

Effect of Irrigation on Yield and Fruit Quality of Rabbiteye Blueberry Growing on Mineral Soils in New Zealand



2014

ERI report number 42

Prepared for Oakberry Farms Ltd.

By Teruko Kaneko and Michael Clearwater

Environmental Research Institute

Faculty of Science and Engineering

University of Waikato, Private Bag 3105

Hamilton 3240, New Zealand

Cite report as:

Kaneko, T., Clearwater, M., 2014. Effect of Irrigation on Yield and Fruit Quality of Rabbiteye Blueberry Growing on Mineral Soils in New Zealand. *Environmental Research Institute Report No. 42*. Client report prepared for Oakberry Farms Ltd. Environmental Research Institute, Faculty of Science and Engineering, The University of Waikato, Hamilton. 43pp.

Reviewed by:

Daniel Laughlin
Research Fellow
Environmental Research Institute
University of Waikato

Approved for release by

John Tyrrell
Business Manager
Environmental Research Institute
University of Waikato

Executive Summary

An experiment was conducted to determine the effect of irrigation on fruit yield and quality, and to provide recommendations for the appropriate level of irrigation for 11-year-old *Vaccinium ashei* Reade var. 'Maru' (a Rabbiteye blueberry cultivar), growing on Horotiu silt loam at Oakberry Orchard near Hamilton, New Zealand. Water was applied twice daily by drip irrigation. The treatments were no irrigation, normal irrigation (one-drip line per row), and additional irrigation (two-drip lines per row). During the observation period (November 2013 to April 2014), rainfall was below normal, particularly during fruit ripening and harvest in February and March when drought conditions created differences in soil moisture vertically and horizontally among the three treatments.

- Predawn leaf water potential of the non-irrigated plants declined to below -0.2 MPa, compared to -0.05 MPa in the two irrigation treatments. There was no significant difference in stomatal conductance between the non-irrigated and irrigated plants, but this variable was only measured once soon after the beginning of the drought period.
- The majority of fine roots were located between depths of 10-30 cm, however some roots were detected between 40 and 60 cm. The plants were therefore probably able to obtain water from these depths, delaying the impact of water deficit on vegetative and fruit growth. Despite impacts on fruit growth, irrigation had very little visible effect on plant condition.
- In all treatments, shoot extension and diameter growth declined during the study period and differed little between treatments. Irrigation caused slightly higher shoot diameter growth near the end of the study period.
- Larger fruit lost weight more quickly and smaller fruit grew more slowly and began to lose weight sooner, when irrigation was withheld. Fruit from irrigated plants were larger at harvest, particularly at the final two of five harvests, were less firm and had slightly lower brix, an effect attributed to increased berry dehydration in the no irrigation treatment. The one-drip treatment increased individual fruit size by 12-13 % compared to no irrigation, and the two-drip treatment increased fruit size by an additional 7-9 % compared to the one-drip treatment.

- Irrigation had no detectable effect on total yield per plant, primarily because there were only three harvested plants per treatment, and the variability in total fruit number per plant was high. The timing of the dry period also meant that irrigation had a positive influence only on the final two harvests, and these two harvests contributed less to total yield. However, the influence of a lack of irrigation on fruit growth and final size of fruit that were growing during the water deficit period was pronounced, indicating that irrigation can have a major positive impact on yield, depending on the timing of any deficits between rainfall and crop water use.
- A basic crop water balance was completed, with Penman Monteith FAO reference evapotranspiration for a short canopy (ET_o) compared with crop water use estimated from the balance of rainfall, irrigation and changes in soil moisture content. Crop factors, the ratio of crop water use to ET_o , were between 0.5-0.7 before the harvest season, increasing to 0.8-1.1 during the harvest season.

Irrigation clearly provided positive benefits in terms of fruit size and quality when compared to no irrigation. The differences between the two irrigation treatments were not large, but two drip lines per row reduced spatial variability in soil moisture levels, and there was some evidence that fruit size was further enhanced by better prevention of soil moisture deficits by two drip lines compared to one drip line. To maximize fruit yield and quality, the capacity to reliably supply irrigation water at a rate close to or exceeding ET_o during extended periods of low rainfall should be a factor considered during orchard establishment.

Table of contents

Executive summary.....	1
Table of contents.....	3
List of tables.....	5
List of figures.....	5
Introduction.....	8
Methods	11
Site information.....	11
Treatments.....	12
Soil moisture measurements	13
Root distribution.....	14
Leaf water potential and stomatal conductance	15
Shoot and fruit growth measmremments.....	15
Harvest	16
Water balance.....	16
Statistics analysis.....	17
Results.....	18
Weather	18
Soil moisture	19
Root distribution.....	25
Leaf water potential and stomatal conductance	25
Shoot growth	27
Fruit growth.....	29
Harvest and fruit quality.....	30
Water balance.....	32
Discussion.....	35
Soil water availability and water stress on plants	35
Plant growth and fruit quality.....	36

Water balance	38
Conclusion	39
Acknowledgements.....	39
References	40
Appendix.....	42

List of tables

Table 1. Average daily maximum and minimum temperature at Oakberry Orchard, from December 2013 to April 2014.....	18
Table 2. Weekly water balance for rabbiteye blueberry ‘Maru’ in Oakberry Orchard for the no irrigation, one-drip and two-drip treatments for 11 weeks from 12 December 2013 to 26 February 2014. ET_o , Penman-monteith FAO reference evapotranspiration; E_{wb} , crop water use estimated from the balance of soil moisture, irrigation and rainfall (see methods); K_c , crop factor, the ratio of crop water use to ET_o	33

List of figures

Figure 1. Weather station, blueberry plants and installation of soil moisture probes at Oakberry Orchard, near Hamilton, New Zealand.....	11
Figure 2. Layout of the treatment plots, plant spacing, positions of drip lines, drip emitters, and soil moisture sensor.....	13
Figure 3. Installation of soil moisture sensors at the depth of 10, 20, 30, and 50 cm (left) and a data logger (right).....	14
Figure 4. Fruit for non-destructive growth measurements. Fruits were marked with wire and diameters were measured every week.....	16
Figure 5. Daily rainfall and Penman-Monteith/FAO evapotranspiration for a short grass canopy (ET_o) at Oakberry Orchard near Hamilton from December 2013 to April 2014.....	18
Figure 6. Vertical soil moisture profiles of the no irrigation (top), the one-drip (middle), and the two-drip (bottom) treatments, at the depth of 10, 20, 30, and 50 cm observed from December 2013 to Apr 2014. Regular small fluctuations are irrigation events, and gaps are periods when irrigation system failed (red arrows).....	20
Figure 7. Spatial soil moisture distribution in the top 10 cm of soil of the no irrigation, one-drip, and two-drip treatments, measured from December	

2013 to March 2014. The values shown are the actual soil moisture measurement, and the colours have been drawn to approximate zones of similar water content.....	21
Figure 8. Distribution of blueberry roots (fresh weight and length per cm ³) as a function of distance from the nearest plant and depth from the soil surface.....	25
Figure 9. Predawn leaf water potentials of the no-irrigation, one-drip and two-drip treatments, measured from November 2013 to April 2014. Values are means of 6 leaves per treatment with standard error bars.....	26
Figure 10. Relationship between leaf stomatal conductance and midday leaf water potential of the no irrigation, one-drip, and two-drip treatments, measured on 4 th and 5 th of February. Each symbol represents the mean and standard error bars. Values for leaf water potential are means of 18 leaves per treatment and values of stomatal conductance were means of 36 leaves per treatment.....	27
Figure 11. Average of shoot growth per day in length (a) and in diameter (b) for the no irrigation, one-drip and two-drip treatments from December 2013 to March 2014 (n=6). Shoots are categorized into two types; upward branch and side branch.....	28
Figure 12. Average fruit weight (g) measured non-destructively using callipers from November 2013 to March 2014 for the three irrigation treatments. The overall average of fruit size (n=90) (a), and the average fruit size by initial size classes; small (n=30) (a), medium (n=30) (b), and large (n=30) (d).....	30
Figure 13. Average total yield per plant at 5 harvests for the three treatments (no irrigation, one-drip and two-drip). Each column presents the mean value of 3 plants and standard error. There were 5 harvests during the season on 22 Jan, 4 Feb, 25 Feb, 15 Mar, and 31 Mar, 2014.....	31
Figure 14. Individual fruit size (a), brix (b), and firmness (c) at harvest for the no irrigation, one-drip and two-drip treatments. Each symbol represents the mean of three plants and standard error bars. The differences in fruit size, brix and firmness between the non-irrigated and irrigated treatments were all significant at the 4 th and 5 th harvest (ANOVA, $P<0.05$).....	32
Figure 15. Weekly crop factor for the no irrigation, one-drip and two drip treatments for 11 weeks from 12 December 2013 to 26 February 2014, including the part of the harvest season.....	34
Figure 16. The total fruit yield of 2014 harvest. For the experiment, there were three trees per treatment, and 5 harvests during the season.....	42
Figure 17. Relationship between fruit weight (g) and firmness (kgf) for all samples of 4 th and 5 th harvests.....	43

Introduction

Appropriate irrigation management is critical for many fruit crops, and blueberry production is no exception. Water status affects the yield of fruit crops, both directly through effects on fruit set, cell division and expansion during fruit development, and indirectly by influencing photosynthesis and partitioning of photosynthates between vegetative and reproductive growth. In some fruit crops a mild soil water deficit may be beneficial during fruit maturation – for example in prunes and grapes, where water stress can reduce vegetative growth and enhance fruit dry matter content and flavour (Ferrerres & Soriano 2007; Lampinen et al. 2001). However, in berry crops grown for fresh fruit, water stress during fruit development is usually undesirable because of reductions in fruit size and total yield (Kirda et al. 2004; Liu et al. 2007). Fruit from irrigated blueberry were larger and had less water loss during storage than fruit from non-irrigated plants, although fruit firmness and soluble solids were slightly reduced (Ehret et al. 2012).

Water requirements of blueberry vary with the age of the plants and between growth periods. While irrigation requirements ultimately depend on the climate and the amount of precipitation, in many growing regions irrigation becomes essential after pollination and fruit set (Bryla 2011). As in many other fleshy fruits, the blueberry fruit exhibits a double-sigmoid pattern of growth, with the fruit growth period divided into three stages; Stage I (rapid fruit growth related to cell division and expansion), Stage II (a brief period of slower fruit growth marking the transition to ripening), and Stage III (rapid fruit growth by cell expansion, and physiological changes associated with ripening, such as accumulation of sugars, coloration and softening). Maintaining optimal soil moisture levels is important throughout all three stages, but is most important during Stage III when cells expand and fruit size increases rapidly (Bryla 2011). There is evidence that the amount of water required by the blueberry plant increases significantly during late stage III (Bryla & Linderman 2007), and then decreases again after harvest (Mingeau et al. 2001).

The selection of an appropriate irrigation method is a key factor for optimising fruit yields from blueberry production. The most common irrigation methods for blueberry are drip, sprinklers, and microsprays (Bryla 2008; Bryla et al. 2009, 2011). Drip irrigation has some advantages compared with sprinklers and microsprays, including more direct water application to the soil, resulting in higher soil moisture content. Consequently, drip irrigation results in a higher water use efficiency (Bryla 2008). In addition, Bryla et al. (2011) observed

that, of the three irrigation methods, plant establishment was better with drip irrigation. However, there are some disadvantages to the use of drip irrigation. Because of the small wetted area, drip irrigation may reduce the spatial extent of root development, a drawback considering that blueberry also has a relatively shallow root system (Bryla et al. 2011). Furthermore, drip irrigation produced higher yields from highbush blueberry, relative to the amount of water applied, but also resulted in softer fruit and lower soluble solids compared to fruit from sprinkler or microspray irrigated plants (Bryla et al. 2009). Thus, careful irrigation management is necessary to achieve an optimal yield and quality of blueberries.

The level of irrigation required varies between blueberry cultivars. The water requirement of highbush blueberry is significantly higher than that of rabbiteye blueberry, indicating that rabbiteye blueberry is more drought tolerant than highbush blueberry (Bryla & Strik 2007; Haman et al. 1997). Among three different cultivars of highbush blueberry; an early season cultivar 'Duke', a mid-season cultivar 'Bluecrop', and a late-season cultivar 'Elliott', 'Duke' had the highest water use whereas 'Elliott' was the lowest during the harvest season (Bryla & Linderman 2007). While water deficit can lower yield and fruit quality, over irrigation can increase the risk of soil saturation (Jara et al. 2011), and increase the occurrence of root rots (Byers & Moore 1987). Susceptibility to root pathogens also differs between cultivars. For example, Bryla & Linderman (2007) found that 'Duke' is highly susceptible to root pathogens caused by high frequencies of drip irrigation.

Soil type also influences plant growth and fruit yield and quality of blueberry. In North Europe, blueberry plants successfully grow in both peat and mineral soils, but typically grow better in peat soil due to higher nutrient contents (Tasa et al. 2012). In New Zealand, blueberries have traditionally been grown on peat soils with a high water table and only occasional irrigation, although recent expansion has included planting on better drained mineral soils. Irrigation can help prevent periodic soil water deficits during fruit growth in summer that almost certainly reduce fruit size and total yield, but the type and level of irrigation needed to achieve maximum yields under New Zealand conditions is unknown.

The goal of this research was to make a preliminary assessment of the water requirements of rabbiteye blueberry growing on mineral soils in the Waikato, and the effect of irrigation on plant water status, fruit yield and quality. Three irrigation regimes, -control (no irrigation), moderate irrigation (one drip line per row) and heavy irrigation (two drip line per row)- were established. Measurements included monitoring of the soil moisture profile horizontally and vertically within each treatment, and quantifying the position of the plant's roots within the

one-drip treatment, which was equivalent to the usual irrigation practice for this orchard. We hypothesized that plants with the two-drip treatment would have larger fruit and higher yields of berry per plant, but also reduced fruit brix and firmness and increased vegetative growth, when compared to plants in the one-drip or no irrigation treatments.

