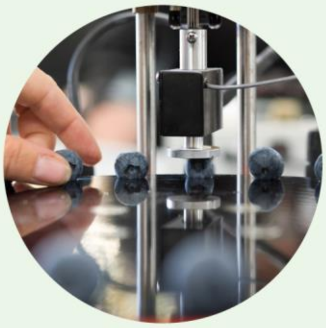







PFR SPTS No. 24618

Rootstock survival for New Zealand orchards

Khaembah EN, Gee M, Moore T, Brown H

October 2023

Report for:

Horticulture New Zealand Incorporated

PUBLICATION DATA

Khaembah EN, Gee M, Moore T, Brown H. October 2023. Rootstock survival for New Zealand orchards. A Plant & Food Research report prepared for: Horticulture New Zealand Incorporated. Milestone No. 98239. Contract No. 41263 var. Job code: P/445019/01. PFR SPTS No. 24618.

KEYWORDS: Modelling**,** rootstock water use, water stress, orchards.

Report prepared by:

Edith Khaembah
Scientist/Researcher, Cropping Systems and Environment
October 2023

Report approved by:

Penny Tricker
Science Group Leader, Cropping Systems and Environment – Sustainable Production
October 2023

Contents

Executive summary

Rootstock survival for New Zealand orchards

Khaembah EN, Gee M, Moore T, Brown H
Plant & Food Research: Lincoln

October 2023

The aim of this project was to provide an assessment of the impact of water stress on the short-term and long-term productivity of an orchard. The assessment was completed under three objectives.

- **Objective 1** – Review literature to identify key physiological responses associated with water stress in fruit tree crops,
- **Objective 2 -** Use information from reviewed literature and expert advice to guide the development of a fruit tree water use model using apple fruit tree as an example,
- **Objective 3 -** Use the model to run scenarios to evaluate the impact of water stress on apple productivity in the current and subsequent seasons.

This report presents details and findings associated with each objective.

A review of literature on fruit tree water stress (**Objective 1**) highlighted the following.

- Water stress reduces yield as plant growth is directly related to transpirational water loss. Leaf wilting, leaf curling, advanced leaf fall are some of the drought avoidance responses of fruit trees to water stress that reduce light interception and photosynthesis as a result of reduced leaf area.
- Fruit tree response to water stress is influenced by many factors including species, cultivar, soil properties, length and severity of water stress, tree age, and the stage of developmental stage (e.g., floral initiation). Regarding species, apples, apricots, pears, and plums are more drought-tolerant than nectarines, peaches and citrus.
- Reduced fruit size and fruit weight are some of the effects associated with water stress. Gross yield may not be affected, but reduced size and weight of fruit may not meet the quality standards of the market, leading to loss of revenue.
- Yield reduction may be temporary with growth restored when soil water is replenished to required volumes. However, growth restoration will depend on the severity of water stress and/or developmental stage.
- Severe water stress can reduce carbohydrate storage of perennial structures leading to reduced shoot length and branching which can negatively affect tree productivity in the following season. Experiments that evaluated the impact of water stress on shoot length and yield were used to calibrate the effect of water stress on the productivity of an apple orchard in the following season.

- We found no published information where water stress has been imposed to the level which resulted in tree death. Without this information, we could not model whole-tree death.

Objective 2 involved development and evaluation of a **S**imple **T**ree **R**esource **U**ptake **M**odel operating in the **A**gricultural **P**roduction **S**ystems s**IM**ulator (STRUM-APSIM). Model performance analysis indicated STRUM-APSIM captured temporal changes of measured variables. There was a strong agreement between measured soil moisture data (which included irrigation and soil type treatments) and predicted data as indicated by strong model performance indices; R^2 of 0.97, a high modelling efficiency (Nash-Sutcliffe model efficiency coefficient (NSE) of 0.95 and a low relative root mean squared error (rRMSE) of 10.7 implying that predicted values explained ~89% of the variation in the measured data. Performance indices were also strong for tree transpiration (R^2=0.97, NSE=0.51, rRMSE=35.6) and fruit weight (R^2=0.91, NSE=0.91, RMSE=17.6). The rRMSE (9.3) showed a strong agreement between simulated and measured radiation interception data, although the correlation and model efficiency coefficients were low (R^2=0.48 and NSE=0.24). The prediction accuracy demonstrated here indicated that STRUM-APSIM could be used to explore the effects of irrigation management on fruit tree productivity across a range of weather and soil conditions.

Objective 3 focused on the use of STRUM-APSIM to evaluate the effect of water stress on apple productivity across a range of conditions with the aim of estimating productive and survival irrigation water requirements. The impact of stress on the number of fruiting buds (assuming post-pruning density of 50 fruiting buds per square meter). Simulations were set up using a combination of climate (six sites) and soil (three types) data. The soil-climate combinations were evaluated across six irrigation treatments generated by progressive withholding of irrigation during the season. Soils ranged in available water capacity (0–100 cm depth) from 128 to 242 mm. Long-term (1972–2015) average annual rainfall and temperature from the sites' Virtual Climate Station Network data ranged from 432–1070 mm and 9.1–14.0°C, respectively. Simulations were run for 30 years to produce long-term averages of the effect of irrigation on the number of fruiting buds.

Conclusions from Objective 3 were:

1. The negative impact of water stress on the number of fruiting buds increased with length of withholding irrigation, reduced soil water storage capacity, reduced annual average rainfall and increased annual average temperature.
2. Based on the irrigation schedule implemented in this study and assuming that loss of fruiting buds should not exceed 10% of the target post-pruning numbers, the model estimated per season irrigation requirements of 0–371 mm (0–3710 m^3 ha^{-1}) for productive orchard and 0–255 mm (0–2550 m^3 ha^{-1}) for apple rootstock survival, depending on soil type and location.
3. There was wide variation in irrigation over the 30-year period of evaluation and an alternative (quantile) analysis indicated rootstock survival irrigation requirements of 0–226 mm (0–2260 m^3 ha^{-1}) and 339 mm (0–3390 m^3 ha^{-1}) at high and low risk tolerance levels, respectively. Details for individual locations and soil types are provided in Table 5.

For further information please contact:

Edith Khaembah
Plant & Food Research, Lincoln
Email: Edith.Khaembah@plantandfood.co.nz

Introduction

The New Zealand horticultural industry is a multi-billion-dollar industry with fresh and processed fruit exports in 2021 totalling $5.9 billion (Freshfacts 2021). In some fruit production regions (e.g., the East Coast and Central Otago) summer rainfall is irregular or insufficient to ensure crop survival, making irrigation is essential (Irrigation New Zealand). "In other regions, irrigation may be used to combat a particularly dry season or to ensure high-value food crops always have the right amount of water during a critical growth phase" (Irrigation New Zealand).

The general trend in fruit-tree production has been towards intensification, achieved by establishing high tree density orchards and using dwarf varieties (e.g., Jackson et al. 1981; FAO 2012). Intensification has successfully increased radiation interception resulting in increased carbon (C) assimilation and yield as well as reduction in production costs as a result of vigour control (Jackson et al. 1981; FAO 2012). One limitation of intensive orchard systems is increased water demand to support high crop yield.

Water shortage is a key crop growth limitation that is predicted to intensify as a result of global climate changes and increasing demand from the growing human population (Anjum et al. 2017; Boretti & Rosa 2019). In New Zealand, lack of availability of water for irrigation is a common and growing problem, and water restrictions are often put in place to limit extraction volumes for irrigated agriculture. Implementation of water restrictions may subject orchards to periodic drought stress. Severe water deficits will reduce yield within the season but could also reduce production in succeeding seasons, increase susceptibility to alternate bearing and lead to tree death (Proebsting et al. 1981; FAO 2012; Lopez et al. 2014). Understanding the response of fruit tree plants to variations in water supply is important for adequate scheduling of irrigation and prioritisation of water needs during periods of water scarcity. A simulation model of a fruit tree that incorporates the relationship between plant growth and drought stress over time is an important predictive tool that would assist growers to manage irrigation in orchard systems.

This project aims to quantify loss/reduction of orchard productivity as a result of restricted water supply during drought periods. The research process was a completed in stages as follows:

- Literature review – review New Zealand and international literature and document fruit tree physiological responses to water stress,
- Model development – use information from literature and expert advice to derive functions for modelling the water balance of fruit orchards and the effect of stress, using the apple tree as an example,
- Modelling – use the apple water use model to run orchard-irrigation scenarios that may be caused by drought and/or water restrictions to estimate the likely production cost to an apple orchard.

1 Objective 1: Literature review

1.1 Irrigation management in orchards

A goal of irrigation is to replace crop evapotranspiration (ET; the sum of water lost via evaporation and transpiration). In many deciduous fruit tree production areas of the world, irrigation is required to maximise yield and optimise fruit quality. Applying water below ET requirements, termed regulated deficit irrigation (DI), is a technique commonly used in many cropping systems including orchards. Originally proposed by Chalmers et al. (1981) and Mitchell & Chalmers (1982), DI has been widely studied across a number of fruit crops with the aim of increasing water use efficiency and reducing water consumption (English et al. 1990; Ruiz-Sanchez et al. 2010). In some cases, regulated DI has been implemented to introduce targeted water stress levels at specific stages of growth to control canopy growth and improve fruit quality (Caspari et al. 1994; Blanco-Cipollone et al. 2020). Deficit irrigation can take many forms, but in orchards, partial root drying (PRD), whereby water is withheld from part of the root zone while another is well watered, is a common strategy (e.g., O'Connell & Goodwin 2007).

A steady yield is important in commercial orchards, and this depends on maintaining a balance between tree structure to provide enough assimilates for the fruit to reach commercial fruit size, as well as ensuring fertile flower bud formation for the next season (Naschitz & Naor 2005). The key to achieving this balance is ensuring adequate vegetative growth to support flower bud formation and supply of assimilates to the carbohydrate pool of the tree (Naschitz & Naor 2005). An understanding of fruit-tree water needs during the annual cycle is therefore important for precise irrigation scheduling. Studies of fruit tree performance under varying rates of water supply and at different growth stages and seasons are also a good resource to further develop this understanding.

1.2 Fruit tree responses to water stress

Fruit trees respond to water stress by modifying their anatomy, physiology, and biochemistry, with potential implications on growth, production, and fruit quality (Kalcsits et al. 2022; Wojcik et al. 2022). Fruit growth and water stress have a dynamic association and can be influenced by several factors including tree species/cultivar, developmental stage, as well as the duration and intensity of water stress (Landsberg & Jones 1981; Syvertsen 1985; Berman & DeJong 1996; Yang et al. 2016). Among species, for example, apples, apricots, pears, and plums are known to be more drought-tolerant than nectarines, peaches and citrus (Sonoma Country Master gardeners; https://sonomamg.ucanr.edu/).

A distinctive characteristic of perennial crops is that water stress can reduce production in the current season, but production in subsequent seasons can also be impacted as a result of carryover effects of water stress. Research has shown that drought stress can deplete C reserves which are a vital resource between bud-burst to leaf area development and consequently compromise the tree’s long-term growth, durability, and survival (Naschitz et al. 2010; Rahmati et al. 2015).

