 (75%).

In 2020, sensory evaluation was carried out at the Mildura Fruit Cooperative (MFC) with marketers, packers and fruit quality experts. Fruit was harvested from early-maturing M7 navels and mid-maturing Washington navels for 2 regulated deficit treatments from 2 rootstocks (*Poncirus trifoliata* and *Troyer citrange*). T1 was the control (100% irrigation) and T6 was the treatment where deficit irrigation was applied in February 2020. Additional treatments were planned, however, substantial rain fell from March through to May, which meant that the water stress planned for T3, T4 and T5, could not be applied.

Before the sensory evaluation, fruit quality was assessed on M7 and Washington navel oranges, although the varieties were harvested at different times of the year based on their maturity. In M7 navel, T6 significantly increased sugar, BrimA and acid levels compared to the control. Rootstock did not affect the quality attributes. In Washington navel, T6 significantly increased sugar and acid levels compared to the control. °Brix levels and acid levels were also higher for *Poncirus trifoliata* rootstock compared to *Troyer citrange*.

The sensory data suggested that in M7, T6 had increased scores for sweetness (85%) compared to the control (50%). The acid levels in the fruit were higher with T6 (71%) compared to the control (51%). The blend of high sugar and acid results in better tasting fruit compared to dull tasting fruit. T6 had better tasting fruit than the control (82% and 49%, respectively). In Washington navels, T6 has increased scores for sweetness (93%) compared to the control (66%). The acid levels in the fruit were higher with T6 (80%) than the control (54%). Generally, T1 had an adequate juice quantity (72%) compared to T6 (61%), however, this effect was not significant.

Drone flights to assess canopy temperatures in RDI treatments

Drone flights were conducted in 2018, 2019 and 2020, by different operators during the RDI periods.

In 2018, the drone flight was conducted by Hort-Eye Pty Ltd over the entire irrigation trial on 28 February to estimate crop water stress index (CWSI) and canopy temperatures. The data on canopy temperature were collected for each tree by Hort-Eye Ltd. Data was provided in an Excel sheet and the data was analysed to determine treatment differences.

There were no differences detected in the canopy temperatures for any of the RDI treatments compared to the control. In M7, Washington navel and Lane Late navels there were no differences detected in canopy temperatures for rootstock or the interaction between irrigation treatments and rootstocks (Table 6.1). The drone with the thermal camera attached flew at 100 m from the trees. Previous measures have had the camera 30 cm from the target (Stagno et., 2011) and in grape vines, the distance between the detection window and fully expanded leaves was kept at 5–10 cm (Chen et al. 2020). It is possible that the altitude used in this trial (100 m) might have been too far from the canopies to detect any changes.

In 2019, another operator was used, and several drone flights were conducted to detect canopy temperatures and provide information about how the trees were responding to the RDI trial on 3 navel varieties and 2 rootstocks. Dr Mark Skewes from SARDI, Loxton conducted 9 flights between 27 February and 16 May. Every flight was conducted at mid-day to avoid variation between the flying time. Canopy temperature data were recorded for all flights and crop water stress index was assessed from 1 April onwards. It was believed that crop stress index would provide a better indicator of crop stress status. However, there were no treatment differences detected in copy temperature or crop water stress index for M7, Washington navel or Lane Late oranges. From this study, it would appear that the drone flights were not appropriate for collecting canopy temperature and perhaps they were collecting air temperatures instead (Figure 10.1).