Methods

Site information

The research was conducted at Oakberry Orchard near Hamilton, New Zealand (37°47'50"S, 175°22'15"E). Hamilton has a temperate climate. The daily maximum temperatures are about 21–26 °C in January and February, and 10-14 °C in July and August. Mean annual rainfall for the past 30 year periods was 1190 mm with the highest in July at 120-130 mm and the lowest in February at 70 mm (Niwa climate database, <http://www.niwa.co.nz/education-and-training/schools/resources/climate>). The soil type on the site was Horotiu silt loam (Singleton 1991).

Measurements were conducted from mid-November 2013 to April 2014 on 11-year-old *Vaccinium ashei* Reade var. 'Maru' (a Rabbiteye blueberry cultivar). This cultivar is typically harvested from late January to the end of March. During the experimental period weeds, insects, and plant growth were controlled by mowing, the application of pesticides, and pruning, respectively.



Figure. 1. Weather station, blueberry plants and installation of soil moisture probes at Oakberry Orchard, near Hamilton, New Zealand.

Rainfall (Generic Tipping Bucket Rain Gauge, Campbell Scientific Inc, Logan, UT), solar radiation (LI200 Pyranometer, LI-COR Inc, Lincoln, NE), air temperature and humidity (HMP50 Temperature and Relatively Humidity probe, Campbell Scientific, Logan, UT), wind speed (Vector A101M Anemometer, Scottech Ltd, Hamilton, New Zealand), and soil temperature (Model 107 Temperature probe, Campbell Scientific Inc, Logan, UT) were recorded every minute and averages saved every 15 minutes with a data logger (CR1000, Campbell Scientific Inc., Logan, UT). From these measurements, hourly potential evapotranspiration for a short grass canopy (ET_0) was calculated using the Penman-Monteith equation (Allen et al. 1998).

Treatments

The orchard was irrigated by pressure compensated drip irrigation tubing laid on the soil surface adjacent to the plants. Plants were spaced approximately 1.6 m apart within rows and 3.3 m apart between rows (Fig. 2). The treatments were subjected to no irrigation, normal irrigation for this orchard (one drip line per row), and additional irrigation (two-drip lines per row), hereafter referred to as no irrigation, one-drip and two-drip treatments. Each treatment was applied to five adjacent plants, within one row, with the three treatments located in three adjacent rows, away from the edge of the block and selected to be as uniform as possible. To avoid edge effects, only the middle three plants of each treatment were used for measurements of fruit and shoot responses. Each drip line had emitters spaced 0.5 m apart, resulting in three emitters per plant per drip line. From each emitter 0.96 L of water was applied twice a day at 630 and 1930 hours. Each plant within the one-drip treatment received 2.88 L of water per time), while the plant with two-drip lines had 6 emitters each (received 5.76 L of water per irrigation). Irrigation levels were determined by the orchard manager, based on previous experience and observation of precipitation and soil moisture. The amounts applied were increased by 30 % on 12th February, and by an additional 20 % on 27th February.

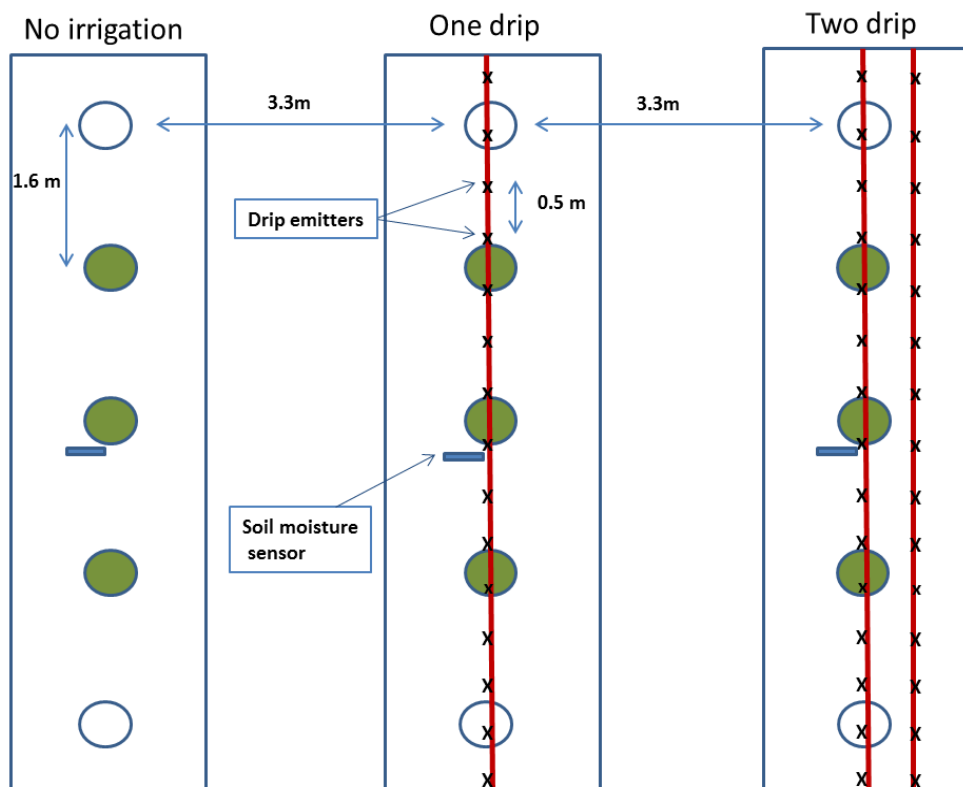


Figure 2. Layout of the treatment plots, plant spacing, positions of drip lines, drip emitters, and soil moisture sensors.

Soil moisture measurements

Soil moisture sensors (EH₂O, Decagon Devices, Inc. WA) were calibrated in the laboratory using dry soil collected from the orchard. Varying amounts of water were added and the soil mixed and packed into buckets to approximate the bulk density of soil in the orchard, probe response recorded, and then volumetric moisture contents were calculated after known volumes of the soil were dried in the oven at 65 °C over 72 hours.

To monitor vertical soil moisture profiles, in late-November 2013, four of the calibrated soil moisture sensors were connected to a multiplexor (AM16/32B, Campbell Scientific Inc., Logan, UT) and the datalogger, and installed horizontally near the centre of each treatment/row at four depths (10, 20, 30, and 50 cm), based on preliminary observation of rooting depth. Volumetric soil moisture content was recorded at each depth at one minute intervals and the average saved every one hour.

Spatial variation soil moisture contents in the top 10 cm were measured manually every two weeks using a portable soil moisture probe (Field Scout TDR 100, Spectrum, Technologies, Inc. Plainfield, IL). Measurements were taken in transects perpendicular to the rows at 0, 20, 40, 60, 80, and 100 cm from the centre of the row, on both sides of the row and at multiple location down the row.



Figure. 3. Installation of soil moisture sensors at the depth of 10, 20, 30, and 50 cm (left) and a data logger (right).

Root distribution

A soil corer was used to quantify the typical root distribution for this cultivar under normal (one-drip) irrigation, in April 2014. Five adjacent trees were selected from a row near the irrigation treatment plots, and four soil cores were collected along a transect on one side of and perpendicular to the row, at 0, 30, 60, and 90 cm from the centre of the row using a stainless steel corer (6 cm in diameter). For each core the distance in a straight line to the nearest drip line emitter and to the root collar of the nearest tree were recorded. Each soil core was 0-60 in depth, and it was split into five depth classes (0-10, 11-20, 21-30, 31-40, and 41-60 cm). In the laboratory, the roots were separated from each soil sample using washing and sieving, classified into coarse (>2 mm diameter) or fine roots (<2 mm diameter), blotted dry and fresh weight recorded. Root length was recorded on a subsample of fine roots using a root scanner (WinRhizo, Regent Instruments Inc., Quebec, Canada), and the relationship between root fresh weight and length used to express fine root density as cm cm^{-3} .

Leaf water potential and stomatal conductance

Predawn (0500-0700 hours) leaf water potential was measured at approximately two weekly intervals from December 2013 to April 2014 using a pressure chamber (PMS Instrument Co. Ltd., Corvallis, OR). For each tree, two healthy mature leaves were chosen randomly, removed from the plant with a razor blade, put in a plastic bag, and immediately measured.

On February 4th and 5th, 2014, during the drought period, midday water potential and stomatal conductance (LI-6400, LI-COR Inc. Lincoln, NE) were measured. These measurements were made on sunny days at 1300-1600 hours. In total, 6 leaves per plant were used for midday leaf water potential, while 12 leaves per plant were used for the stomatal conductance measurement.

Shoot and fruit growth measurements

For the shoot growth measurements, growing shoots were classified into two types; upward (prthotropic) and side (plagiotropic) branches. On each tree of the experiment, 6 upward branches and 6 side branches were marked, total length and diameter measured each week from December 2013 to March 2014, and daily growth calculated.

Fruit measurement began in mid-November 2013. Fruit sizes were highly variable because of differences in flowering date. Fruit were therefore categorized into three initial size classes; small, medium and large. First, 10 fruiting-stems per plant were randomly selected, and on each stem, one small, one medium and one large fruit were selected at random and marked (30 fruit per plant in total). The diameters of these marked fruit were measured using digital callipers every week over the observation period and fresh weight estimated from diameter based on the diameter/weight relationship of harvested fruit ($n=100$, sampled periodically during the study period from adjacent plants; from November to December pre-mature fruit weight (g) = $0.0004973 \times \text{diameter (mm)}^{2.9815788}$, $R^2 = 0.997$, and from January to March pre-mature fruit weight (g) = $0.0005704 \times \text{diameter (mm)}^{2.9179275}$, $R^2 = 0.996$ and mature fruit weight (g) = $0.001562 \times \text{diameter (mm)}^{2.5588893}$, $R^2 = 0.956$). Prior to harvest, any fruit lost to damage were replaced by selecting and marking another fruit of similar size. Marked fruit were monitored until they shrivelled and abscised naturally, after the date equivalent fruit would normally have been harvested by selective picking.



Figure 4. Fruit for the non-destructive growth measurement. Fruits were marked with wire and diameters were measured every week.

Harvest

The harvest season started from the end of January, and finished at the end of March. Ripened fruit were hand-picked and weighed in five harvests over the season. For each harvest, 100 fruit per tree were randomly chosen, and carried to the laboratory.

In the laboratory, each berry was weighed individually, juice squeezed from a subsample of 30 fruit per plant and brix measured with a refractometer (ATC-1, Atago, Tokyo, Japan). At the 3rd, 4th and 5th harvests, berry firmness was measured on 30 fruit per plant using a penetrometer with a 2 mm diameter probe (SVH-1000N, IMADA, Aichi, Japan).

Water balance

Over 11 weeks from 12 December 2013 to 26 February 2014, for each treatment, the evapotranspiration by the crop was calculated using a water balance equation:

$$E_{wb} = P + I - D \pm \Delta C$$

where E_{wb} is the water consumption of the crop (mm), P is the precipitation (mm), I is the irrigation application (mm, assuming the irrigation volume stated above was applied to a row

width of 2 m), D is the drainage (mm) below the root zone, ΔC is the change in soil water content (mm) obtained from weighted averages of the vertical soil moisture profiles. During the water balance period there was little fluctuation in soil moisture at the depth of 50 cm, suggesting that drainage was negligible, allowing the assumption that $D = 0$. The crop factor was calculated as;

$$K_c = E_{wb} / ET_0$$

Daily estimates of crop factor increased on days when rainfall occurred, suggesting that unaccounted-for drainage was occurring on these days. Weekly crop factors were calculated after excluding any day that rain fell, and the following day.

Statistics analysis

Data were analysed by one-way ANOVA using software STATISTICA, to compare the mean values of no irrigation, one-drip, and two-drip treatments (significant P -value < 0.05).

Results

Weather

Significant rainfall occurred until late January, following by a drier harvest period in February and March (Fig. 5). In December, total rainfall was 124 mm including heavy rainfall events on the 4th (30 mm) and 5th (41 mm). There was 57 mm of additional rainfall in January. However, from the end of January the amount of precipitation was reduced. In February and March, rainfall was only 15 and 14 mm respectively. Over the experimental period, February was the hottest month with an average maximum temperature of 26.1 °C and a minimum of 11.7 °C (Table. 1).