Yield reduction from water-stressed fruit trees in the season of exposure has been reported in a number of studies. For example, low yield as a result of reduced fruit size and/or fruit weight in water-stresses fruit trees has been reported in apple (Chauhan et al. 2005; Kucukyumuk et al. 2020), avocado (Zuazo et al. 2021), apricot (Torrecillas et al. 2000), peach (Berman & DeJong 1996), cherry (Vosnjak et al. 2021), plum (Proebsting et al. 1981), pear (Marsal et al. 2008) and kiwifruit (Miller et al. 1998). Reduction in yield was the result of an interaction of physiological responses that affected tree morphology. Under water stress, fruit trees close their stomata, which causes a reduction in transpirational water loss and photosynthetic C assimilation, and adjustment of water relationships and C balance. This reduces the growth rate, size and number (e.g., branches) of tree components (Rahmati et al. 2015; Yang et al. 2016).

The negative impact on yield in subsequent seasons can be due to a number of factors. For example, in ‘Braeburn’ apple, water stress in early summer reduced floral initiation and return bloom (Behboudian et al. 1998). Reduced fruit set in the following year after water stress has also been reported in in other fruit trees. In apricot, Ruiz-Sanchez et al. (1999) found that reduced fruit set in previously water-stressed trees was due to reduced pollen vitality. In peach, Lopez et al. (2007) reported reduced fruit set as a consequence of decreased concentration of carbohydrates in the roots, although yield was not reduced. These authors concluded “that reductions in return bloom and fruit set may not have a negative effect on yield when low crop loads are required for promoting commercial fruit size. However, for cultivars whose profitability depends more on fruit number than on fruit size, reductions in return bloom and fruit set could have a negative impact on yield.” Severe water stress can cause significant mortality of branches and reduce the fruit bearing capacity of the tree in the following season. Such a response was observed in plum and cherry trees where researchers estimated a 2-year recovery period for the trees (Lopez et al. 2014).

Besides quantitative reductions in yield as a result of water stress, fruit disorders (quality) could be another factor reducing marketable yield following water stress in the previous season. For example, substantial increase of double fruits in peach (Patten et al. 1989; Wang et al. 2020) and fruit cracking in apple (Goodwin et al. 2022) are quality issues associated with water deficits.

The reduction in fruit size/weight as a result of water stress may not reduce yield but the grower will lose revenue if commercial quality standards are not met. Criteria for fruit quality differ between consumers or distributors, and size, external look, taste, firmness, are among the common determinants.

1.3 Sample experiments of response to water stress for specific fruit tree species

1.3.1 Water stress in apples

In apples, rootstock and tree age are factors influencing the response to stress (Chandel & Chauhan 1990; Fernandez et al. 1997; Atkinson et al. 1998). In comparing water use by apples in New Zealand orchards, Clothier et al. (2014) reported higher water use by fruit trees on vigorous rootstocks than those on dwarfing rootstocks. However, water use (and therefore potential stress under drought) at orchard level may not differ between rootstocks because plant population is often higher for dwarf varieties, and differences in root systems between rootstocks disappear when trees attain the age of 5–8 years (Clothier et al 2014). Reports on rootstock drought tolerance are inconsistent as the dwarfing rootstock M.9 has displayed more tolerance to drought than the vigorous MM.111 in some studies, although other studies have reported the opposite (Wright et al. 2019). Variations have been attributed to differences in drought application between studies e.g., continuous versus interrupted drought stress (Wright et al. 2019).

Work in the semi-arid environment of central Washington State by Ebel et al. (2001) provided an example of staged introduction of stress to apple fruit trees growing on different soil types. The experiment used 5-year-old ‘Delicious’ (on M.7 and MM.111 rootstocks) apple trees growing on 0.8 and 1.2 m deep sandy loam soils. Irrigation was withheld all season or every fortnight starting from 3–17 weeks (i.e., 42–140 days after full bloom) to harvest. Results showed decline in total available soil water after irrigation was terminated for each treatment, and slower depletion of water on deeper than shallower soils. Mid-day stem water potential (Ψ_{stem}) decreased after irrigation jointly with declining soil moisture and was lower on shallow than deep soils. As total available soil water decreased to 35%, Ψ_{stem} reduced by 7% and fruit growth rate reduced by 3% compared with the control. Leaves started senescing when total available water dropped below 30%. Compared with the control, leaf conductance of unirrigated trees on shallow and deep soils was 12 and 17%, respectively.

Data analysis indicated that drought response was not influenced by the rootstock, but the authors observed that the larger non-spur type trees (on MM.111) “exhibited slightly greater symptoms of drought stress than the smaller spur-type trees” (on M.7). Another observation was that unirrigated trees on shallow soils shed nearly all leaves within 2–3 weeks during active tree growth in June. Irrigated treatments shed leaves at rates comparable to the controls until total available soil water and Ψ_{stem} reached ~30% and –1.5 MPa, respectively. Shoot lengths of unirrigated trees on shallow and deep soils were reduced by 50 and 16%, respectively. A 16% reduction in shoot length was also observed in trees on shallow soils that were irrigated once. Fruit growth was reduced by drought, and nearly stopped in unirrigated trees. At 35% soil moisture, fruit growth was 97% of the controls. Earlier work (Ebel et al. 1995) indicated that some reduction in fruit size may occur when soil moisture drops to 35% but restoring moisture can increase fruit growth resulting in fruit size that was similar to the control, at harvest. In the following year, all trees were well-watered and all survived, but the effect of drought in the previous season was reflected in reduced fruit weight and yield (Ebel et al. 2001).

Points to note from this study were:

1. Water stress suppresses fruit growth and yield. However, there is evidence that yield reduction could be temporary (except in extreme cases e.g., nil irrigation in this study) with growth restored when soil water is replenished to required volumes.
2. Apple fruit water stress was influenced by soil type and duration of withholding irrigation, with the carryover effect more likely under excessive stress and/or shallow soils.
3. From the trial, it was possible to determine CWDI which was also shown to linearly correlate with fruit weight at harvest.
4. Stressed trees responded by shedding leaves (drought avoidance strategy) earlier than expected.
5. The authors identified Ψ_{stem} of –1.5 and total soil water of ~30% as threshold points below which stress starts to negatively impact fruit growth. Mid-day stem water potential can be used to schedule irrigation under the conditions of the experiment.

A 7-year (2007–14) study of 3-year-old “Granny Smith’ trees (on M9 rootstock) by Yang et al. (2016) demonstrated the effect of repeated exposure of apple fruit trees to water stress. Trees were either well-watered or subjected to progressive water stress between June and August (fruit season=01 April–15 September). Results showed that water stress significantly reduced the total (vegetative [short, medium, long] and floral) number of growth units developed per branch, and also increased transition probability toward short and dead growth units. Under water stress, tree vigour decreased as a result of shorter vegetative growth units and fewer growth units. The proportion of floral growth units was greater under water stress, resulting in a higher fruit number and reduced biennial bearing. Per tree fruit number and yield accumulated over five years 2010–2014 did not differ between irrigation treatments.

Key points from the experiment are:

- Water stress affected the number of growth units and the balance between vegetative and reproductive growth.
- Yield accumulated over 5 years did not differ between irrigation treatments, but the low fruit weight raises concern about quality which was not considered in the experiment.

There is extensive research where DI has been targeted at specific times during the apple tree season. A New Zealand study by Mills et al. (1997b) investigated the effect of withholding irrigation at specific periods of the season on 4-year-old ‘Braeburn’ apple trees growing in drainage lysimeters. In the study, full irrigation (Control; well-watered to cause daily drainage) was compared with early deficit (ED) where trees were irrigated from 55 to 100 days after full bloom (DAFB) and late deficit (LD; irrigation from 105 DAFB to 177 DAFB). Results indicated a reduction in leaf water potential for the ED and LD trees compared with the control. Relative to the Control, “the LD fruit showed no change in fruit water relations, composition, or size during the stress period.” “These data indicate that fruit water relations, composition, and size are modified if stress is induced early in the season but unaffected under a late-season water deficit”. “Additionally, fruit water relations showed minimal diurnal fluctuations irrespective of treatment, but leaf water potential showed a large diurnal variation in all treatments”. A similar study in the USA by Reid & Lee (2020) assessed 2-year old ‘Honeycrisp’ apple trees to early season irrigation deficit implemented from 16 to 45 days after full bloom (DAFB; during cell division), mid-season irrigation deficit (46 to 75 DAFB; early fruit expansion) and late season irrigation deficit (76 to105 DAFB; late fruit expansion). “Soil moisture of the well-watered control was maintained at 80–90% of field capacity for the entire season.” Results showed reduced stem water potential, stomatal conductance, net gas exchange under water limitation. Early season (cell division phase) water limitations had a lower impact on plant response than late-season (fruit expansion phase) limitations. On average, “water deficits during fruit expansion contributed to fewer large fruits and decreased overall bitter pit incidence with no negative effects on fruit quality”. The low number of fruits under water deficit observed by Reid & Lee (2020) is a depiction of fruit drop, a drought avoidance strategy of fruit trees.

Key points:

- The impact of water stress on apple fruits depends on the growth phase/stage at which the tree is exposed water deficit.
- The study found that the fruit expansion phase was more sensitive to water stress than the cell division phase.

In ‘Gala’ apple trees, Chenafi et al. (2016) compared optimal irrigation with a range of DI treatments and included the use of a plant-based water status indicator. Evaluated irrigation treatments were: “rain-fed (T1; no irrigation), optimal irrigation except during summer (T2), optimal irrigation except during summer when RDI with a threshold for irrigation at –1.2 MPa midday Ψ_{stem} was utilised (T3), optimal irrigation (T4). Results indicated that irrigation treatments had no significant impact on fruit yield. However, compared with optimal irrigation (T4) and RDI (T3), the absence of irrigation in summer (T1, T2) induced low Ψ_{stem} (<–1.2 MPa), decreased fruit size and slightly increased the soluble solid, vitamin C and polyphenol contents of the fruits. The RDI (T3) during summer allowed a water-use reduction of 47% without loss in fruit yield, fruit weight and fruit quality compared with the optimal irrigation (T4).”

Key points:

- Opportunities exist to reduce water consumption without impacting yield.
- Reliable indicators of plant water status are required to achieve target yield without compromising fruit quality.

The response of an apple fruit tree to water stress can also be influenced by the cultivar. In mature (8-year-old) ‘Gala’ and ‘Fuji’ apple trees (on M.9 rootstocks) subjected to either full irrigation “(CI; 100% of crop evapotranspiration), partial root zone (PRD, 50% of CI on one alternated side of the root-zone) and continuous deficit irrigation (CDI, 50% of CI delivered on both sides of the root-zone)”, Lo Bianco (2019) reported reduced yield, trunk growth, leaf hydration and gas exchange in ‘Fuji’ under CDI. The same effects were observed in “Gala’ but yield and gas exchange were not affected. In another study involving 2-year-old ‘Honeycrisp’ and ‘Yanfu 3’ apple trees (on M9-T337 rootstock), Bai et al. (2019) reported that drought reduced photosynthesis, but the impact was “greater in ‘Yanfu-3’ than ‘Honeycrisp’. Similarly, stomatal conductance, intercellular CO_2 concentration and transpiration rate were markedly reduced in ‘Yanfu 3’ while changes in ‘Honeycrisp’ were minor. Greater drought tolerance in ‘Honeycrisp’ was attributed to its curled, longer, larger and heavier leaves.” ‘Yanfu-3’ showed opposite characteristics i.e., smaller, flatter leaves. Other studies which have reported cultivar differences in tolerance to water stress include Mihaljevic et al. (2021).