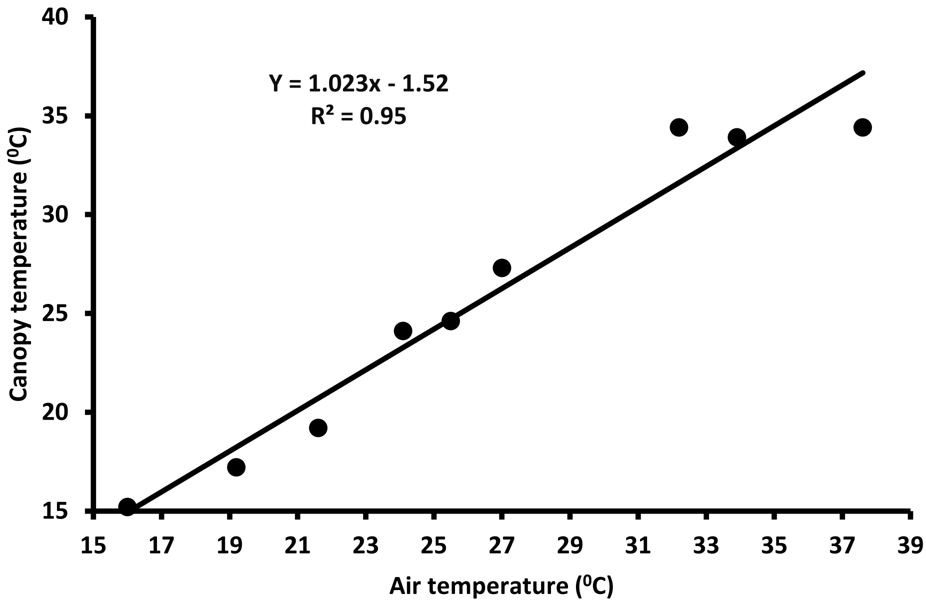

Figure 10.1: The relationship between air temperature and canopy temperature for 9 drone flights between 27 February and 16 May 2019 in the RDI trial at Dareton. Each dot represents a single flight. Regression coefficient R^2 = 0.95 is significant at $p < 0.001$ (***).

On the recommendation of the PRG committee, a new operator was used for the 2020 growing season. StevTech Pty Ltd conducted a drone flight over the trial area on 21 April 2020 to collect crop normalised digital vegetation index (NDVI) data. NDVI has been used in field crops such as culture beans (Guilherme-Fernando et al. 2016) and apples (David et al. 2017). The drone was fitted with a multi-spectral camera. Using a multi-spectral camera attached to a drone flown at 100 m elevation failed to assess water stress in citrus trees in the RDI trial conducted on 3 navel varieties.

Storage trials

Fruit was harvested from M7, Washington and Lane Late navel varieties in the 2021 growing season and stored to determine how well fruit from RDI treatments lasts in storage compared with fruit from trees that were fully irrigated.

Fruit from 2 regulated deficit irrigation treatments T1 (control) and T6 (stressed in February) were used in the storage trial.

In M7, °Brix values from fruit in T6 were higher at day 0 (harvest), 7, 14 and 28 (Table 7.1). At Day 35, there was no different in °Brix between T6 and T1 (Table 7.1). This suggests that fruit from the RDI trial could be stored up to 35 days without any change in total soluble solids values. BrimA values were higher in fruit from T6 than T1 from harvest to day 14 in storage, after which there were no differences. The acid per cent did not differ between the groups during storage, which could explain the absence of differences in BrimA values beyond day 14 in storage. There was no difference in juice per cent for T1 or T6 at harvest or during storage up to 35 days. There were no storage disorders detected. Therefore, sweeter fruit can be stored up to 35 days without any storage disorders or changes to internal quality.

In Washington navel, °Brix values were higher in T6 than T1 on day 0, 7, 14 and 28 in storage. This suggests that fruit from the regulated deficit irrigation trial could be stored up to 28 days without change in total soluble solids values. BrimA values were higher in fruit from T6 than T1 from day 0 to day 14, after which there were no differences found. These are promising results showing that sweeter fruit (RDI treated) can last in storage. There were no storage disorders detected, indicating that sweeter fruit can be stored up to 35 days without changes in internal quality.

In Lane Late, °Brix values were higher in T6 than T1 from day 0 to day 21, indicating that fruit from the RDI treated trees can be stored up to 21 days without change in total soluble solids values. BrimA values were higher in T6 than T1 at harvest (day 0) and day 21, but not different at day 14. Acid values were not different between T6 and T1 at harvest but were higher in T6 on days 14 and 21. There was a gradual (but not significant) decrease in acid level during storage for fruit harvested from the control trees. These results suggest sweeter fruit can store well if they have high acid levels. There was no difference in juice per cent. While fruit from the control trees was heavier at harvest, this difference did not continue during storage. Although there were no storage disorders detected, some fruit discolouration and pitting were found in both T1 and T6. The current data suggest that sweet fruit can be stored up to 21 days however, extended storage trials are recommended in collaboration with Mildura fruit company (MFC).