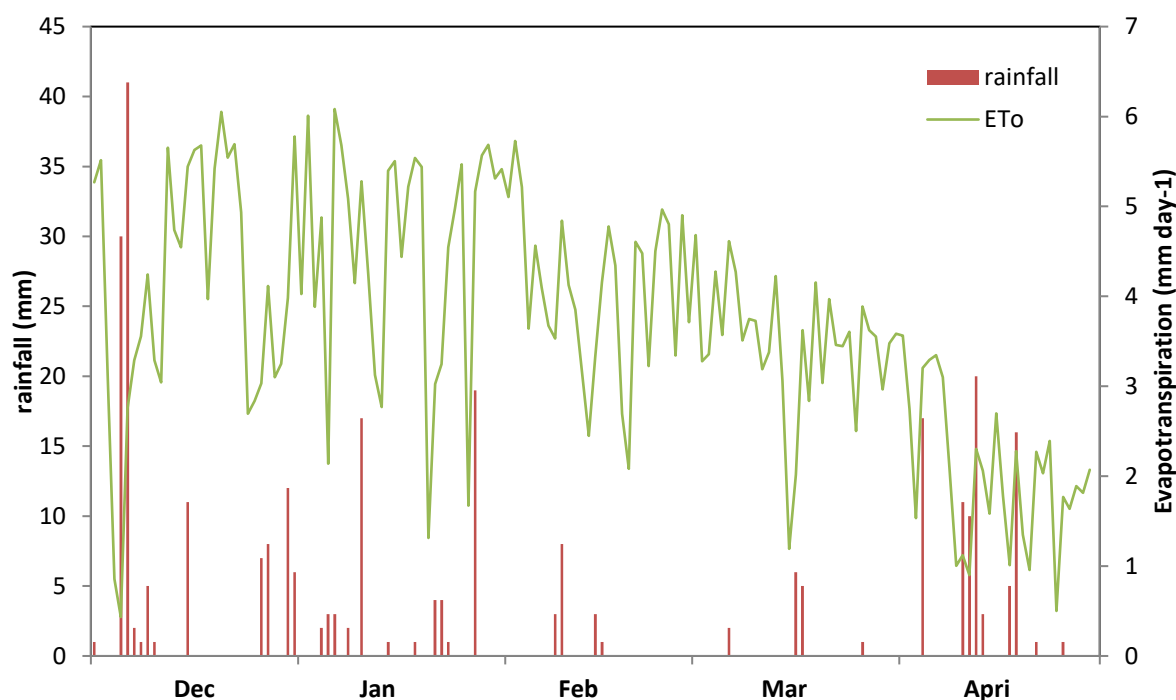


Figure 5. Daily rainfall and Penman-Monteith/FAO evapotranspiration for a short grass canopy (ET_0) at Oakberry Orchard near Hamilton from December 2013 to April 2014.

Table 1. Average daily maximum and minimum temperature at Oakberry orchard from December 2013 to April 2014.

Month	Dec	Jan	Feb	Mar	Apr
Maximum temperature (°C)	23.8	24.4	26.1	25.2	22.5
Minimum Temperature (°C)	11.4	10.4	11.7	9.5	11.1

Soil moisture

The vertical soil moisture profiles clearly illustrate the effects of the three irrigation treatments (Fig 6). The no irrigation treatment received only precipitation, resulting in a near continuous decline in soil moisture at all depths from 30-40 % in December to 10-15 % in March. A sharp increase occurred in April as rainfall resumed. The one-drip and two-drip treatments showed daily fluctuations in soil moisture at the depths of 10 and 20 cm in response to irrigation. However, there was little fluctuation of soil water content at a depth of 50 cm. Soil moisture of the one-drip treatment was stable at around 30 % at 10 and 20 cm deep, although a gradual decline occurred at the depths of 30 and 50 cm from 35 % in December to below 30 % at the end of March. In contrast, throughout the observation period, the two-drip treatment had higher soil water contents at all depths, relative to the other treatments.

The spatial distribution of moisture content of the top 10 cm of soil and its variation from mid-December to late-March was clearly related to the location of plants and drippers, and the level of irrigation (Fig. 7). Water content of the no irrigation treatment was lower surrounding the plants and increased toward the edge of the canopy. The one-drip and two-drip treatments had high soil wetness near the emitters.

In December and January, the soil water contents of the no irrigation treatment were constant at 10-30 % due to frequent rainfalls, while the irrigated treatments had constantly higher soil moisture contents at over 35 %. However, in late-February, there was a decline in soil moisture contents in all treatments. In March, soil moisture surrounding the plants in the no irrigation treatment decreased to less than 10 %. There was also more localised drying of the upper soil layers in the one-drip treatment as distance from the drippers increased.

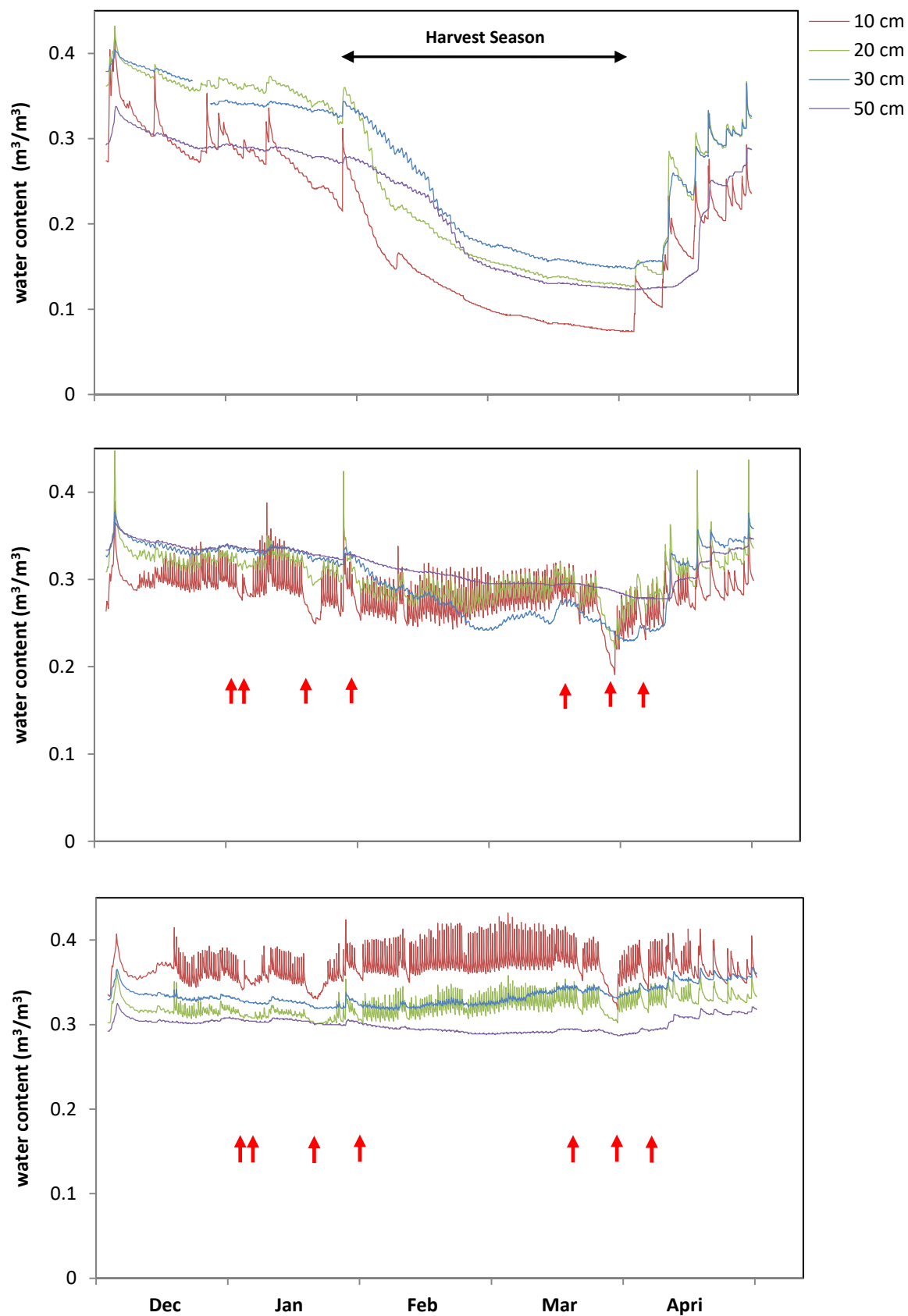
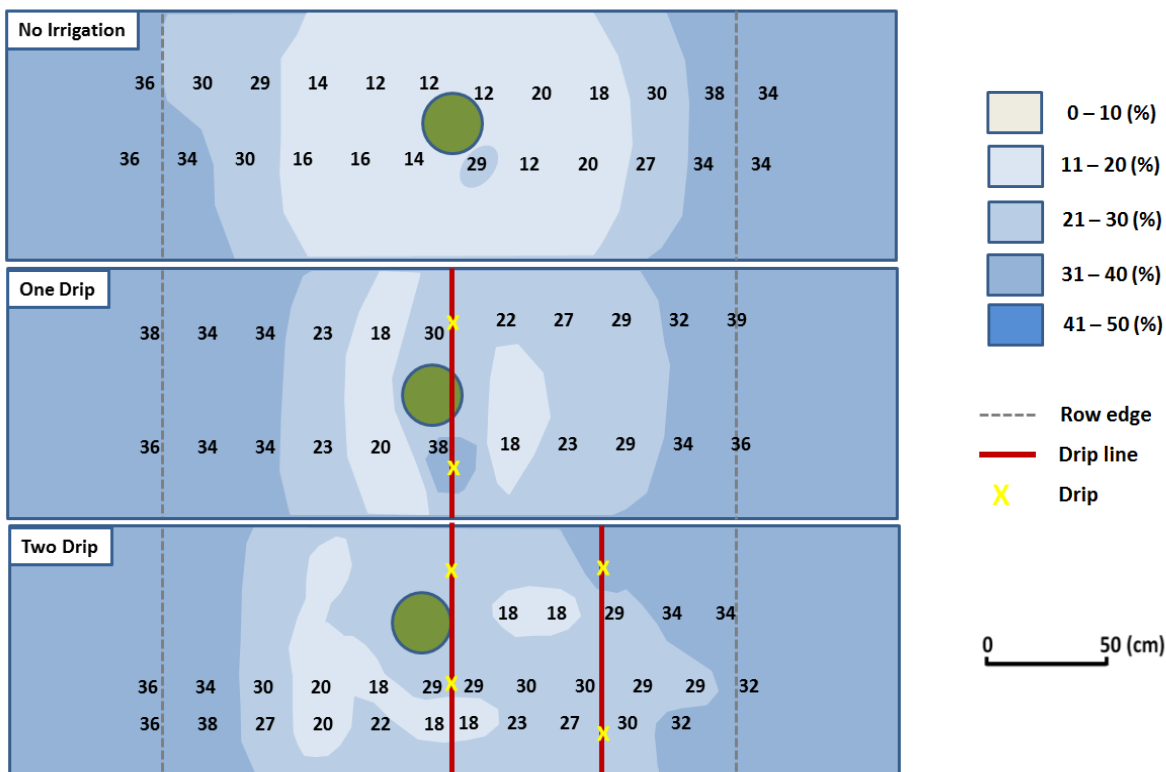


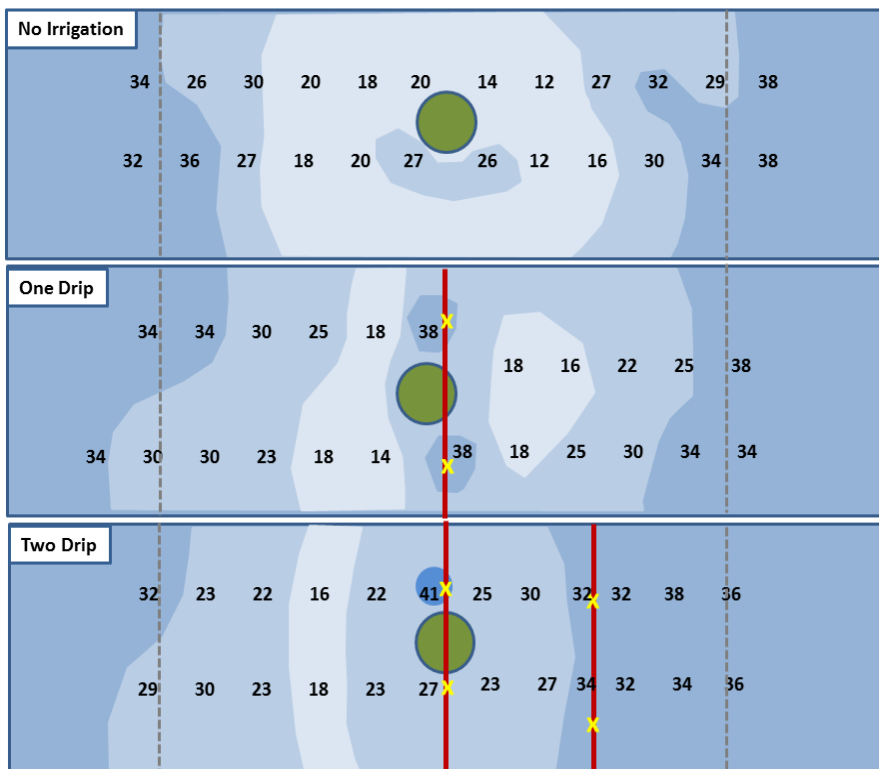
Figure 6. Vertical soil moisture profiles of the no irrigation (top), the one-drip (middle), and the two-drip (bottom) treatments, at the depth of 10, 20, 30, and 50 cm observed from December 2013 to April 2014. Regular small fluctuations are irrigation events, and gaps are periods when irrigation system failed (red arrows).