Crop load (number of fruit/tree) is another factor known to affect the response to water stress in apple and other fruit trees. When subjected to DI, fruit was smaller for a high (commercial) than a lower crop load, representing 60% of the commercial crop load (Mpelasoka et al. 2001). These authors reported increased fruit weight, but gross yield decreased in the low crop load treatments. These results indicate that apple fruit size is influenced by water supply and crop load. A similar result was found by Naschitz & Naor (2005) in their evaluation of the effect of crop load on water consumption of mature ‘Golden Delicious’ apple in relation to fruit size.

The response of the apple fruit tree to water stress differ depending on age and growth stage. Boland et al. (2002) provided information on susceptible stages as summarised in Figure 1.

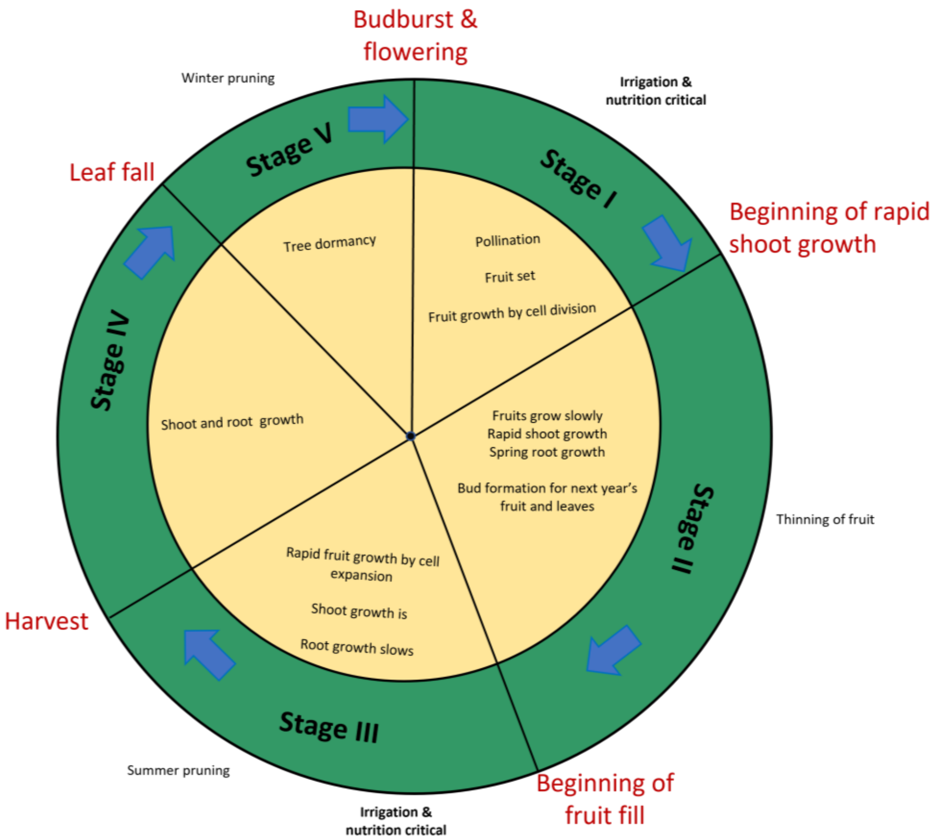

Figure 1. Fruit growers guide to irrigation: the growth cycle. Adapted from Boland et al. (2002).

1.3.2 Water stress in peach trees

The introduction of the Berman & DeJong (1996) paper gives a concise review of how different peach growth-phases relate to water supply requirements. In peach, “rapid initial fruit growth is followed by an intermediate phase of slow growth. This is followed by a period of rapid flesh and dry weight increase that ends with maturity and ripening. During the final growth phase, which consists of a third of the growth period, 65% of a fruit's dry weight and 80% of a fruit's fresh weight are accumulated." The authors allude to differential sensitivity to water stress between the vegetative and reproductive growth phases.

In their study, Berman & DeJong (1996) evaluated the effect of water stress on fruit fresh and dry weight in 5-year-old 'Elegant lady' peach trees under light, moderate and heavy crop loads. "Water stress was imposed during the final four weeks of the season. Results indicated that the degree of water stress increased with increasing crop load in trees receiving reduced irrigation. In contrast, crop load did not affect tree water status of well-watered trees. Water stress reduced fruit fresh weight across crop loads. Fruit dry weight was not reduced in trees having light to moderate crop loads, indicating that the degree of water stress did not affect the dry weight sink strength of fruit. Water-stressed trees with heavy crop loads had significantly reduced fruit dry weights, which were likely due to carbohydrate source limitations resulting from large C demands and water stress limitations on photosynthesis."

In peach trees exposed to different water stress levels (low, moderate, and severe) from mid-pit hardening until harvest, Rahmati et al. (2015) found that "water stress significantly reduced gas exchange, and fruit, and shoot growth, but increased fruit dry matter concentration. Growth was more affected by water deficit than photosynthesis, and shoot growth was more sensitive to water deficit than fruit growth. Reduction of shoot growth was associated with a decrease of shoot elongation, emergence, and high shoot mortality." Compared with low water stress, tree C assimilation under moderate and severe stress was reduced due to interacting effects of reduced leaf photosynthesis and reduced leaf area. Data indicated "a Ψ_{stem} threshold of -1.5 MPa below which daily net C gain became negative, i.e., C assimilation became lower than C needed for respiration and growth. Negative C balance under moderate and severe stress was associated with decline of trunk carbohydrate reserves which may have led to drought-induced vegetative mortality."

1.3.3 Water stress in pears

A New Zealand study by Caspari et al. (1994) investigated 5-year-old 'Hosui' Asian pear (*Pyrus serotina* Rehder) growing in lysimeters across three irrigation treatments; Control – soil water content (SWC) kept at pot capacity, regulated DI before rapid fruit growth (RDI, SWC ~50% of pot capacity), late DI (LDI) - SWC ~75% of pot capacity during the period of rapid fruit growth. DI reduced "WU during RDI and LDI by 20%. The reduced WU was caused by lower stomatal conductance in DI treatments. RDI trees had more negative diurnal leaf water potentials. The leaf water potential, stomatal conductance and WU remained lower for 2 weeks after RDI was discontinued. The RDI reduced shoot extension and summer pruning weights, whereas winter pruning weights did not differ between treatments. Except for the final week of RDI, fruit growth was not reduced, and fruit from RDI grew faster than the control during the first week after RDI. In contrast, fruit volume measurements showed that fruit growth was clearly inhibited by LDI. Final fruit size and yield, however, were not different between treatments. Return bloom was reduced by RDI but was not affected by LDI."

1.3.4 Water stress in avocadoes

Silber et al. (2019) assessed "the water demand for heavy fruit load of 'Hass' avocado throughout the growth periods and to investigate the effects of deficit irrigation during sensitive phenological phases on yield. The experimental set-up allowed the comparison between tree responses to three irrigation strategies during the entire growth period (well-watered; constant water stress) as well as the comparison between regulated deficit irrigation (RDI) managements applied during the early or the late growth period. During three experimental years, the well-watered treatments produced significantly higher yields than water-stressed treatments (25–31 versus 16–21 t ha^{-1}). In addition, the well-watered treatments were not susceptible to alternate bearing while yield was substantially reduced during off-crop years in water-stressed treatments. The authors noted less effect on yield when trees were continuously subjected to constant water stress than imposing short periods of water stress during summer. The authors attributed the response to the possibility of the tree adapting to conditions of constant water deficiency by decreasing the vegetative part and reducing plant evapotranspiration.”

In a 3-year monitoring study with ‘Hass’, Zuazo et al. (2021) compared three sustained DI strategies of applying 33, 50 or 75% with 100% (Non-stressed; Control) of the estimated crop water demand. These researchers found that leaf water potential and stomatal conductance reduced in proportion with the degree of stress. Tree height, canopy size and fruit size were also reduced in proportion with the degree of water stress. Compared with the Control, water-stressed trees produced 8–33% less yield over the 3-year study period.

Non-stressed trees showed less susceptibility to alternate bearing while water-stressed trees produced considerably lower yields in the off-seasons, similar to the findings of Silber et al. (2019). Water stress was associated with fruit quality improvement where an increase in omega and oleic fatty acids was observed under the 33% and 75% sustained DI treatments. The study recommended the 75% sustained DI as a strategy that reduces water supply and increases fruit quality without adverse effects on tree performance.

Cultivar differences in response to water have been indicated in avocado. 'Fuerte' and 'Hass' trees subjected to water stress responded by reducing stomatal conductance, photosynthesis and pre-dawn leaf water potential, and growth data indicated greater drought tolerance by ‘Hass’ than ‘Fuerte’ (Chartzoulakis et al. 2002).

Overall, research shows similar responses (at least physiologically) to water stress by fruit trees. However, phenological stages that are more sensitive to water stress may be species-specific. “Studies have shown that fruit size at harvest is not affected by drought during the early phases of fruit growth, but fruit size decreases when drought occurs during the main period of cell enlargement” (e.g., Failla et al. 1987; Genard & Huguet 1996). In stone fruits, “flowering and fruit set are the most sensitive phenological stages to drought, while pit hardening is the most resistant” (Goldhamer 1997; Moriana et al. 2003). “The post-harvest period has also been identified as less sensitive to water stress in stone fruit trees, and moderate induced stress can help avoid undesired budding and favour initiation of tree dormancy without negatively affecting the following year’s yield” (reviewed by Moñino et al. 2020). “However, severe water stress in this period can result in yield losses due to a reduction in the number of flowers or an increase in fruit setting problems, as observed in apricot”, peach and Japanese plum (Moñino et al. 2020). Knowledge of the most water-stress-sensitive phases is important for designing an irrigation schedule to achieve orchard management objectives (i.e., profitable yields of high quality).

1.4 Modelling water use by apple trees

Water loss through the stomata and also through evaporation from surfaces of leaves, flowers and stems is the major use of water by land plants and is the main driver of movement of water from the soil, into and through the roots, up the stem, out to the leaves and into the atmosphere (DeJong 2022). As reviewed by Mohamed et al. (2020), irrigation scheduling in commercial orchards traditionally uses soil-water balance with calculation of crop evapotranspiration (ET) based on refence ET and crop coefficients”. The “coefficients are often chosen based on correlations with canopy size and height”. However, uncertainties around planting density, tree architecture, row widths and tree ages as detailed by Doltra et al. (2007) have led to development of alternatives such as soil- and weather-based approaches which enable plants “to match the water demand of their environment and keep in balance with the water supply from the soil” (Mohamed et al. 2020). The soil-based irrigation scheduling method relies on soil moisture measurements while soil-water balance and estimations of

ET and ET model such as Penman–Monteith (Allen et al. 1998) are requirements for scheduling weather-based irrigation.

Woody crops generally have deep roots which presents challenges in estimating soil moisture using traditional methods. A number of physiological responses to stress such as stem and leaf water potential, stem diameter variations (Fernandez & Cuevas 2010; Intrigliolo et al. 2011; Reid & Lee 2020), are alternatives known to be accurate estimating plant water status and therefore reliable indicators for scheduling irrigation. The majority of physiological processes driving plant growth and productivity depend on the plant instead of the soil water status. It has been proposed that combining plant-based stress indicators and soil moisture measurements would enable a better understanding of the plant water status.