RDI for Afourer mandarin in Riverina and Sunraysia

Two demonstration trials were established at Southern Cross Farms, a grower's property in Leeton, NSW and Ellerslie, Victoria. In each trial, 4 rows (12 trees/row) were selected, and 2 regulated deficit irrigation (RDI) treatments were applied. The control (2 rows) received 100% irrigation water as per Ec and the water stress (RDI) was applied to the remaining 2 rows. In RDI treatments, the soil profile was dried for 2 weeks and no irrigation was applied. After the end of drying period, 50% of full irrigation applied for 8 weeks (15 April to 15 June) followed by 100% irrigation every second day. Data on fruit size was collected from represented trees at harvest for 4 growing seasons from 2018 to 2021. Fruit quality components were recorded for each treatment at harvest for each growing season.

In the Riverina, in 2018, the °Brix and BrimA values increased with RDI compared to the control. Although there was a slight increase in acid levels with RDI treatment, the effect was not significant. RDI significantly decreased the fruit size at harvest by 1.6 mm. The 2018 growing season was a dry season and no significant rainfall was recorded. In 2019, there were no significant differences between the °Brix value for RDI compared to the control. Acid values were slightly higher than the control although non-significant. The fruit size was not different at harvest for control or RDI treatments. Substantial rain fell throughout the growing season and trees did not experience the required stress levels. Therefore, the results are not conclusive. In 2020, there were no differences in °Brix, BrimA or acid values for RDI treatments compared to the control. Fruit size at harvest was 2 mm higher for the RDI treatment compared to the control. This is a rather an unusual result and is most likely attributable to the 111 mm of rain that fell in April; hence, these the results are not conclusive.

In 2021, there were no differences in °Brix values for RDI treatments compared to the control, however, BrimA values were significantly increased with RDI. Fruit size at harvest was similar for both RDI and the control. In the 2021 growing season, a lot of rain fell in March (71 mm), May and June (18 and 76 mm respectively), preventing the trees from going into an irrigation deficit. It is important to notice that in 3 rainy seasons the acid levels were higher compared to 2018, which was a dry season. This could be due to the low sugar levels that otherwise could have been attained if RDI treatments were fully effective.

In Sunraysia in 2018, the °Brix values were increased by 1.2 with RDI compared to the control. There was also an increase in acid levels with RDI treatment by 0.3 and this effect was statistically significant. RDI significantly decreased the fruit size at harvest by 2.3 mm. The 2018 growing season was a dry season and no significant rainfall was recorded. In 2019, there was an increase of 1 °Brix with RDI treatment. The BrimA values were slightly increased with RDI treatments compared to the control. One of the reasons for these results is the rainfall (26 mm) experienced during May. This could have contributed to the low sugar and acid levels in RDI treated fruits. Fruit size at harvest was similar for the RDI treatment compared to the control. In 2020, there were no differences in °Brix, BrimA or acid values for RDI treatments compared to the control. Fruit size at harvest was similar for the RDI treatment and the control. There was significant rainfall recorded throughout the growing season. In March there was 26 mm rainfall and in April 72 mm. Therefore, trees did not experience the required stress levels and these results were not conclusive.

In 2021, the °Brix values were increased by 0.9 with RDI compared to the control. BrimA values were significantly increased by 26 units with RDI treatment compared to the control. Acid levels were also higher in DRI treated trees. However, the fruit size at harvest was similar for both RDI and the control. In 2021, there no significant rainfall experienced during stress periods. This means the trees were able to achieve the required stress levels in this season, and differences in sugar and acid levels were observed in for both treatments. These results are more likely to be a true reflection of the effects of RDI than in the wet seasons.

The work from these 2 parallel trials suggests that RDI should be applied in March. In the Riverina district, there were 3 rainy seasons out of 4, and 2022 was also a rainy season with 70 mm of rain in April. Therefore, in future, research work should be carried out in Curlwaa area of NSW, which has clay soil conditions similar to the Riverina. This area is only 10 km from the Dareton Primary Industries Institute and mature 'Afourer' trees are available for trial at the grower's property.