Spatial soil moisture

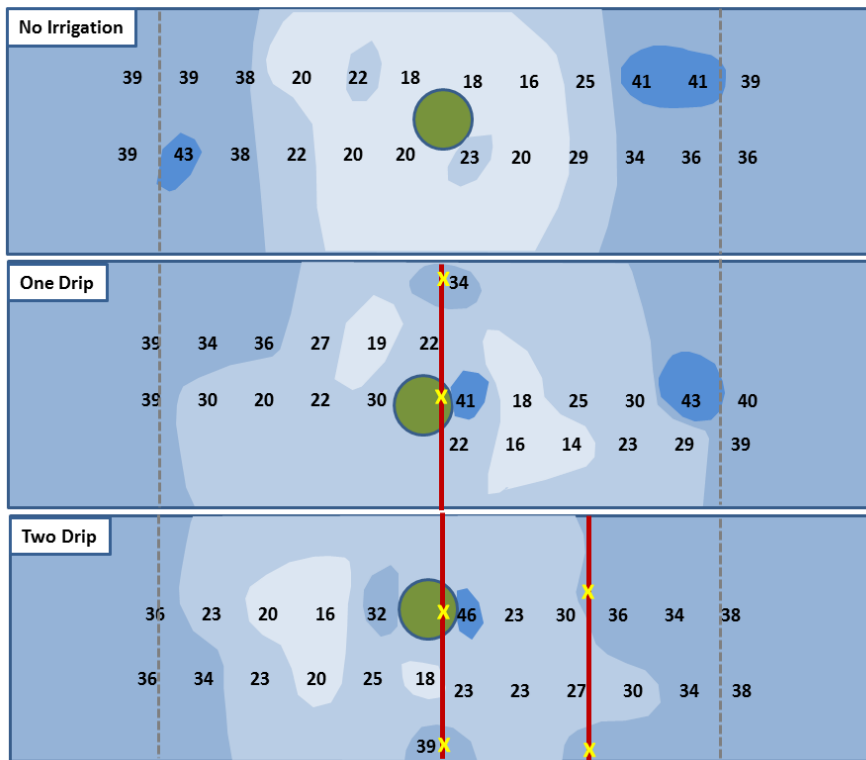
21/12/2013



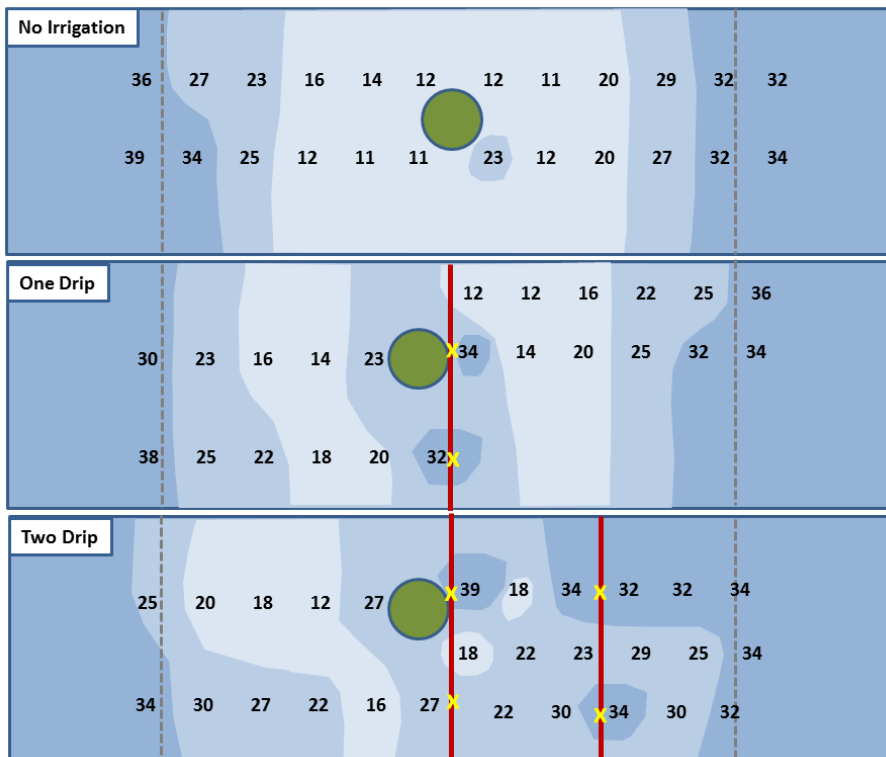
03/01/2014



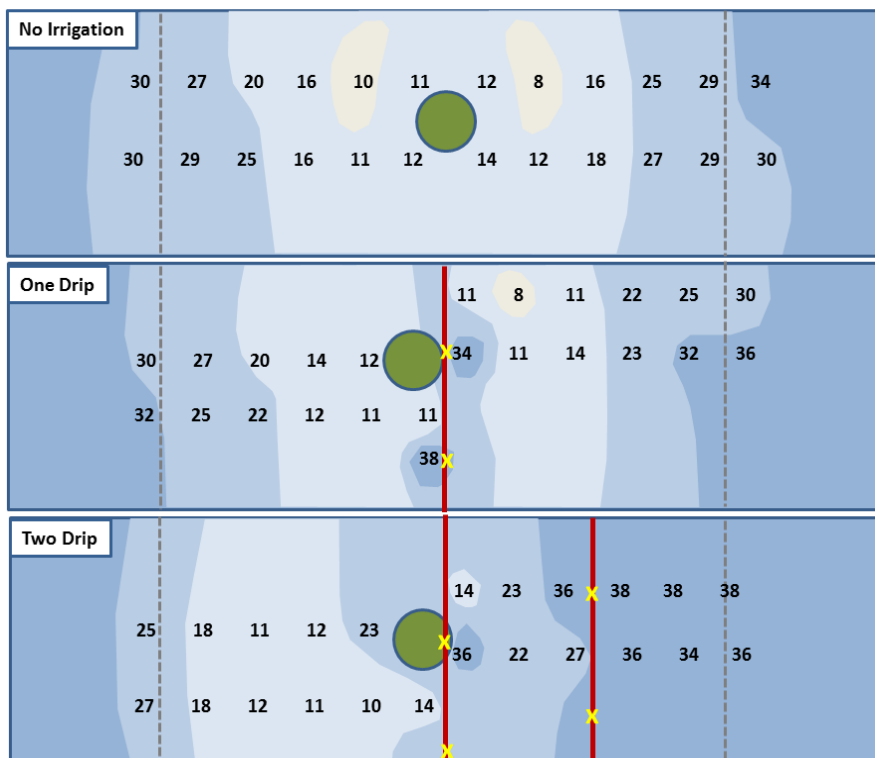
10/01/2014



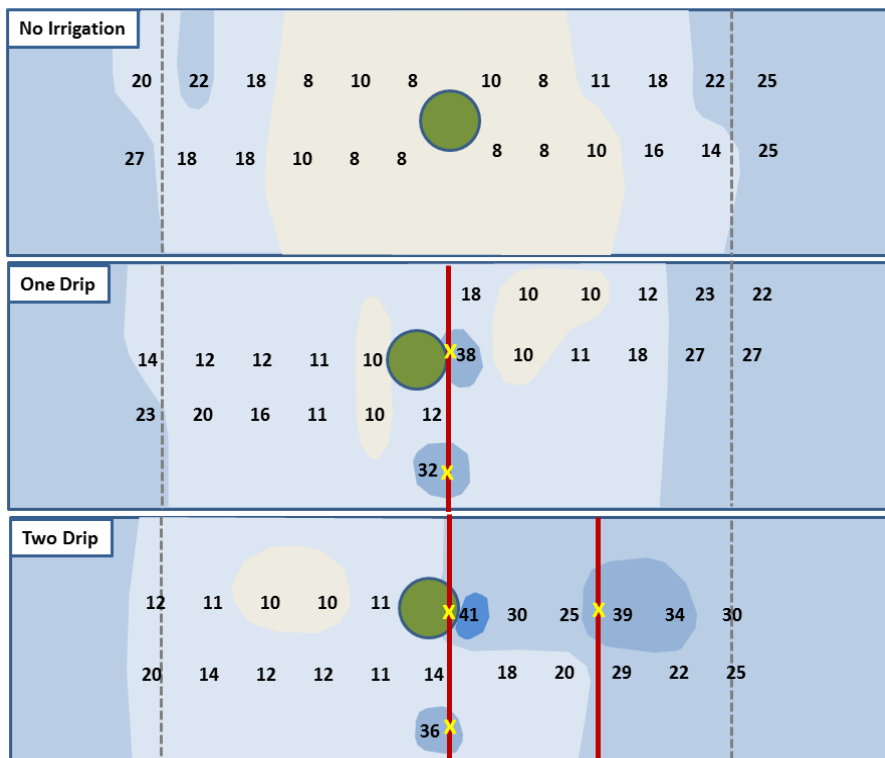
25/01/2014



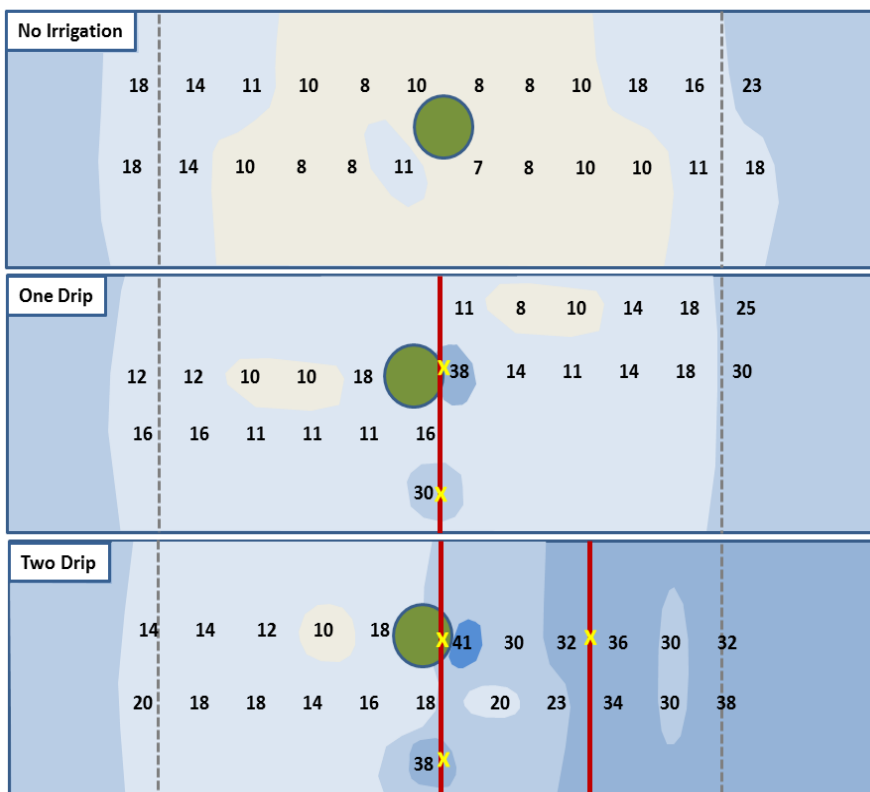
10/02/2014



26/02/2014



18/03/2014



29/03/2014

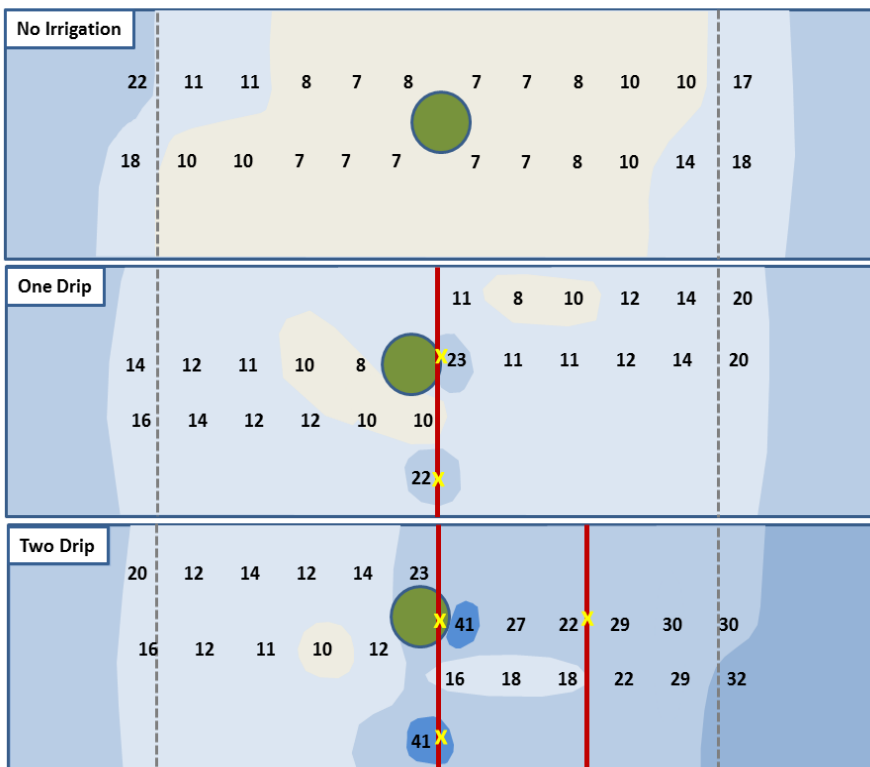


Figure 7. Spatial soil moisture distribution in the top 10 cm of soil of the no irrigation, one-drip and two-drip treatments, measured from December 2013 to March 2014. The values shown are the actual soil moisture measurements, and the colours have been drawn to approximate zones of similar water content.

Root distribution

Root density was most closely related to distance from the plant and depth (Fig. 8), rather than distance from the irrigation emitters (not shown). Approximately 83 % of total fine roots were within the upper 30 cm of soil, with the highest root density at the depth of 21-30 cm. The density of roots declined with increasing distance from the plants, extending to a maximum of approximately 95 cm. Root density decreased rapidly below a depth of 30 cm, but approximately 4 % of total fine roots were found between depths of 41-60 cm, indicating that water can be withdrawn from these depths.