Improvement of crop water use and optimising applied irrigation requires real-time detection of crop water status. Techniques such as the use of canopy temperature (measured by infrared thermometers) have “received considerable attention in detecting and diagnosing water stress” and have been used to develop indices associating plant water stress signs to soil water status (Andrews et al. 1992; Katimbo et al. 2022). The crop stress index (CWSI) is a well-known index that uses normalised canopy temperature to detect stress (Mohamed et al. 2020; Katimbo et al. 2022). Critical to these indices “is the threshold or lower limit value, which indicates the degree to which the soil can dry before irrigation is required” (Thompson et al. 2007; Mohamed et al. 2020). Index values range from 0 for a non-stressed crop to 1 for an extremely stressed crop. Indices can be either plant-based (e.g., CWSI) or soil-based such as soil water content or soil water potential (Khorsand et al. 2021).

Integration of water stress in process-based models can provide predictions of fruit-tree responses to changing climate and irrigation management. “The **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM; www.apsim.info) is a well-known process-based model that simulates physical and biological processes in agricultural systems” (Khaembah et al. 2017). A fruit tree model will be developed in the APSIM framework using a soil-based index to quantify water stress.

2 Objective 2: Fruit tree model development and analysis

The fruit tree model developed in this study is the **S**imple **T**ree **R**esource **U**ptake **M**odel operating in APSIM (STRUM-APSIM). The model was developed using the Plant Modelling Framework of Brown et al. (2014). The Plant Modelling Framework contains a library of plant organs and process sub-models that can be coupled, at runtime, to construct a model in much the same way that models can be coupled to construct a simulation. The software contains several modules (plant/crop, soil water, soil temperature, soil C and nitrogen) which interact on a common interface.

2.1 Model structure, parameterisation, and testing

Figure 2 shows the representation of the fruit model. The model simulates development and growth, both driven by temperature and radiation interception. For the initial parameterisation, optimal supply of growth resources is assumed i.e., trees sufficiently provided with water, nutrients, and protection from biotic stress. The fruit tree model comprises four organs (leaf, fruit, trunk, and root; Figure 2).

The leaf is represented by the simple leaf class and provides estimates (1) leaf area index which the microclimate model uses to estimate radiation interception of the tree canopy, (2) water uptake demand which the soil arbitrator uses to estimate soil water extraction, (3) photosynthesis estimates (using radiation use efficiency) to drive tree biomass production and (4) biomass demand which is used to grow leaf biomass and determine nitrogen demand for leaf growth. The fruit represents the biomass and nitrogen that may be removed from the orchard each year as harvested product.
The trunk represents the perennial biomass of the trees and will grow a small amount each year but is mostly pruned out at the end of the year and may be returned to the soil surface. The root is the organ which extracts water and nitrogen from the soil for plant growth, grows a small amount of biomass each year and senesces a proportion of this to the soil.

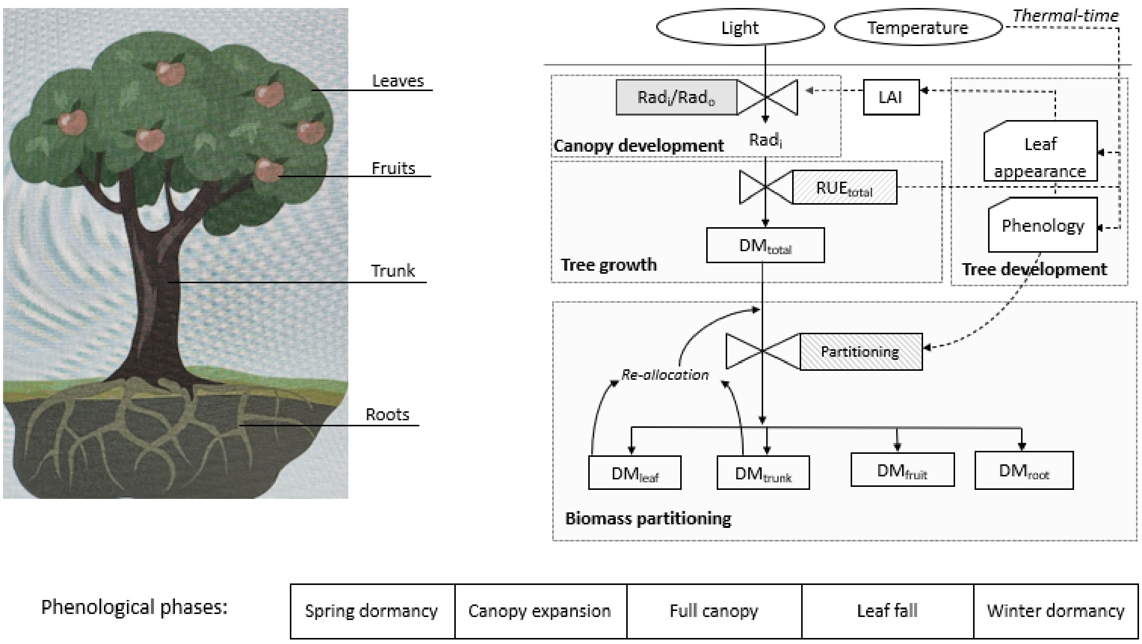

Figure 2. "Schematic of the components and controlling environmental variables in the fruit tree model. RUE_{total}=radiation use efficiency for total [tree] biomass, LAI=leaf area index, DM=dry matter, Rad_o=total incident solar radiation, and Rad_i=intercepted solar radiation" (Khaembah et al. 2017). Picture source: https://www.freepik.com.

A new apple orchard cycle is initialised by “planting” fruit trees on the winter solstice. Initial biomass is assigned based on the age (user-defined) of the true. The STRUM-APSIM is, therefore, described by five post-planting phenological phases, namely: (1) Spring dormancy (dormant–bud break) - the tree is a bare trunk during this phase, uses no water, grows no biomass, and does not take up nitrogen, (2) canopy expansion (bud break –start of fruit growth) – this occurs in spring) during which the bulk of biomass assimilation is partitioned to the new leaves with smaller proportions allocated to trunk and root growth, (3) fruit growth (from start of fruit growth– ripe fruit) – during this phase the bulk of biomass assimilation is partitioned to the growing fruit with smaller proportions allocated to leaf, trunk, and root growth, (4) leaf fall (ripe fruit–bare tree) – trees lose leaves and enter their dormancy period. Any assimilated biomass is partitioned to the trunk and roots, and (5) winter dormancy (bare tree–spring dormancy) - the tree is a bare trunk during this phase and can be pruned before buds begin to swell.

The STRUM-APSIM is a stand-alone model. However, fruit trees are often planted in rows with a grass or herb ley in the alleys. In such cases, the orchard system was set up with two rectangular zones: one established in fruit tree and the other in grass or herb ley. A different model, APSIM-SLURP (e.g., Teixeira et al. 2018), was used to represent energy, nitrogen, and water balance of the alleys.

Calibration/parameterisation and testing of the fruit tree model was based on apple fruit tree data collated under unstressed (i.e., adequate water and nitrogen supply) and water-stressed conditions. A number of experiments (Table 1) were identified for this purpose. The experiments shown in Table 1 had specific research focuses, and none fully evaluated water-stress effects on the whole set of yield and yield components. Therefore, some assumptions were made in the modelling.

Table 1. Details of experiments used in model development, evaluation and sense-checking.

Location	Season/Trial type	Treatment*	Variety	Relevant measurements/data	Reference
Palmerston North, New Zealand	1995–96/ lysimeter	Irrigation: intensity and timing*	‘Braeburn’/MM.106	Soil moisture, trunk growth, leaf area	Behboudian et al. (1998)
Palmerston North, New Zealand	1994–95/field	Optimal conditions*	‘Splendour’/MM.106	Leaf area, tree height, radiation absorption, transpiration	Green & McNaughton (1997)
Palmerston North, New Zealand	1994–95/field	Optimal conditions*	‘Splendour’/MM.106	Light interception, transpiration, leaf area (end of trial)	Green et al. (2003a)
Nelson, New Zealand	2000–01/field	Optimal conditions*	‘Braeburn’/M.9	Light interception, transpiration, leaf area (end of trial).	Green et al. (2003a)
Palmerston North, New Zealand	1996–97/field	Optimal conditions*	‘Splendour’/MM.106	Transpiration, soil moisture	Green et al. (2003b)
Hastings, New Zealand	2008–09	Optimal conditions	‘Pink Lady’	Light interception, transpiration, soil moisture	Green et al. (2013)
Hastings, New Zealand	2008–09	Optimal conditions	‘Royal Gala	Light interception, transpiration, soil moisture	Green et al. (2013)
Palmerston North, New Zealand	1992–93/field	Irrigation	‘Braeburn’/MM.106	Soil moisture, photosynthesis, trunk circumference (to estimate plant growth), fruit weight	Mills et al. (1994)
Palmerston North, New Zealand	1997–98/ lysimeter	Irrigation*fruit load*	‘Braeburn’/MM.106	Soil moisture, water use transpiration, fruit growth, fruit volume	Mpelasoka et al. (2001)
Palmerston North, New Zealand	1994–95/ lysimeter	Irrigation (intensity and timing): Control, deficit (early & late)	‘Braeburn’	Soil moisture, fruit weight	Mills et al. (1997a)
Nelson, New Zealand	1968–73/field	Irrigation*	‘Delicious’/Malling XVI, Malling XII or Northern Spy	Trunk cross-section, shoot growth, crop load, fruit growth rate, fruit size, yield, evapotranspiration.	Hewett (1976)
Hawkes Bay, New Zealand	2013–19/field	Planting systems*	‘Gala’, ‘Fuji	Light interception, fruit yield, leaf area	Tustin et al. (2022)
Prosser, USA	1986–87/field	Irrigation*soil type	‘Delicious’/M.7 or MM.111)	Soil moisture, shoot length, fresh fruit weight.	Ebel et al. (2001)

*Data used to sense-check model outputs

2.2 Integration of water stress

In APSIM, water characteristics of the soil are specified in terms of the lower limit, drained upper limit, and saturated water content. Soil water stress ratio is calculated by dividing actual soil water available by the potential water supply (supply/demand ratio) which is calculated by the difference between lower limit and drained upper limit. Soil water deficit stress factors were calculated to simulate the effects of water stress on different physiological processes (extinction coefficient, photosynthesis, and the number of fruiting buds).

Water stress factors range from 0 to 1, where the value of 0 corresponds to complete stress, while 1 corresponds to no stress. Soil water stress on biomass accumulation (photosynthesis) is calculated as the ratio of the total daily water uptake from the system to the soil water demand of the leaves. In the model, water stress starts when the water supply:demand ratio reaches 0.8 and increases linearly with the water supply:demand ratio (Figure 3). For the extinction coefficient, a linear increase in water stress is triggered when the supply:demand ratio reaches 0.9 and plateaus when the ratio reaches 0.4 (Figure 3).