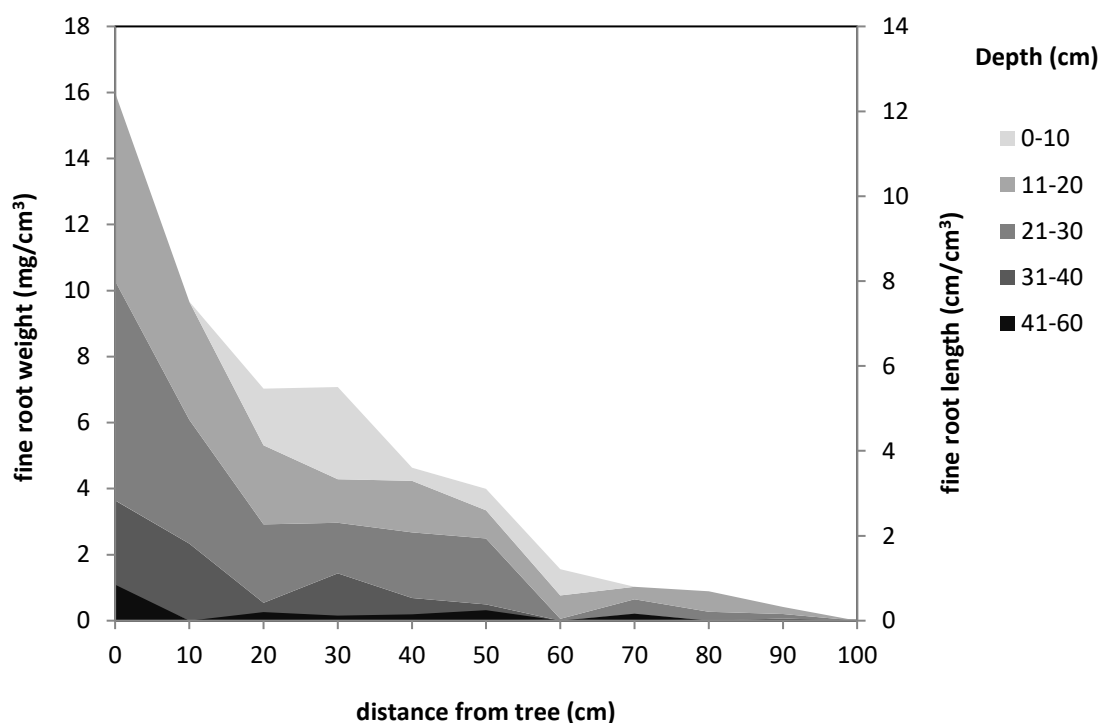


Figure 8. Distribution of blueberry roots (fresh weight and length per cm³) as a function of distance from the nearest plant and depth from the soil surface.

Leaf water potential and stomatal conductance

As Fig. 9 shows, all treatments had similar predawn leaf water potential until the end of January, and there were no significant differences between the non-irrigated and the irrigated treatments ($P > 0.05$). However, leaf water potential of the no irrigation plants started to

decline from -0.06 MPa in late-January to -0.18 MPa in February, and to below -0.2 MPa in March, while the one-drip and two-drip treatments had stable leaf water potential values around -0.05 MPa. These differences between the non-irrigated and irrigated treatments were statistically significant ($P < 0.05$). In late-April, leaf water potential of the no irrigation treatment increased, and all treatments had a value of around -0.05 MPa at the end of the experiment.

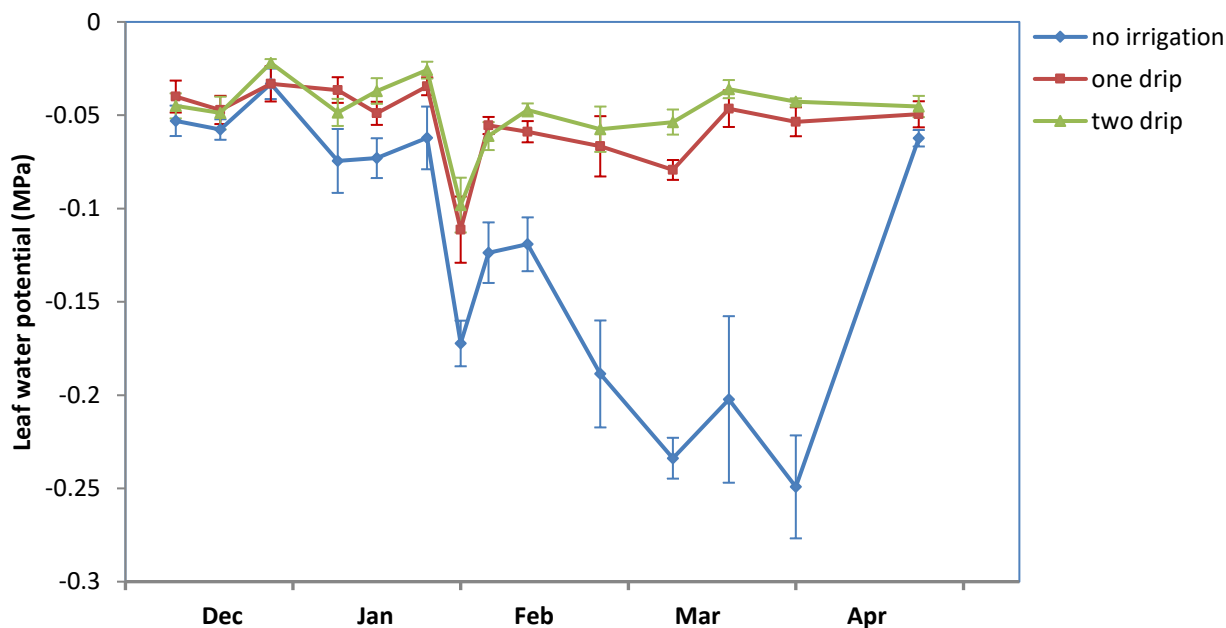


Figure 9. Predawn leaf water potentials of the no irrigation, one-drip and two-drip treatments, measured from November 2013 to April 2014. Values are means of 6 leaves per treatment with standard error bars.

Midday leaf water potentials differed between treatments in early February, but there was no differences in stomatal conductance (Fig. 10). On average, the non-irrigated plants had lower midday leaf water potentials at -0.81 MPa, whereas the one-drip and two-drip plants had slightly higher values at -0.631 and -0.57 MPa respectively. The differences in water potential between the non-irrigated and irrigated plants were statistically significant ($P < 0.01$). However, there were no significant differences in stomatal conductance among the three treatments on these dates. The averages of stomatal conductance of the no irrigation treatment was $0.12 \text{ mol m}^{-2}\text{s}^{-1}$, the one-drip treatment was $0.133 \text{ mol m}^{-2}\text{s}^{-1}$, and the two-drip treatment was $0.126 \text{ mol m}^{-2}\text{s}^{-1}$ ($P > 0.05$).

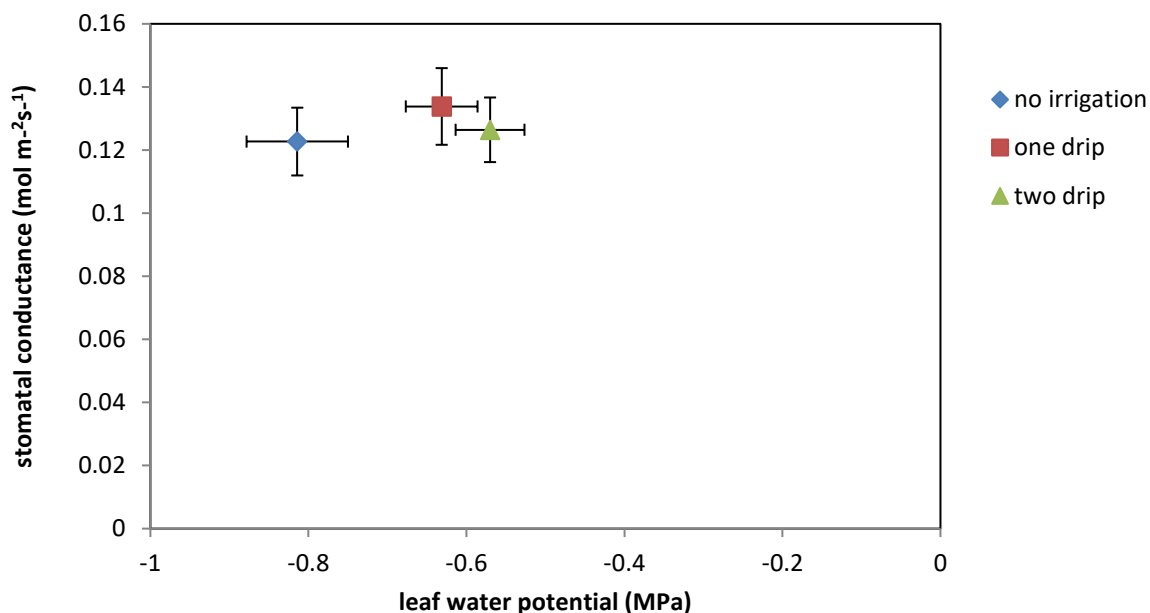


Figure 10. Relationship between leaf stomatal conductance and midday leaf water potential of the no irrigation, one-drip and two-drip treatments, measured on 4th and 5th of February. Each symbol represents the mean and standard error bars. Values for leaf water potential are means of 18 leaves per treatment and values of stomatal conductance were means of 36 leaves per treatment.

Shoot growth

Shoot elongation (Fig. 11a) and diameter growth (Fig. 11b) rates decreased steadily over the measuring period from December 2013 to March 2014.

The averages of upward branch elongation of the no irrigation, one-drip and two-drip plants were 7.18, 7.96, and 6.81 mm/day in December 2013, and declined to 5.13, 5.72, and 5.43 mm/day in January, to 2.30, 2.69 and 2.88 mm/day in February, respectively. In March, the average stem elongation of the non-irrigated plants was 0.47 mm/day, while the one-drip grew by 0.75 mm/day and the two-drip by 0.86 mm/day, but these differences were not statistically significant ($P>0.05$).

Diameter growth of these stems also showed a continuous decline. From December to March, the average diameter growth of the non-irrigated plants dropped more quickly from 0.036 to 0.0028 mm/day compared to the one-drip treatment, which decreased from 0.032 to 0.013 mm/day, and the two-drip from 0.035 to 0.014 mm/day. These differences were statistically significant ($P<0.01$).

The side stems grew more slowly, compared with the upward stems. In December, stem lengths grew only 0.632 mm/day on the no irrigation, 0.602mm/day on the one-drip, and

0.484 mm/per day on the two-drip treatments, but all of observed side stems stopped growing in length from mid-January, even though the diameter of these stems continued to increase until the end of the measuring period. In March, the non-irrigated plants had slower diameter growth (0.002 mm/day) than the one drip and two drip (0.005 mm/day), but these differences were not statistically significant ($P>0.05$).

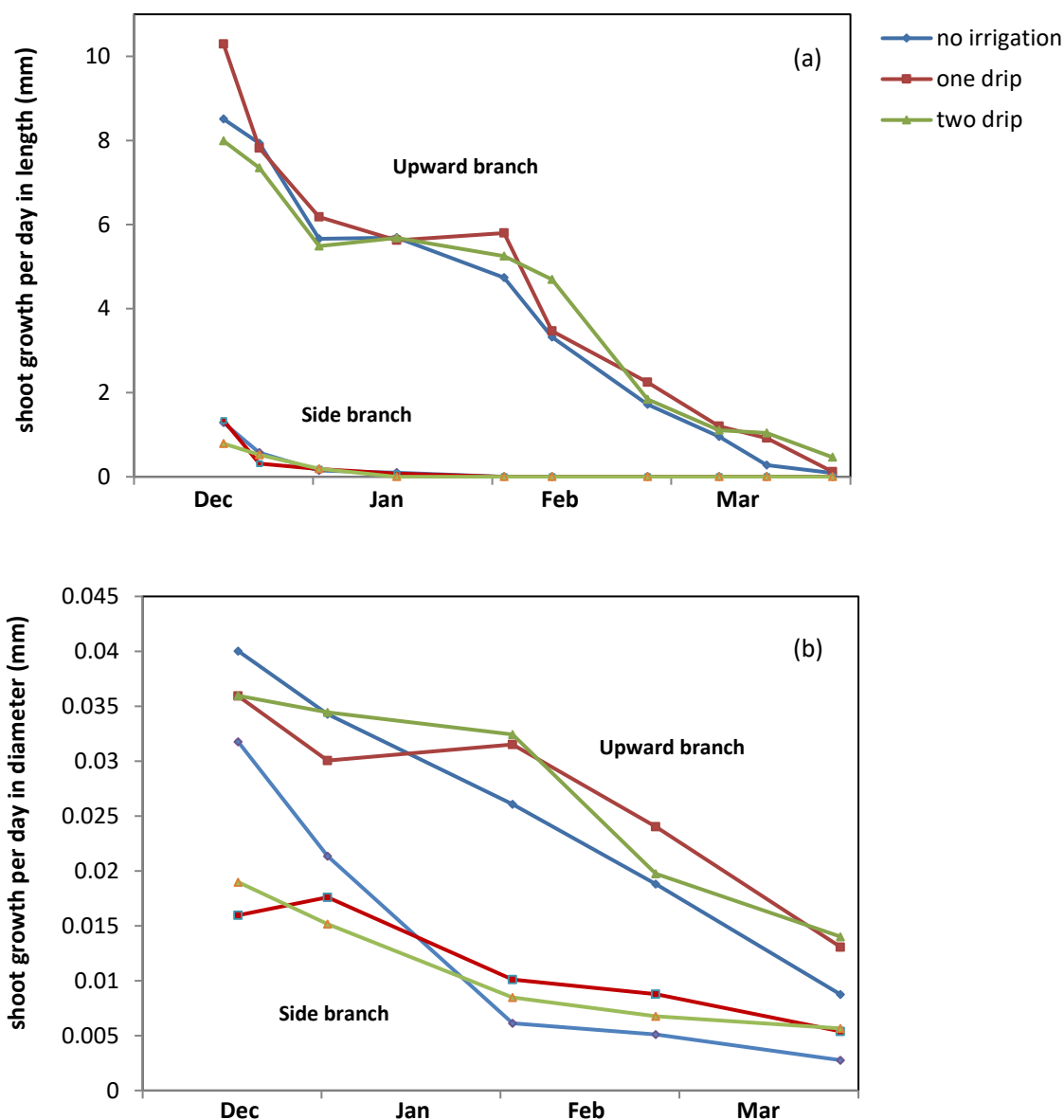


Figure 11. Average of shoot growth per day in length (a) and in diameter (b) for the no irrigation, one-drip and two-drip treatments from December 2013 to March 2014 ($n=6$). Shoots are categorized into two types; upward branch and side branch.

Fruit growth

Fruit exhibited continuous growth over the summer (Fig. 12). The mean fruit weight at the first observation was 0.3 g in mid-November, and fruit in the three treatments all increased in size in December and January. During this period the non-irrigated plants had a slightly bigger average fruit size than the average of the one-drip or two-drip plants, but these differences were not statistically significant ($P>0.05$). Significant differences in fruit growth between the non-irrigated and irrigated treatments appeared during the late harvest period. Fruit size of the no irrigation treatment reached a maximum of 0.9 g in February, then started decreasing in early-March, as opposed to the one-drip and two-drip treatments which showed continuous fruit growth up to a maximum size of 1.0 g in March.

Comparison between the different fruit size classes revealed that the effect of drought on fruit growth varied with the stage of development. The large (early) fruit had reached maximum size by the beginning of the harvest season, and they started to decrease in size after fully ripening, exhibiting visible shrivelling. There were no clear effects of irrigation on fruit size for these fruit, except for a more pronounced decrease in fruit size on the final measurement date. Fruit of medium and small size classes completed the lag phase and began to mature later than the large fruit. In March both small and medium classes showed differences in fruit growth between the non-irrigated and irrigated treatments. Non-irrigated fruit grew more slowly (small fruit) or decreased in size (medium fruit), while fruit of both size classes on irrigated plants continued to increase in size (Fig. 12a, b, c).

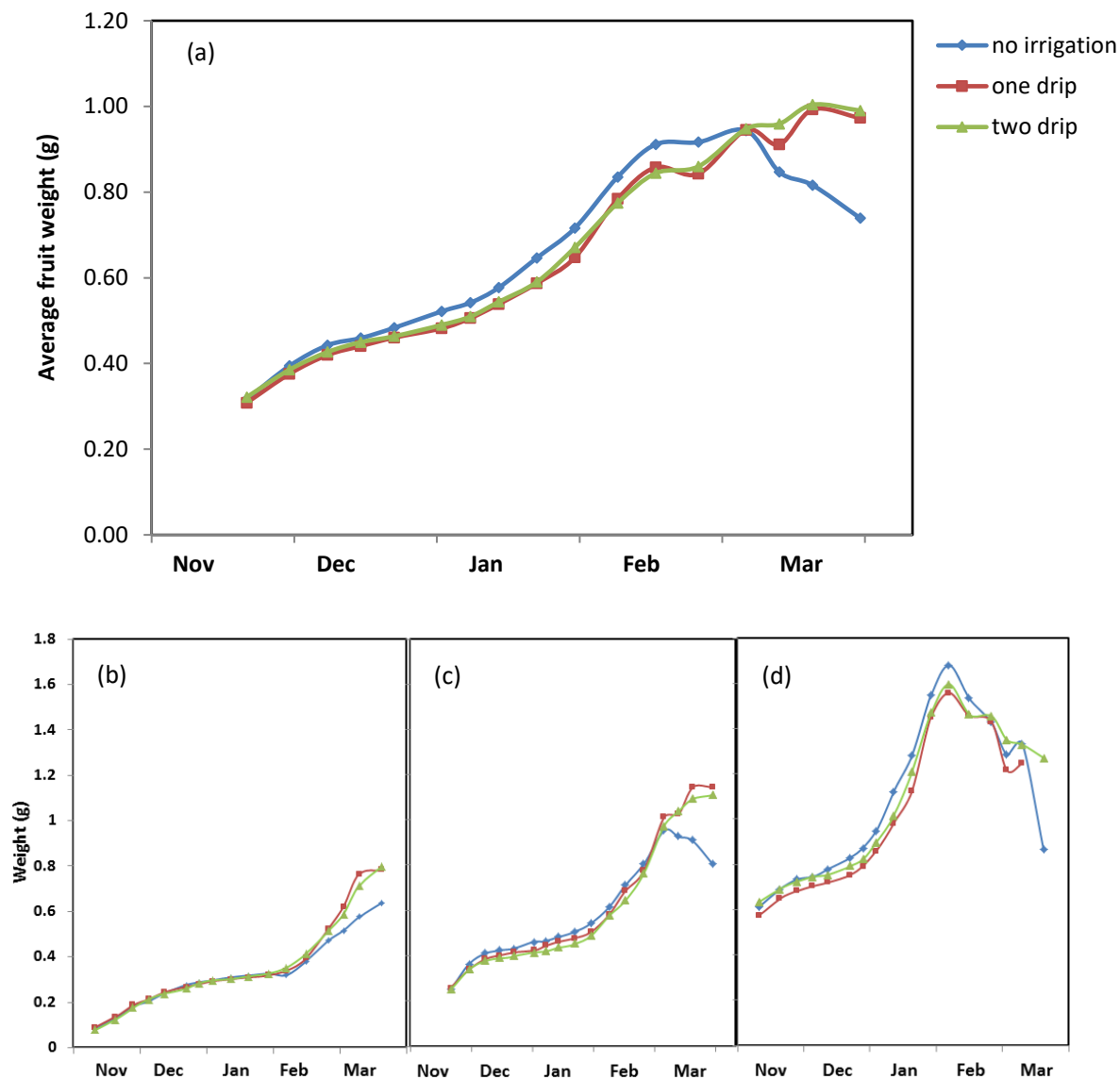


Figure.12. Average fruit weight (g), measured non-destructively using callipers from November 2013 to March 2014 for the three irrigation treatments. The overall average of fruit size (n=90) (a), and the average fruit size by three initial size classes; small (n=30) (b), medium (n=30) (c), and large (n=30) (d).

Harvest and fruit quality

There were 5 harvests during the season, beginning from mid-January, reaching a peak in February, and then finishing at the end of March (Fig. 13). Overall, the no irrigation treatment had the highest total yield at 16.15 (SD±2.73) kg/plant, whereas the two-drip treatment had a slightly lower total yield of 14.45 (SD±3.18) kg/plant, and the one-drip treatment had the lowest value of 12.22 (SD±1.11) kg/plant.

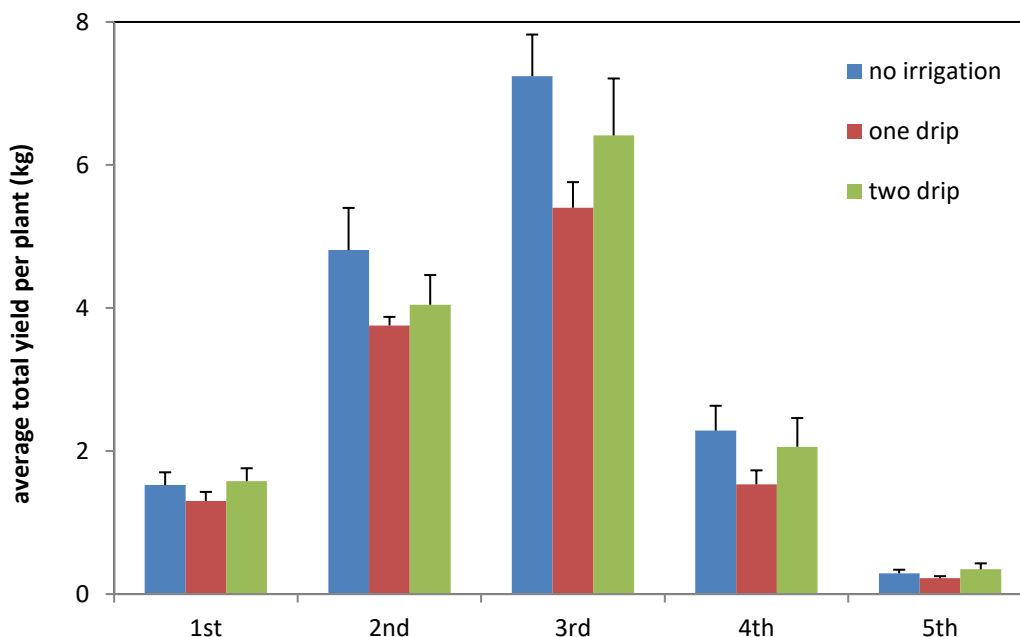


Figure 13. Average total yield per plant at 5 harvests for the three treatments (no irrigation, one-drip and two-drip). Each column presents the mean value of 3 plants and standard error. There were 5 harvests during the season on 22 Jan, 4 Feb, 25 Feb, 15 Mar, and 31 Mar, 2014.

The average of individual fruit size, firmness and brix are shown in Fig. 14. Throughout the harvest season, fruit size became smaller regardless of the treatment types, but the no irrigation treatment had a sharper decline from the 1st harvest at 2.069 (SD±0.050) g to the 5th harvest at 0.781 (SD±0.022) g, compared with the one-drip treatment which went from 2.039 (SD±0.097) g to 1.036 (SD±0.037) g or the two-drip treatment from 2.151 (SD±0.040) g to 1.103 (SD±0.032) g (Fig. 14a). In contrast, fruit brix increased over the season. From the 1st to 3rd harvests, the three treatments had similar brix values at around 12 %. However, the average brix of the non-irrigated plants increased dramatically to 17.82 (SD±0.15) % at the 5th harvest, whereas fruit brix of the one-drip and two-drip treatments showed only small increases up to values at the final harvest of 14.36 (SD±0.31) % and 14.31 (SD±0.51) %, respectively (Fig. 14b). Fruit firmness also increased from the 3rd to 5th harvests among the three treatments (Fig. 14c). At the 4th and 5th harvests, the differences in fruit weight, brix and firmness between the non-irrigated and irrigated plants were all significant ($P<0.01$). Also, the regression analysis from all samples of 4th and 5th harvests resulted in a weak negative correlation between fruit size and fruit firmness ($R=0.398$, $n=540$, $P<0.01$) (Appendix, Fig. 17).

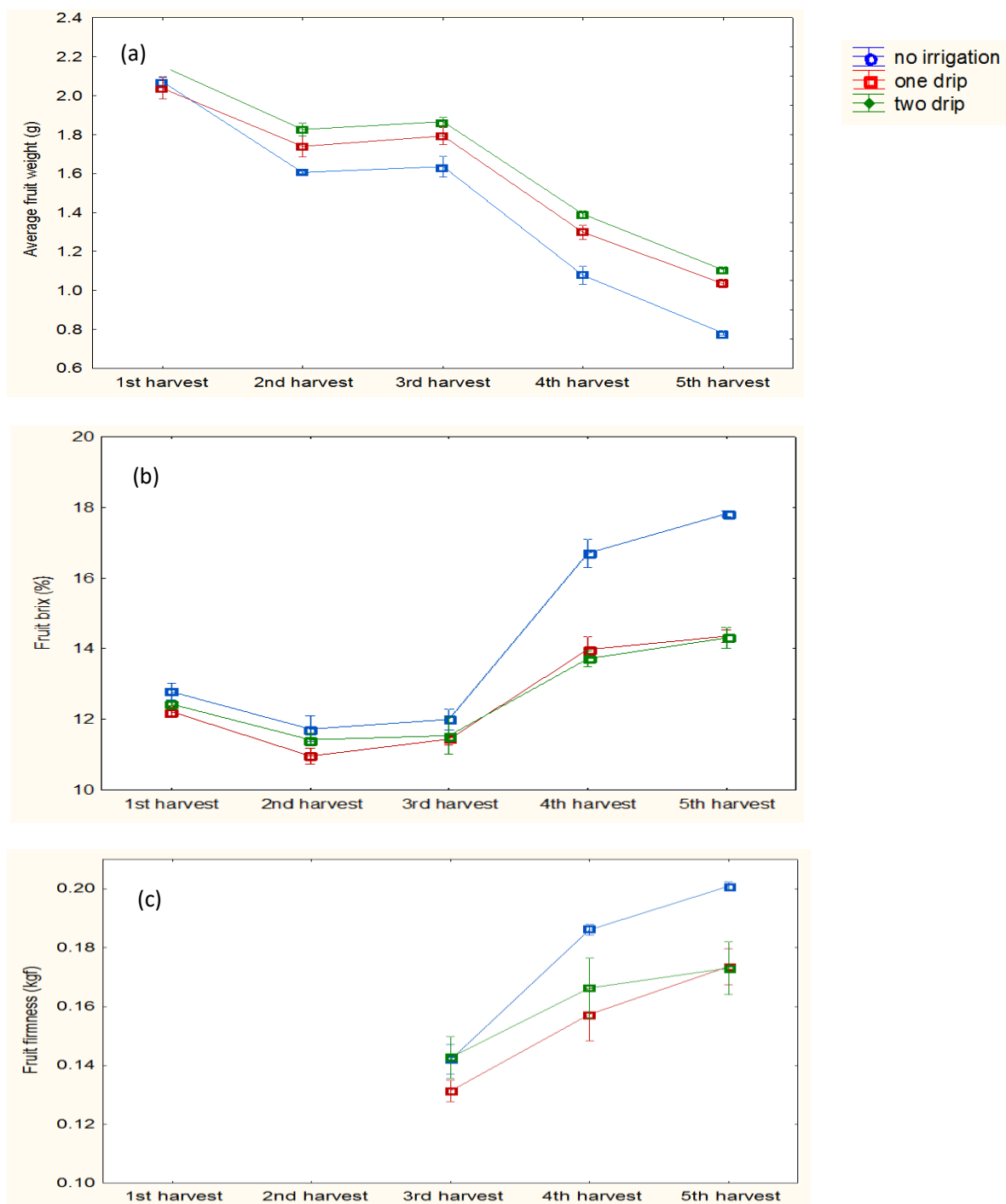


Figure 14. Individual fruit size (a), brix (b), and firmness (c) at harvest for the no irrigation, one-drip and two-drip treatments. Each symbol represents the mean of three plants and standard error bars. The differences in fruit size, brix and firmness between the non-irrigated and irrigated treatments were all significant at the 4th and 5th harvests (ANOVA, $P < 0.05$).