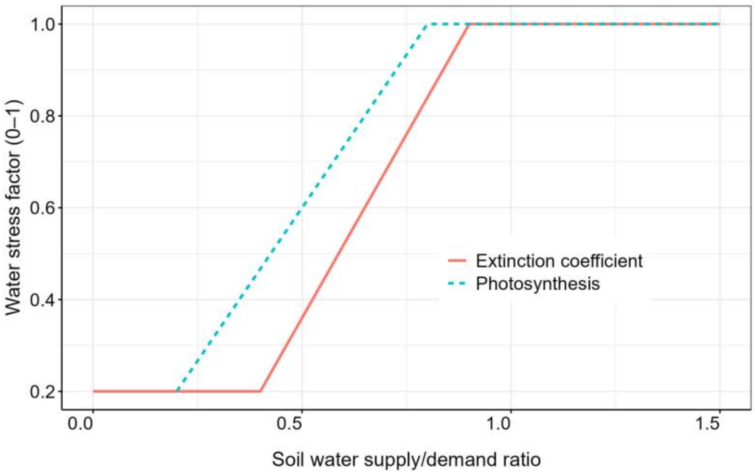

Figure 3. Soil water stress factor affecting photosynthesis and extinction coefficient in relation to and supply:demand ratio.

The effect of water stress on the productivity of the orchard in the next season was estimated as the product of the number of fruits retained post-thinning and accumulated stress (Y; Eq. 1).

$$Y = \sum_{i=1}^{n}(1 - X_i) \qquad \text{(Eq. 1)}$$

Where n is the number of days in a season, X_i represents the daily water stress value for day i.

A post-thinning density of 50 fruits/m^2 was considered as a benchmark for a productive orchard. In the model, a reduction in the number fruiting buds began at an accumulated water stress of ≥70 and following a logarithmic change (Figure 4). The calibration of the effect of accumulated water stress on the number of fruiting buds was based on the findings of Ebel et al. (2001). These researchers reported a 16–50% reduction in shoot length from unirrigated apple trees established on shallow and deep soils and those that received the lowest amount of water on the shallow soils.

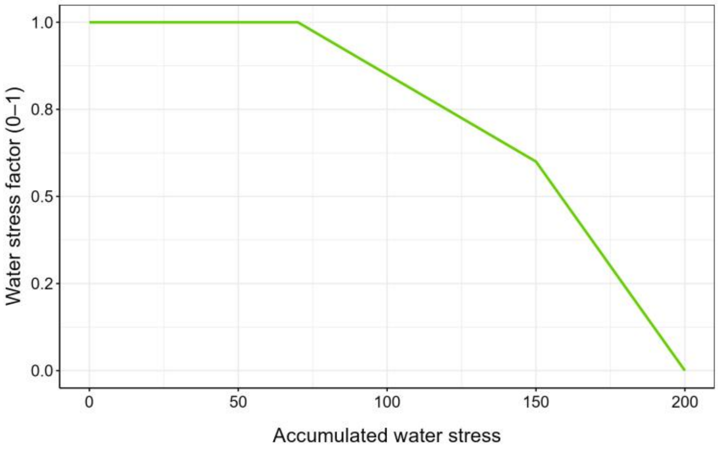

Figure 4. Accumulated daily water stress as a function of soil water stress factor.

2.3 Assumptions

The following assumptions were made.

- Tree roots spread out into the zone and reach 3 m deep in the soil,
- Irrigation is only applied to the row area (the alley is excluded),
- There is no water table contributing to the water balance.

2.4 Analysis of model performance

Four model performance indicators were used to evaluate the model's goodness-of-fit.

1. The coefficient of determination (R^2) which represents the proportion of variance of the variance in the dependent variable that is predictable from the independent variable.
2. The absolute root mean squared error (RMSE) measuring the scatter of data points around the 1:1 relationship line:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(o_i - p_i)^2}{n}} \qquad \text{(Eq. 2)}$$

Where n is the number of observations while o_i and p_i are the model observed and predicted values, respectively.

1. Relative RMSE (rRMSE) i.e., RMSE expressed as a percentage of the observed mean ($\bar{o}$) of the observed data:

$$rRMSE = \left(\frac{RMSE}{\bar{o}}\right) * 100 \qquad \text{(Eq. 3)}$$

2. The Nash-Sutcliffe model efficiency coefficient (NSE), which measures the proportion of variance in the observations accounted for by the model's predictions:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(o_i - p_i)^2}{\sum_{i=1}^{n}(o_i - \bar{o}_i)^2} \qquad \text{(Eq. 4)}$$

Values of NSE can be negative or positive with a maximum of 1. An efficiency of 1 (NSE=1) corresponds to a perfect match between modelled and observed data. An efficiency of zero (NSE=0) indicates that the model predictions are as accurate as the mean of the observed data. A negative value (NSE<0) shows that the observed mean is a better predictor than the model, i.e., the residual variance (described by the numerator in Eq. 4) is larger than the data variance (described by the denominator). The closer the NSE is to 1, the more accurate the model is. Model efficiency threshold of 0.5<NSE<0.65 is generally considered sufficient quality (Smith et al. 1997; Ritter & Munoz-Carpena 2013).

2.5 Results and discussion

Model performance indices indicated varying degrees of prediction accuracy among evaluated variables (Figure 5, Table 2). Graphs of predicted and observed changes over time for evaluated variables are in Appendix Figures A1–A6. The pattern of soil water dynamics was well captured by the model as indicated by the good agreement between predicted and measured data (Figure 5a). Accurate prediction of soil water content was supported by prediction accuracy indices i.e., a strong correlation between predicted and measured values, high modelling efficiency (NSE=0.95) and a large proportion (>89%) of variation (rRMSE=7.9) in the observed data (Table 2). Appendix Figures A1–A2 show that the model captured the trends in soil moisture in response to irrigation management.

The prediction of transpiration was accurate as graphically indicated in Figure 5b and model performance indicators (Table 2). Predicted values correlated well with measured data (R^2=0.79), the modelling efficiency of 0.51 indicated acceptable prediction accuracy, and modelled data explained a substantial variation (~64%) in the observed data. A plot of transpiration during the course of the experiment (Appendix Figure A3) indicated the model followed the season trend estimating greater water use in summer and a reduction in autumn.

The fraction of intercepted radiation was the least accurately modelled variable, as revealed by low performance indices (R^2=0.48, NSE=0.24). There was increased bias late in the season (Appendix Figures A4b) which resulted in outliers seen in Figure 5b. Nevertheless, the model accounted for a large proportion of the variation in the data (~91%) as indicated by an rRMSE of 9.3 (Table 2).

Predicted values were in good agreement with measured values for fresh fruit weight (Figure 5, Table 2). The model accounted for 82% of the variation in the measured data (Table 2). Simulated data strongly correlated with measured data (R^2=0.91) and the modelling efficiency was also high (NSE=0.91). The time series depiction of experiments indicated that the model accurately captured the trends of measured data (Appendix Figures A5–A6).

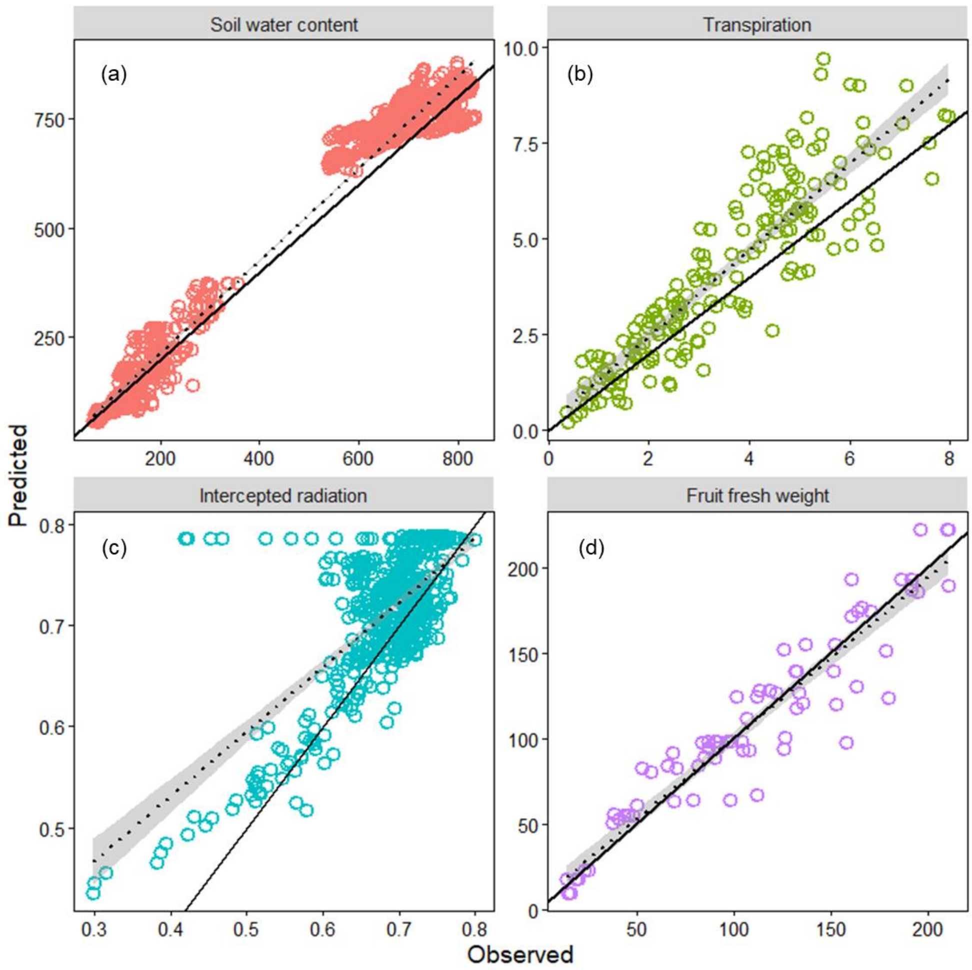

Figure 5. The STRUM-APSIM-predicted values in relation measured values of (a) soil water content (mm**), (**b) transpiration**,** (c) fraction of intercepted radiation, and (d) fresh fruit weight (g/fruit) for apples growing in New Zealand and USA**.** The solid line is a 1:1 relationship and the dotted line is the linear relationship between observed and predicted with a 95% confidence interval.

Table 2. Statistical analysis results of observed versus predicted values for evaluated variables. n=number of measurements, $R^{2=}$coefficient of determination, RMSE=root mean squared error, rRMSE=relative RMSE, NSE=Nash-Sutcliffe model efficiency coefficient.

Variable	n	R^2	RMSE	rRMSE	NSE
Soil water content	1237	0.97	57.9	10.7	0.95
Transpiration	178	0.79	1.26	35.6	0.51
Intercepted radiation	508	0.48	0.06	9.3	0.24
Fruit fresh weight	82	0.91	17.7	17.6	0.91

3 Objective 3: Analysis across a range of conditions

3.1 Scenario set-up

Verification of the accuracy of STRUM-APSIM in predicting soil water dynamics, water use, light interception and fruit yield from experiment indicated that the model could be applied in the evaluation of scenarios across a range of growing conditions. Therefore, the model was used to run a range of simulations to test the effect of water stress on the productivity of the orchard in the following season(s) as follows:

- *Scenario 1:* For 30 years (1985–2014), simulating one season (season starting from 01 June and ending 31 May of the following year) at a time. In these simulations, the starting soil conditions were the same in each season.
- *Scenario 2:* For 30 years continuously (1985–2014). Starting soil water/N conditions were determined by the previous season.

A row width of 1.3 m (narrow, planar design) was used in both scenarios. In scenario 2, a second row spacing of 2.5 m (wide, spindle design) was included to test the effect of orchard design. Simulations were run across a combination of soil types (Table 3) and weather conditions (Table 4). The aim was to determine estimates of accumulated water stress on the number of fruiting buds as affected by soil properties and temporal variations in weather conditions. Water stress was imposed during the irrigation window (i.e., 01 October to 30 April). The effect of water stress was evaluated across a range of irrigation managements created by progressive withholding of irrigation during the irrigation window. The treatments were: application of irrigation applied over October–November, October–December, October–January, October–February, October–March and October–April (whole season). Nil (rainfed) treatment where, no irrigation was applied for the entire season and all-year application of irrigation (January–December) were included as controls. Irrigation was scheduled based on soil water deficit. An irrigation event was triggered when moisture in the top 1 m of the soil profile was ≤70% of the profile available water. The trigger resulted in application of 15 mm of water. A minimum return period of 3 days was used in the model.

Table 3. Details of the soils used in STRUM-APSIM long-term (1986–2014 simulations. PAW represents profile available water in the top 1 m of the soil profile.

Soil water holding capacity (WHC)	Bulky density (top layer, kg/m^3)	PAW capacity (mm)
Low	0.801	128
Medium	1.189	157
High	0.300	242

Table 4. Long-term (1972–2015) averages of four Virtual Climate Station Network (VCSN) weather data used in STRUM-APSIM simulations.

VCSN name	Region	Rainfall (mm yr^{-1})	Mean temperature (°C)	Radiation (MJ m^{-2})	Evaporation (mm)	Wind speed (m s^{-1})	Vapor pressure (hPa)
Brightwater	Tasman	1070	12.4	15.5	2.6	3.3	11.1
Palmerston North	Manawatu	988	13.3	13.8	2.5	3.1	12.6
Jervoistown	Hawkes Bay	781	14.0	14.7	2.8	3.6	12.0
Martinborough	Wellington	756	12.9	14.0	2.4	3.2	11.8
Ranfurly	Otago	457	9.1	13.8	2.1	2.5	8.7
Cromwell	Otago	432	12.4	15.5	2.6	3.3	11.1

3.2 Model estimations

Model estimates of total irrigation from a series of simulations with 30 years of climate data from six Virtual Climate Station Network (VCSN) sites and three soil types (Scenario 1) are shown in Figure 6. As expected, volumes of applied irrigation decreased with increased periods of withholding irrigation. There was little difference in irrigation volumes when all-season (Oct–Apr) and all-year (Jan–Dec) irrigation regimes were implemented. On average, the model predicted 1–11 mm more water applied in the all-year control than the all-season (Oct–Apr) treatment. Such marginal difference between these two irrigation treatments can be attributed to nil–minimal tree water requirements during leaf fall and dormancy stages. The effect of soil type on the amount of applied water was influenced more by site than soil type. For example, with the greatest and least amounts applied at minimal (Figure 6). In contrast, irrigation was influenced by weather conditions. On average, irrigation was lowest in wetter sites e.g., Palmerston North and Brightwater with average annual rainfall of 988 and 1070 mm, respectively (Table 4; Figure 6). Conversely, drier sites like Cromwell (average annual rainfall of 432 mm; Table 4) were associated with the highest amount of irrigation. In addition to rainfall, other weather factors e.g., temperature, influenced the amount of irrigation applied. For example, Jervoistown had the third highest amount of rainfall (annual average of 781 mm) but also the highest mean temperature, wind speed and evaporation which resulted in the second highest amount of applied irrigation ((Table 4; Figure 6).

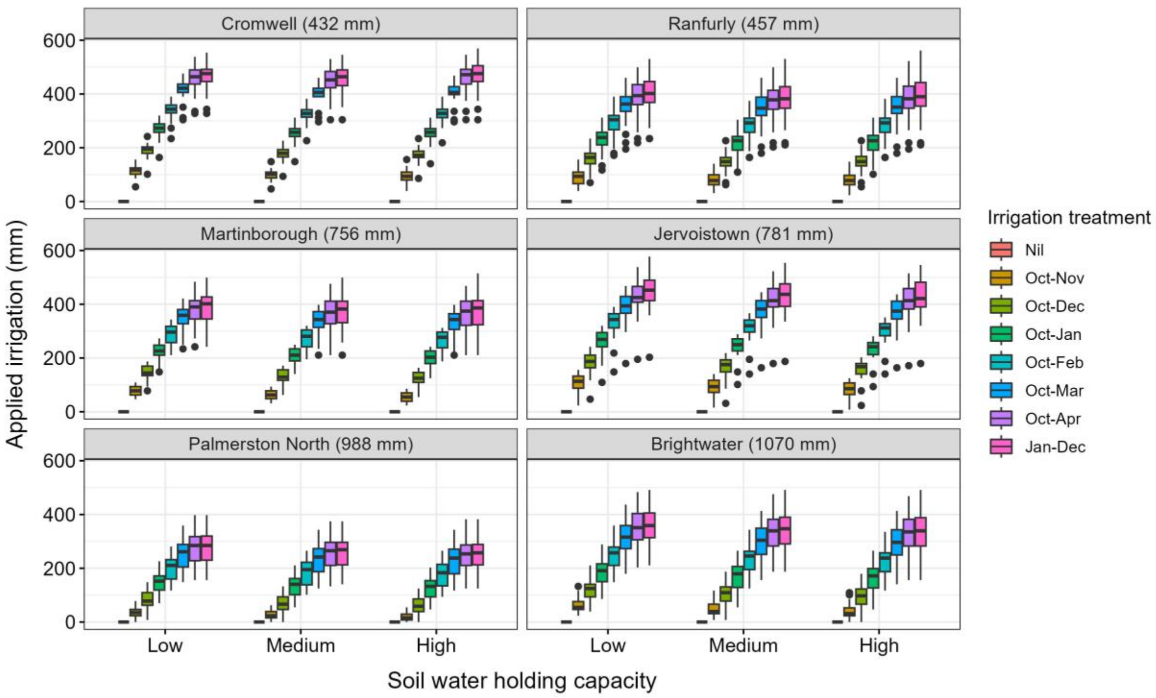

Figure 6. Boxplots showing annual total applied irrigation predicted by STRUM-APSIM for apple orchards established on different soil types and subjected to different irrigation managements and weather conditions (determined by location). Results are based on one-season (01 June to 31 May) simulations repeated for 30 (1985–2014) years.

Figure 7 shows greater estimated water stress with longer periods of withholding irrigation, as expected. There was a soil type effect, with water stress increasing with decreasing water holding capacity of the soil (Figure 7). At most sites, the model predicted nil/minimal water stress on medium and high water-holding capacity soils under all-year, all-season and over Oct–Mar irrigation regimes (Figure 7). There were site differences in water stress with the greatest and least water stress predicted at Cromwell and Palmerston North, respectively, similar to the pattern predicted for applied irrigation (Figure 6 and 7).

The number of fruiting buds is a key factor determining the productivity of the orchard in the following season. As shown in Figure 8, water stress negatively impacted the number of fruiting buds. The response of fruiting bud number to irrigation varied across soil types with reduced impact predicted with increased water holding capacity of the soil (Figure 8). In addition, there were site differences with the greatest and least impact predicted at Cromwell and Palmerston North, respectively (Figure 8). Model estimations in Figures 7 and 8 collectively indicate that trees can tolerate some level of stress without adverse effects on the number of fruiting buds. However, the risk of losing orchard productivity under water restrictions is greater in drier and warmer regions. Also, orchards established on deep soils with high water holding capacity are bound to withstand water stress better than those on shallow and low water holding capacity soils.

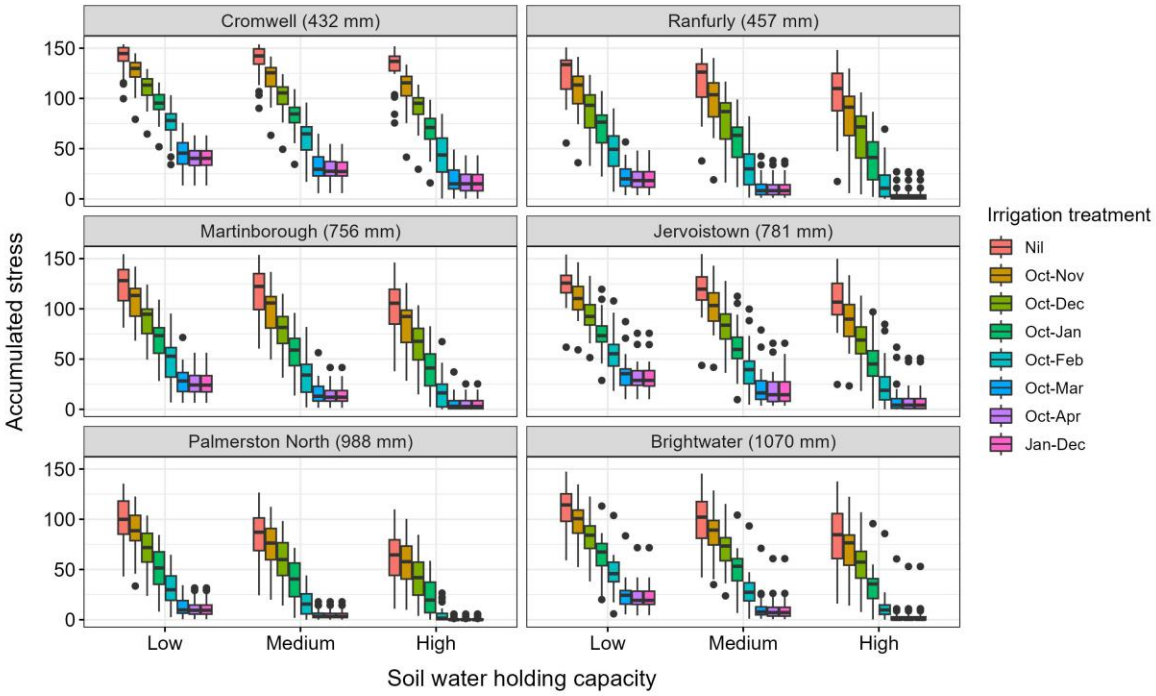

Figure 7. Boxplots showing STRUM-APSIM-estimated water stress accumulated during the season for apple orchards established on different soil types and subjected to different irrigation managements and weather conditions (determined by location). Results are based on one-season (01 June to 31 May) simulations repeated for 30 (1985–2014) years.