Water balance

Over the 11 weeks between 12th December 2013 and 26th February 2014 total rainfall was 116 mm, and cumulative ET_0 was 337.6 mm. Cumulative E_{wb} (crop evaporation estimated

from the soil water balance) of the two-drip treatment was 18 % higher than cumulative ET_o (Table 2). In contrast, cumulative E_{wb} of the no irrigation treatment and one-drip treatment were 31 % and 15 % lower than ET_o , respectively. Weekly ET_o varied from 23 to 35 mm, while E_{wb} fluctuated, especially in the one-drip and two-drip treatments. Fluctuations in E_{wb} corresponded with rainfall events, suggesting that drainage was occurred during these events, resulting in corresponding fluctuations in daily crop factor (K_c). The weekly average crop factors presented in Table 2 and Fig. 15 were calculated after excluding periods affected by rainfall. The increase in crop factors in early January was probably due to overestimated E_{wb} following abundant precipitation, and the trend of increasing overall K_c with increasing irrigation is probably the result of a higher amount of unaccounted for drainage in the irrigation treatments.

Ignoring the fluctuations caused by rainfall, estimated weekly K_c for all treatments varied between 0.3 and 1.5. Across treatments K_c was approximately 0.5-0.7 from December until January, increasing to 0.8-1.1 over the fruit maturation and harvest period (Table 2, Fig. 15).

Table 2. Weekly water balance for rabbiteye blueberry ‘Maru’ in Oakberry Orchard for the no irrigation, one-drip and two-drip treatments for 11 weeks from 12 December 2013 to 26 February 2014. ET_o Penman-Monteith FAO reference evapotranspiration; E_{wb} crop water use estimated from the balance of soil moisture, irrigation and rainfall (see methods); K_c , crop factor, the ratio of crop water use to ET_o .

week		Rain (mm)	ET_o (mm)	Irrigation (mm)		Change in soil moisture (mm)			E_{wb} (mm)			K_c		
				One drip	Two drip	No drip	One drip	Two drip	No drip	One drip	Two drip	No drip	One drip	Two drip
1	12 Dec – 18 Dec	11	35.7	13.4	26.9	-8.4	-2.3	2.3	19.4	26.8	40.2	0.5	0.6	0.8
2	19 Dec – 25 Dec	7	33.2	13.4	26.9	-9.0	-0.2	-1.5	16.0	20.6	35.3	0.3	0.4	0.8
3	26 Dec – 1 Jan	26	27.3	13.4	26.9	1.5	-0.1	-0.4	24.5	39.6	53.2	-	-	-
4	2 Jan – 8 Jan	10	33.8	7.7	15.4	-5.5	-2.5	-1.9	15.5	20.1	27.3	0.3	0.4	0.6
5	9 Jan – 15 Jan	18	30.5	13.4	26.9	-0.6	0.1	-0.2	18.6	31.4	45.0	0.5	0.7	1.2
6	16 Jan – 22 Jan	10	28.2	5.8	11.5	-7.8	-5.9	-3.5	17.8	21.7	25.0	0.4	0.6	0.6
7	23 Jan – 29 Jan	19	33.1	10.6	21.1	-0.1	-1.1	3.8	19.1	30.6	36.3	0.5	0.6	0.5
8	30 Jan – 5 Feb	0	35.0	12.48	25.0	-31.5	-10.1	-0.9	31.5	22.6	25.9	0.9	0.7	0.8
9	6 Feb – 12 Feb	11	27.3	12.8	25.5	-14.7	-5.2	-0.2	25.7	29.0	36.7	0.9	0.7	1.1
10	13 Feb – 19 Feb	4	23.8	17.5	34.9	-20.7	0.2	3.2	24.7	21.3	35.8	1.1	1.0	1.5
11	20 Feb – 26 Feb	0	29.9	17.5	34.9	-19.0	-5.9	-2.1	19.0	23.4	37.0	0.6	0.8	1.3
Total		116	337.6	138.0	275.9	-115.8	-33.0	-1.3	232.8	287.0	397.7			

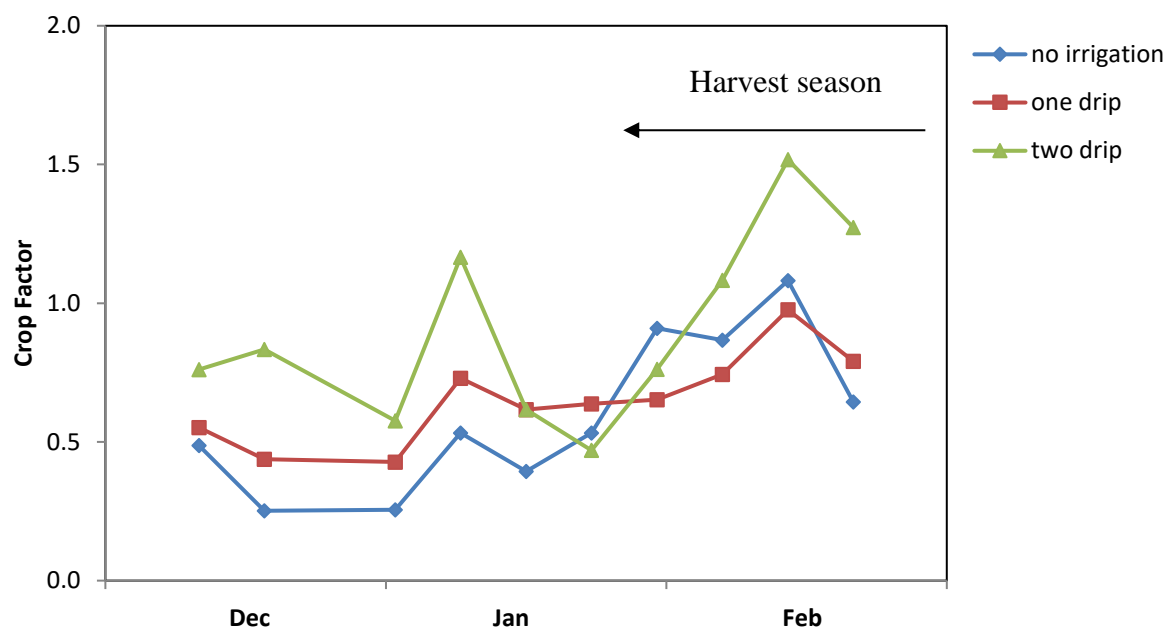


Figure 15. Weekly crop factor (K_c) for the no irrigation, one-drip and two-drip treatments for 11 weeks from 12 Dec 2013 to 26 Feb 2014, including part of the harvest season.

Discussion

Over the growing season reported here the temperatures were slightly below the average for the Waikato region, and rainfall levels were less than half of that normally received (Niwa climate summaries, <https://www.niwa.co.nz/climate/summaries>), particularly over the second half of the summer. Dry conditions created strong differences between the three irrigation treatments, especially in February and March.

Soil water availability and water stress on plants

Even though soil moisture gradually declined, the non-irrigated plants did not show any signs of water deficit from December 2013 to late-January 2014. These plants were probably able to obtain enough water from precipitation and the soil profile, so there was no difference in predawn leaf water potential or fruit growth between the non-irrigated and irrigated treatments.

Soil water content of the no irrigation treatment decreased dramatically starting from late-January, with the declines apparent in both the vertical and horizontal soil moisture profiles. Also, water stress on non-irrigated plants was reflected in predawn leaf water potential, with clear decline in February and March compared to the irrigation plants. These decreases in soil moisture and leaf water potential in February and March were probably caused by both a decrease in precipitation and an increase in water use by the plants during fruit ripening (Bryla & Strik 2007). Increasing soil moisture in the vertical profile and leaf water potential in April can be explained by rewatering from precipitation and lowering plant water use after the harvest season (Bryla 2011).

In general, the roots of highbush blueberry are concentrated in the top 50 cm or less of the soil profile with the highest root density at 10–20 cm (Bryla & Strik 2007; Holzapfel 2009). Rabbiteye cultivars tend to have a deeper root system than highbush cultivars (Bryla 2011). We identified the highest root densities at 21–30 cm from the surface, as well as the presence of roots at depths of 41–60 cm. According to the vertical soil moisture measurements, the no irrigation treatment showed a decline in soil water content at a depth of 50 cm. This suggests that the non-irrigated plants were withdrawing water from the deeper soil layers (>40 cm) during the dry conditions in late summer, explaining the delayed onset of the effects of water stress in this treatment.

The spatial soil moisture distribution clearly demonstrated increasing soil moisture with increasing irrigation, as the no irrigation treatment had the lowest and the two-drip treatment had the highest water contents at the soil surface throughout the observation period. In our experiment, the two-drip treatment had not only a higher irrigation level but also a larger wetted surface area, and this might be beneficial for plants with a shallow rooted system (Ehret et al. 2012). However, in our experiment, the position of the drip lines of the two-drip treatments was problematic. Because the second drip line was added temporarily on one side of the row, water was not evenly distributed surrounding plants, increasing the spatial variability in soil moisture. If multiple drip lines are to be installed during orchard establishment, they should be positioned more evenly on both sides of the row.

In many plants including blueberry, stomata close during the day in response to water stress (Bryla 2011). Ameglio et al. (2000) and Bryla & Strik (2006) observed that highbush blueberry showed a decrease in stomatal conductance when plants were water stressed. However, our measurement on rabbiteye blueberry did not detect any significant differences in stomatal conductance between the non-irrigated and irrigated treatments, although midday leaf water potential of the non-irrigated plants was significantly more negative compared with the irrigated plants. This might be because our measurements of stomatal conductance were made only in early February, early in the drought period, and because rabbiteye blueberry is probably more drought tolerant than highbush blueberry (Haman et al. 1997). A decline in stomatal conductance on the non-irrigated plants probably would have been observed if the measurements were repeated in late-February or early-March.

Plant growth and fruit quality

Shoot growth declined in all treatments over the measuring period. Shoot elongation of upward branches became slower, especially during the harvest season, and all of the side branches stopped growing in length in January, even though they continued to grow in diameter. Bryla (2011) reported that shoot growth declined after fruit maturation starts. Following a period of fruit ripening, fruit becomes a strong sink for carbohydrates and other nutrients, and it causes less availability of resources to vegetative parts of plants. Mingeau et al. (2001) also stated that the shoot elongation growth period is typically short relative to the diameter growth period. The results of our research were consistent with their findings. In our research, there were no obvious differences in vegetative shoot elongation growth between

the three treatments. However, water deficit influenced diameter growth of the non-irrigated plants, probably because diameter growth continued for longer into the drought period. A decrease in diameter growth of side branches could reduce the production of flower buds in mid to late-summer, consequently, this would affect the following year's harvest.

Non-destructive fruit growth data showed all treatments had similar fruit growth until January, but there was an earlier decline in non-irrigated fruit growth and size in the late harvest season, compared to irrigated fruit. Fruit growth was similar in the one-drip and two-drip treatments over the summer. These results agree with fruit size measured at harvest, as the average fruit weight of the no irrigation treatment dropped more rapidly with successive harvests compared to the one-drip or two-drip treatments.

Water status throughout ripening is important, because there is a correlation between irrigation levels and fruit sizes (Ehret et al. 2012; Holzapfel et al. 2004; Perrier et al. 2000). In our experiment, the water deficit brought a large impact on fruit growth of the no irrigation plants, especially on the 4th and 5th harvests. Compared with the no irrigation treatment, the one-drip treatment increased the average fruit size by about 12 % at the 4th harvest and 13 % at the 5th harvest, and compared with the one-drip treatment, the two-drip treatment had a larger average fruit size by 7 % at the 4th harvest and 9 % at the 5th harvest. These results clearly demonstrate increasing fruit size with increasing irrigation. Fruit size is most sensitive to plant water status during the middle of the third stage of growth. In this experiment the timing of the dry period meant that the growth of the two smaller size classes of fruit and average fruit size on the final two harvest dates were the yield variables most strongly affected by irrigation. If the dry period had occurred earlier then fruit size and yield from the three earlier harvests would have been more strongly affected by irrigation.

Despite smaller fruit size, the no irrigation treatment had higher total yield than the one-drip or two-drip treatments. We did not count the number of fruit per tree, but it can be assumed that the non-irrigated plants had more fruit than the one-drip or two-drip plants due to variation between plants. Plant 1 of the two-drip treatment was visually smaller relative to the other trees in our experiment. This small plant had the lowest yield of berries, contributing to the lower total yield of the two-drip treatment. If resources allow, the treatment plots for an irrigation experiment should be much larger than 5 plants. Holzapfel et al. (2002) reported the irrigation level is positively correlated with the number of fruit set on a plant. However, our research started in mid-November 2013, after the fruit had already set, so our experiments

could not have affected fruit set. In this experiment, the effect of irrigation on average fruit size is the most appropriate indicator of the potential effects of irrigation on total yield.

Furthermore, the irrigation treatments affected not only fruit size, but also fruit quality. The irrigated blueberries were larger and had lower brix and firmness than non-irrigated fruit during the late harvest period. Lower brix of irrigated fruit is probably due to a dilution effect by irrigation (Bryla 2008; Ehret et al. 2012). In addition, as Bryla (2008) observed, fruit with a higher water content may have lower firmness. However, Ehret et al. (2012) found that increased fruit size in response to irrigation was not correlated with decreasing fruit firmness. In our observation, the correlation between fruit firmness and fruit size was weak, suggesting that firmness is not strongly associated with fruit size. We also observed that berries exhibiting signs of shrivel during the later harvests were more likely to give higher firmness measurements, suggesting that increased firmness and brix in the no irrigation treatment was caused by berry dehydration. Increased firmness by this mechanism is probably not a positive indicator of fruit quality.