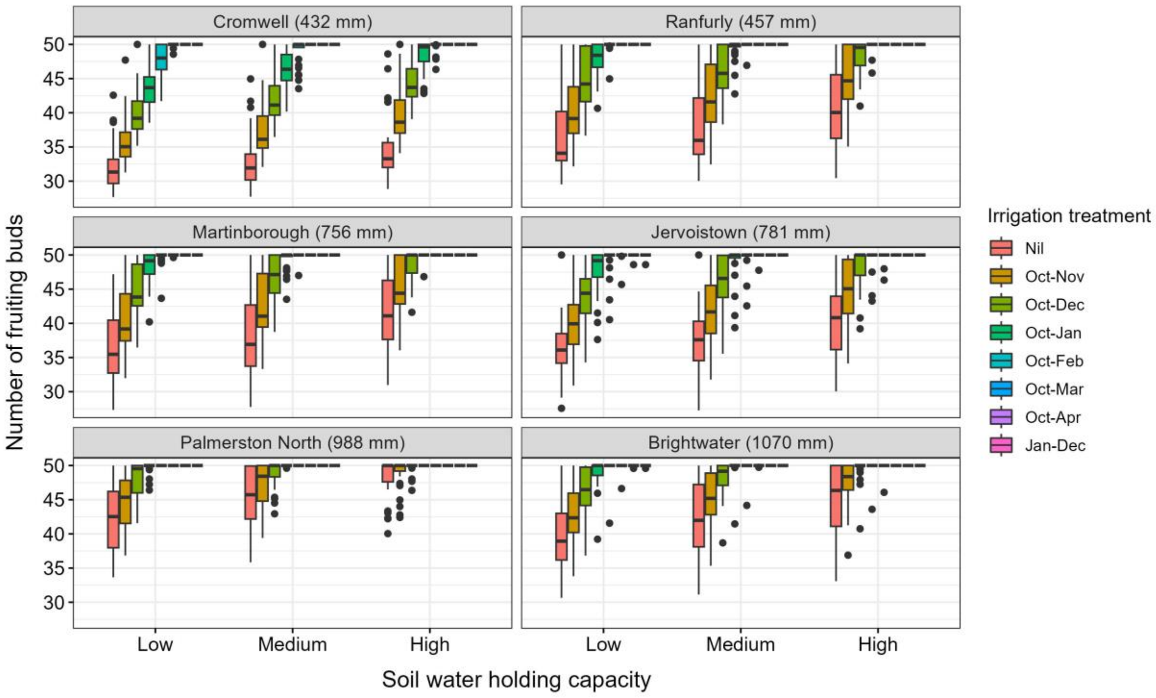

Figure 8. Boxplots showing STRUM-APSIM-estimated effect of irrigation management on the number of fruiting buds for apple orchards established on different soil types and subjected to different irrigation managements and weather conditions (determined by location). Results are based on one-season (01 June to 31 May) simulations repeated for 30 (1985–2014) years. Note: colours of some irrigation treatments (Oct–Mar, Oct–Apr, Jan–Dec) do not appear on the graph because they resulted in nil loss of fruiting buds.

Predictions from simulations run continuously for 30 years to evaluate carry-over effects from season to season produced similar responses to those from individual seasons (Appendix Figures A7–A9). The model predicted minimal differences between orchard designs (Appendix Figures A7–A9). From Appendix Figure A9 summary, the reduction in the number of fruiting buds was affected by the period of withholding irrigation, soil type and weather conditions. Also, the risk of bud loss was highest and lowest at Cromwell and Palmerston North, respectively. On soils with high water holding capacity, the model predicted nil impact on the number of fruiting buds except in extreme cases i.e., applying irrigation for 0–2 months (Nil and Oct–Nov treatments), except for Cromwell (Appendix Figure A9). On high WHC at Palmerston North, there was no reduction in fruit bud number irrespective of the irrigation treatment (Appendix Figure A9). On low water holding capacity soils, trees needed to be irrigated for at least three months to eliminate the negative impact of water stress on fruiting buds (Appendix Figure A9).

3.3 Estimation of rootstock requirements

Model estimates from simulations run continuously for 30 years (*Scenario 2*) based on a planar design orchard were used for estimating orchard water requirements.

3.3.1 Productive irrigation requirements

Productive water requirements for an apple orchard i.e., irrigation application required to meet the demand of fruit trees, was estimated as the lowest amount of applied irrigation to support 100% post-pruning fruit bud density. As tree water requirement was influenced by soil and weather conditions, there were differences in irrigation regimes for productive irrigation water requirements among sites and soil types. For each site and soil type, productive water requirement was represented by the irrigation regime that supplied the least amount water without penalising the number of fruiting buds.

Average values (and standard deviation) of irrigation water for these selected irrigation regimes per site and soil type are shown in Table 5. A further analysis of the selected data i.e., regression of applied irrigation on rainfall deficit (calculated as potential evapotranspiration minus rainfall) showed a good relationship (R^2=0.45–0.85, Figure 9). Linear regression of data pooled across sites indicated a strong association of irrigation application rates and rainfall deficit (R^2=0.75; Figure 10). Therefore, the resulting equation (y=0.537x + 43.9) derived from the regression can be used to estimate productive irrigation requirements across sites given that drier areas (e.g., Cromwell) were associated with greater deficit and irrigation rates compared with lower irrigation requirements from wetter and cooler sites such as Palmerston North (Figure 10).

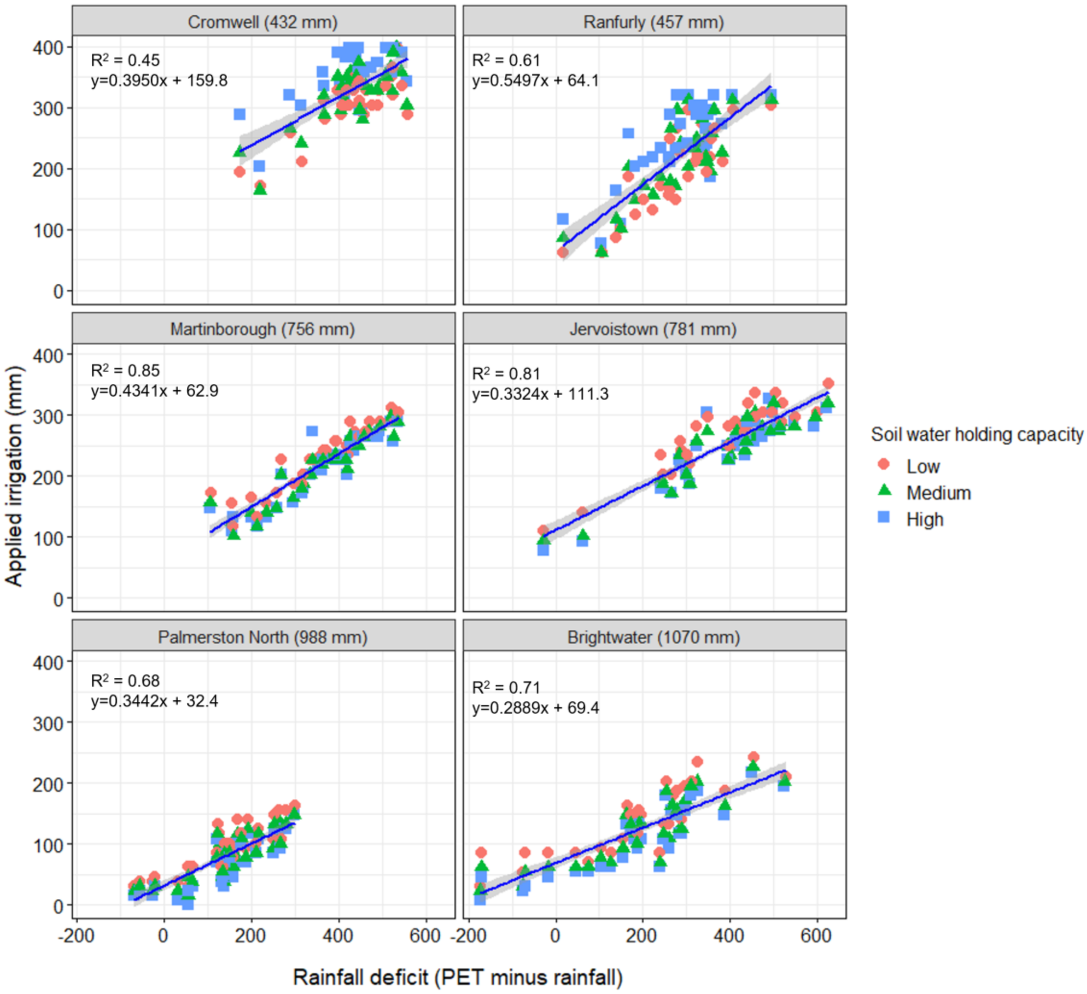

Figure 9. Summarised relationship between applied irrigation and rainfall deficit predicted by STRUM-APSIM from apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation management and weather conditions (determined by location). Results are based on simulations running continuously for 30 (1985–2014) years. PET represents potential evapotranspiration.

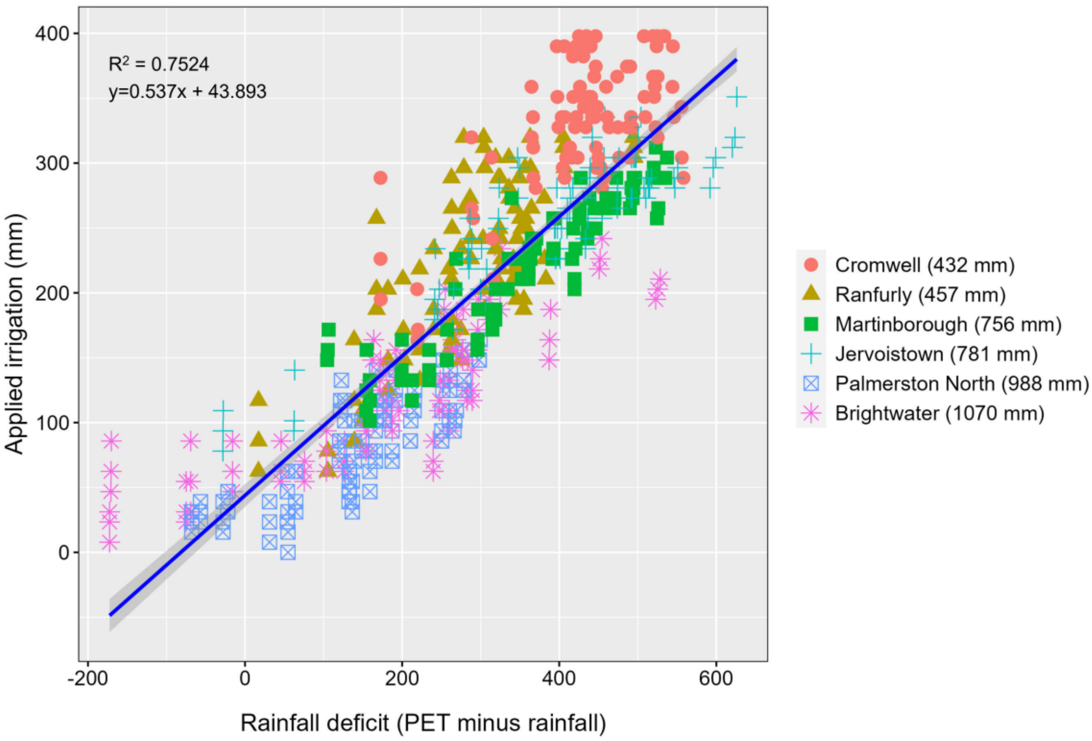

Figure 10. Relationship between applied irrigation and rainfall deficit predicted by STRUM-APSIM from apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation management and weather conditions (determined by location). Results are based on simulations running continuously for 30 (1985–2014) years. PET represents potential evapotranspiration.