Water balance

Until mid-January 2014, there was no visual crop drought stress, and the estimated crop factors (K_c , ratio of crop water use to ET_o) were 0.5-0.7. During the harvest season, especially in February, additional irrigation was necessary as the crop factors increased without precipitation to 0.8-1.1. By week 11 (late February), the crop factors of the no irrigation treatment may have been underestimated, because plants were subjected to water stress. The crop factors of the two-drip treatment were higher than the no irrigation or one-drip treatments. To estimate a water balance without access to drainage measurements we assumed zero loss of water to drainage during our water balance period, based on the lack of fluctuations in soil moisture measured at the depth of 50 cm. However, some drainage may have been occurring, particularly during the brief periods of rainfall and in the two-drip treatment. Any unaccounted for drainage will have resulted in over-estimation of K_c , explaining the fluctuation in K_c when rainfall occurred, and possibly contributing to the higher average K_c estimated for the two-drip treatment.

Conclusion

The results of this research clearly demonstrated the effects of water status on blueberry production, supporting the hypothesis that fruit yield and quality of this rabbiteye cultivar are positively influenced by irrigation. There was only a small increase in fruit size and no effect on vegetative growth between moderate and heavy irrigation, possibly because a significant water deficit did not occur until late in the growing season and the water status of these two treatments did not differ significantly. From this experiment it can be concluded that the capacity to irrigate at a rate equivalent to the single drip treatment used in this experiment should be considered a minimum for optimum fruit yield and quality. An additional one or two drip lines per row would increase the uniformity of soil moisture during low rainfall periods and shorten the irrigation periods needed, but careful attention would need to be paid to the amount of water applied to avoid over irrigation and loss of water and nutrient to drainage, and to avoid the risk of water logging. Based on the limited water balance presented here, crop factors of 0.5 to 0.7, rising 0.8 to 1.1 during fruit maturation appear to be appropriate for this combination of cultivar, climate and soil. Further research could consider crop water use, the level of irrigation and the position of the drip line in more detail, and the significance of irrigation for return bloom and yield over more than one season. In this experiment, water deficit affected the growth of fruit on non-irrigated plants in the current season, but the impacts of water stress on floral bud initiation, vegetative growth and the resulting fruit number and yields in the following season should also be considered.

A broader study toward general irrigation recommendations for the New Zealand blueberry industry as a whole would also need to consider the interactions between cultivar, soil type and time since development of the orchard.

Acknowledgements

This study was funded by Oakberry Farms Ltd. We thank Dan Peach for contributions and enthusiastic support, David Campbell, Louis Schipper and Dean Sandwell for guidance and the use of equipment. All photographs were taken by Dan Peach and the authors.

References

- Allen RG, Pereira LS, Raes D, Smith M 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Rome, FAO - Food and Agriculture Organization of the United Nations.
- Ameglio T, Le Roux X, Mingeau M, Perrier C 2000. Water relations of highbush blueberry under drought conditions. *Acta Horticulturae* 537: 273-278.
- Bryla DR 2008. Water requirements of young blueberry plants irrigated by sprinklers, microsprays and drip. *Acta Horticulturae* 792: 135-139.
- Bryla DR 2011. Crop evapotranspiration and irrigation scheduling in blueberry. In Gerosa, G ed. *Evapotranspiration – From measurements to agricultural and environmental applications*. Rijeka, Croatia, InTech. pp. 167-187.
- Bryla DR, Gartung JL, Strik BC 2011. Evaluation of irrigation methods for highbush blueberry – I. Growth and water requirements of young plants. *HortScience* 46: 95-101.
- Bryla DR, Linderman RG 2007. Implications of irrigation method and amount of water application on *Phytophthora* and *Pythium* infection and severity of root rot in highbush blueberry. *HortScience* 42: 1463-1467.
- Bryla DR, Strik BC 2006. Variation in plant and soil water relations among irrigated blueberry cultivars planted at two distinct in-row spacings. *Acta Horticulturae* 715: 295-300.
- Bryla DR, Strik BC 2007. Effects of cultivar and plant spacing on the seasonal water requirements of highbush blueberry. *Journal of the American Society for Horticultural Science* 132: 270-277.
- Bryla DR, Yorgey B, Shireman, AD 2009. Irrigation management effects on yield and fruit quality of highbush blueberry. *Acta Horticulturae* 810: 649-656.
- Byers PL, Moore JN 1987. Highbush blueberry plants in Arkansas. *HortScience* 22: 52-54.
- Ehret DL, Frey B, Forge T, Helmer T, Bryla DR 2012. Effect of drip irrigation configuration and rate on yield and fruit quality of young highbush blueberry plants. *HortScience* 47: 414-421.
- Fereres E, Soriano MA 2007. Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany* 58: 147-159.
- Haman DZ, Smajstrla AG, Pritchard RT, Lyrene PM 1997. Response of young blueberry plants to irrigation in Florida. *HortScience* 32: 1194-1196.

- Holzappel EA 2009. Selection and management of irrigation systems for blueberry. *Acta Horticulturae* 810: 641-648.
- Holzappel EA, Hepp RF 2002. Effect of irrigation on six years old bluetta blueberry plants. *Acta Horticulturae* 574: 253-259.
- Holzappel EA, Hepp RF, Marino MA 2004. Effect of irrigation on fruit production in blueberry. *Agricultural Water Management* 67: 173-184.
- Jara J, Holzappel E, Quinonez A, Soto M 2011. Evaluation of drip irrigation systems for blueberry orchards in South central Chile. *Acta Horticulturae* 889: 489-497.
- Kirda C, Cetin M, Dasgan Y, Topcu S, Kaman H, Ekici B, Derici MR, Ozguven AI 2004. Yield response of greenhouse grown tomato to partial root drying and conventional deficit irrigation. *Agricultural Water Management* 69: 191-201.
- Lampinen BD, Shackel KA, Southwick SM, Olson WH 2001. Deficit irrigation strategies using midday stem water potential in prune. *Irrigation Science* 20: 47-54.
- Liu F, Savic S, Jensen CR, Shahnazari A, Jacobsen SE, Stikic R, Andersen MN 2007. Water relations and yield of lysimeter-grown strawberries under limited irrigation. *Scientia Horticulturae* vol. 111, pp. 128-132.
- Mingeau M, Perrier C, Ameglio T 2001. Evidence of drought-sensitive periods from flowering to maturity on highbush blueberry. *Scientia Horticultuae* 89: 23-40.
- Perrier C, Mingeau M, Ameglio T 2000. Effects of water stress on transpiration, radial growth and yield in highbush blueberry. *Acta Horticulturae* 537: 923-928.
- Singleton PL 1991. *Soils of Ruakura – a window on the Waikato*. Lower Hutt, N.Z., DSIR Land Resources. p. 127.
- Tasa T, Starast M, Vool E, Moor U, Karp K 2012. Influence of soil type on half-highbush blueberry productivity. *Agricultural and Food Science* 21: 409-420.

Appendix

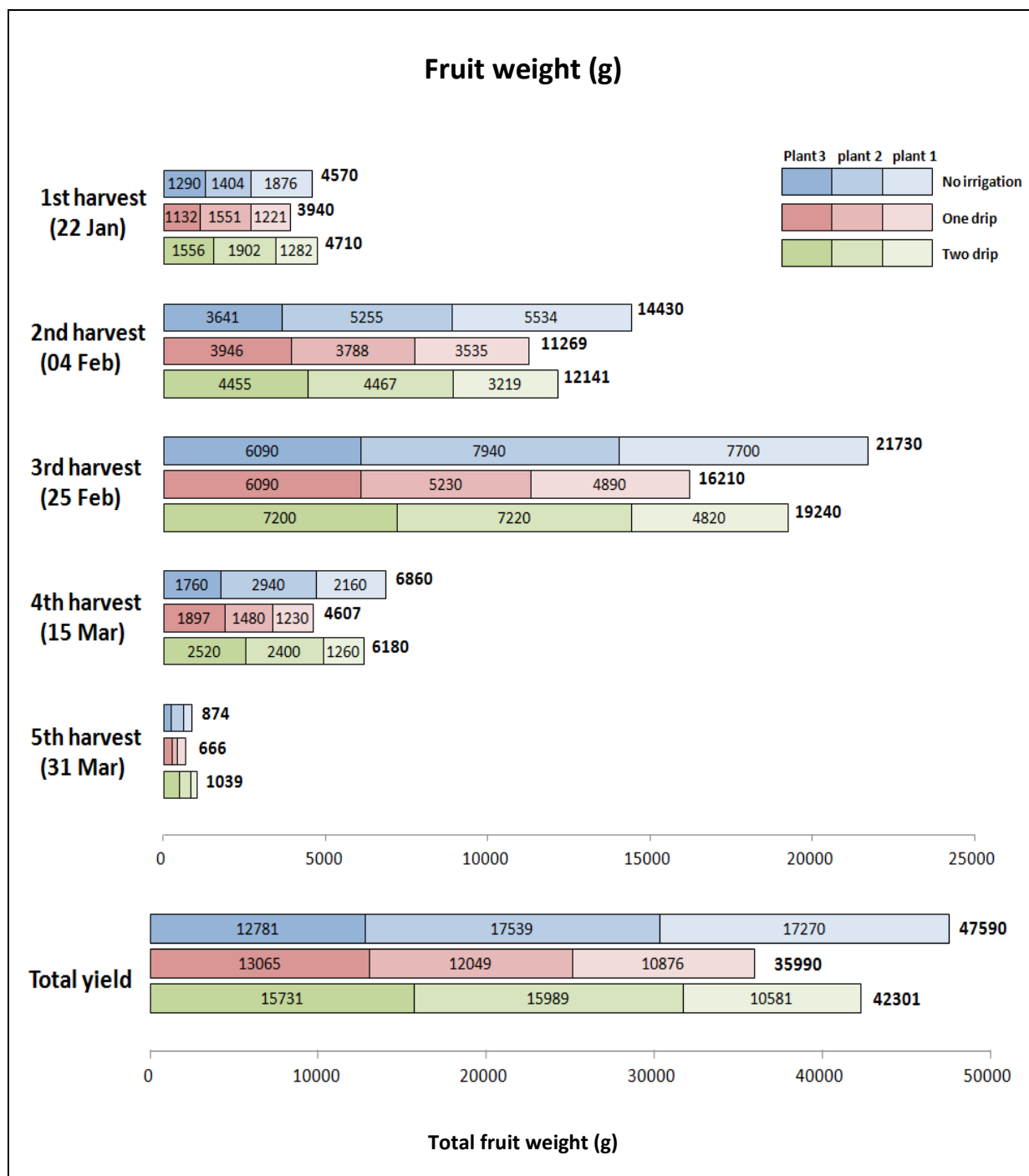


Figure 16. The total fruit yield in 2014. For the experiment, there were three trees per treatment, and 5 harvests during the season.

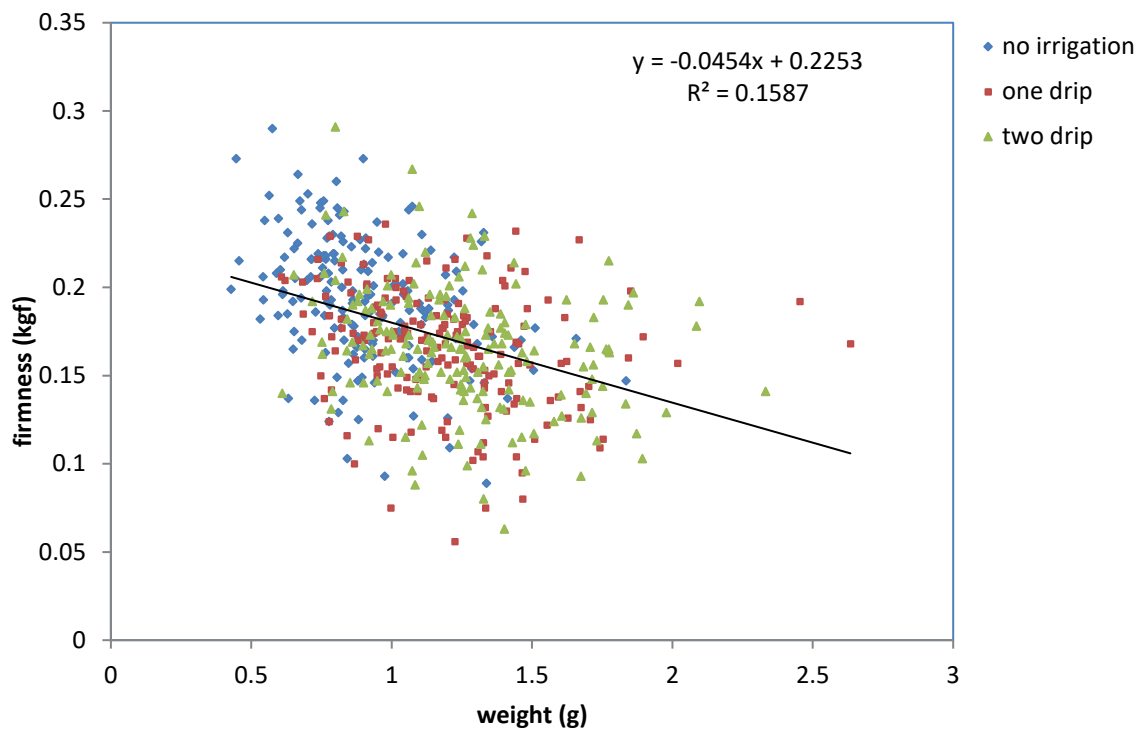


Figure 17. Relationship between fruit weight (g) and firmness (kgf) for all samples of 4th and 5th harvests.