3.3.2 Survival irrigation requirements

Graphs of fruiting bud proportion versus total irrigation were constructed from average values of simulations run continuously for 30 years (1985–2014) across soil types and irrigation treatments (Figure 11–12). The aim was to estimate the amount of water required to support orchard productivity in the following season as estimated by the percentage of fruiting buds. Our assumption was that an apple orchard would be unproductive if the number of fruiting buds per square meter dropped below 45 (i.e., 90%). As shown in Figure 11–12, the percentage of fruiting buds increased with the amount of applied irrigation, reaching a maximum at rates that were site-specific. The exception was for orchards on medium and high water holding capacity soils at sites with the highest annual average rainfall (i.e., Brightwater and Palmerston North) for which showed nil–negligible reduction of fruiting buds was predicted across irrigation treatments (Figure 11–12). This result indicates that the risk of loss of orchard productivity under water restrictions is low in regions receiving high rainfall and areas with high water retention soils. For the remaining treatments, the relationship between percentage of fruit buds and irrigation rates during the linear phase (Eq. 5) was used to calculate the amount of irrigation required for rootstock survival (estimated as irrigation required to support a 90% fruiting bud density.

$$Y = a + bX \qquad \text{Eq. 5}$$

where Y (dependent variable) is the proportion of fruiting buds (percentage out of 50), where X (independent variable) is the amount of irrigation (mm/season), a is the intercept and b is the slope. The coefficient of determination (R^2) ranged from 0.21–0.67. Calculated values of irrigation for rootstock survival are presented in Table 5.

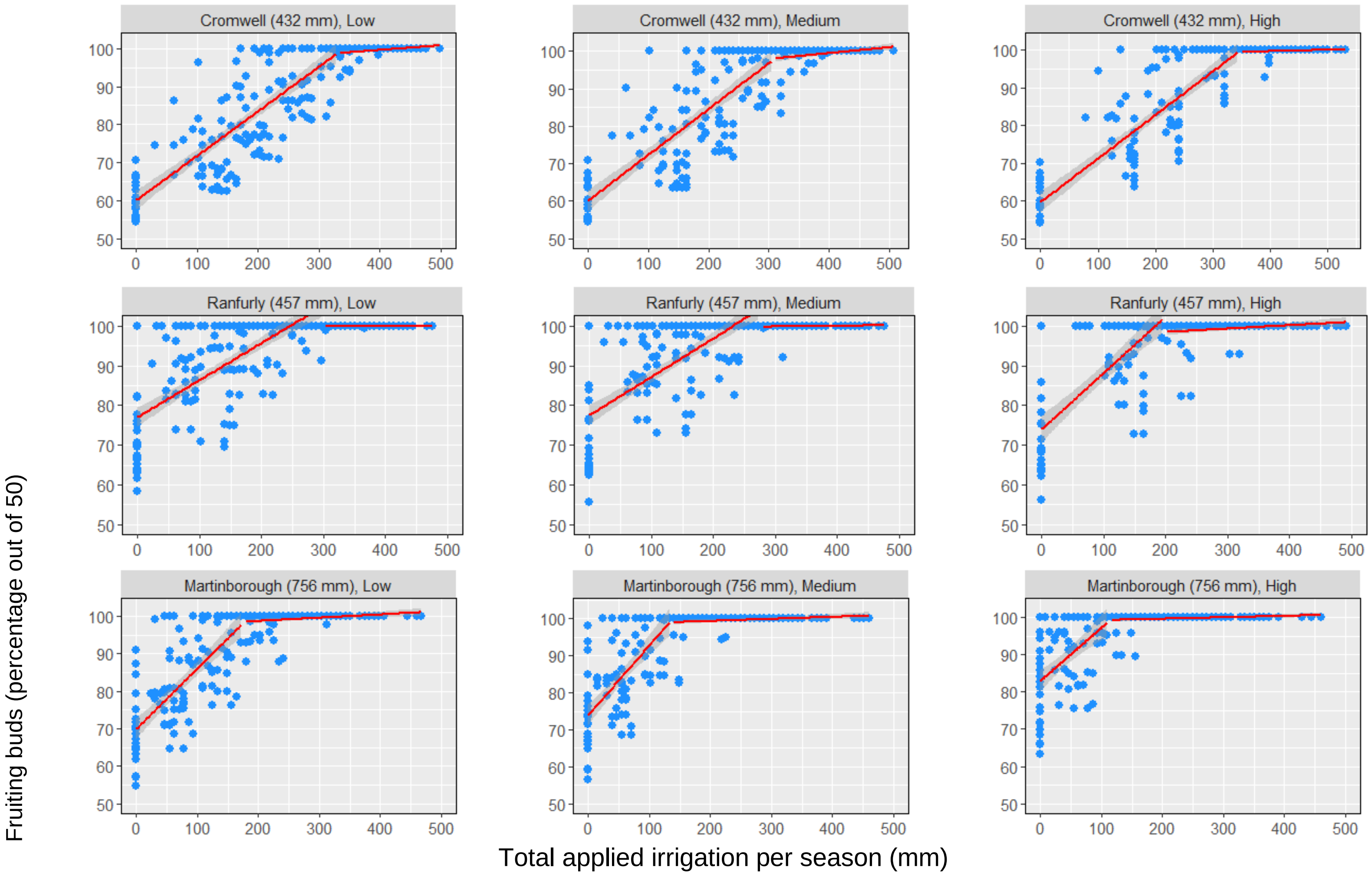

Figure 11. Percentage of fruiting buds in relation to applied irrigation and water stress predicted by STRUM-APSIM for apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation management and weather conditions (determined by location). Results are based on simulations running continuously for 30 (1985–2014) years at Brightwater, Cromwell and Martinborough sites.

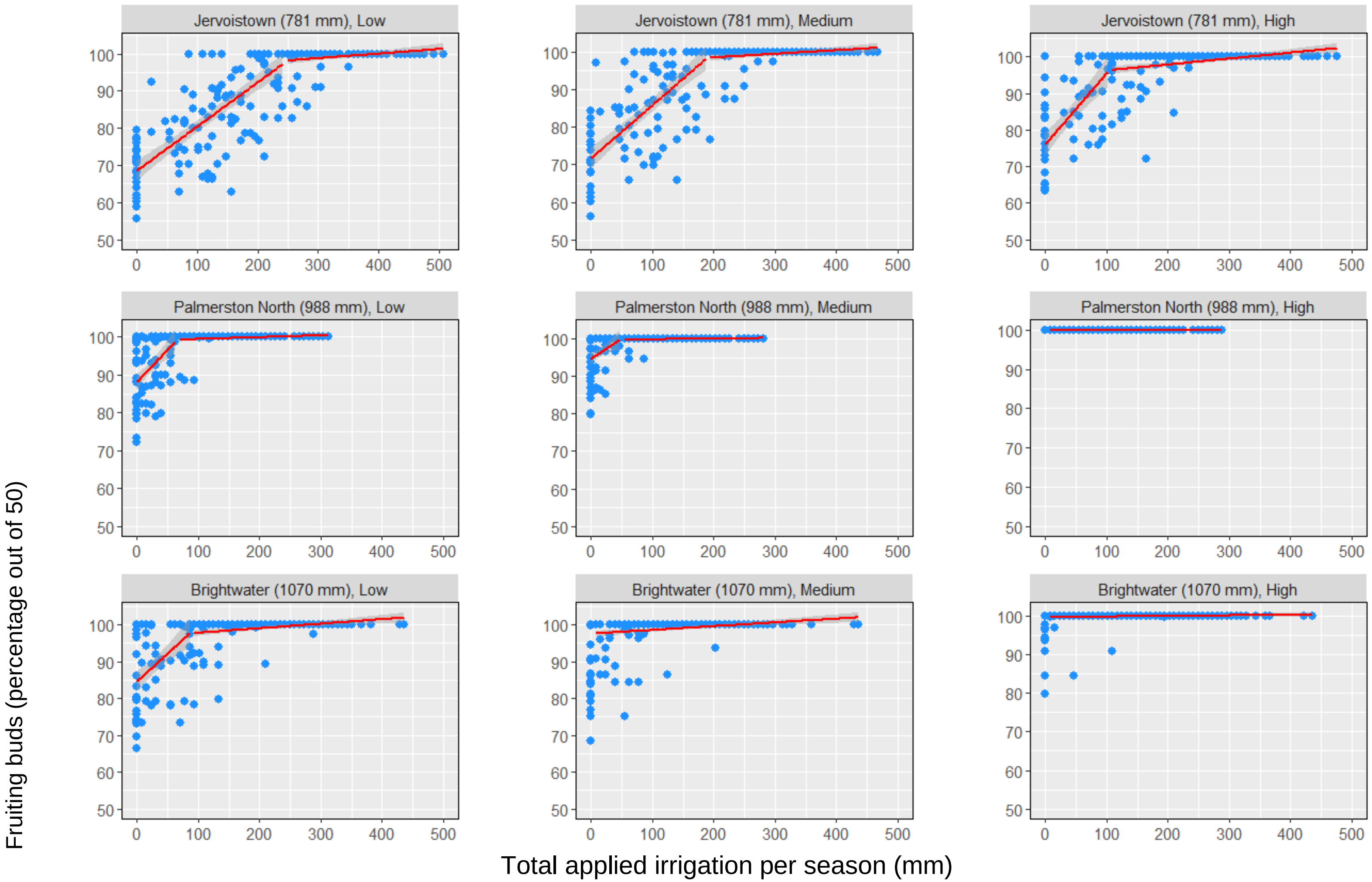

Figure 12. Percentage of fruiting buds in relation to applied irrigation and water stress predicted by STRUM-APSIM for apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation management and weather conditions (determined by location). Results are based on simulations running continuously for 30 (1985–2014) years at Jervoistown, Palmerston North and Brightwater sites.

Table 5. Estimates of rootstock productive and survival water requirements for apple orchards at different New Zealand sites. Values in the parentheses are the standard deviation. VCSN represents Virtual Climate Network (NIWA 2020).

Region	VCSN station	Long-term average rainfall (mm/yr)	Soil water holding capacity	Irrigation per season (* mm)		Quantile boundaries for survival irrigation		
				Productive	ΨSurvival (average)	High risk tolerance (mm/season)	Low risk tolerance (mm/season)	Quantile range
Otago	Cromwell	432	Low	371 (59)	255	226	339	0.25–0.60
			Medium	324 (50)	243	210	325	0.25–0.60
			High	358 (46)	252	230	332	0.25–0.60
Otago	Ranfurly	457	Low	295 (84)	138	90	195	0.25–0.60
			Medium	261 (76)	129	68	186	0.25–0.60
			High	246 (65)	138	107	203	0.25–0.50
Wellington	Martinborough	756	Low	230 (53)	126	116	155	0.25–0.60
			Medium	156 (44)	90	79	114	0.25–0.60
			High	155 (43)	49	12	85	0.25–0.60
Hawkes Bay	Jervoistown	781	Low	270 (54)	179	151	217	0.25–0.60
			Medium	194 (42)	129	111	169	0.25–0.60
			High	189 (44)	82	63	124	0.25–0.60
Manawatu	Palmerston North	988	Low	94 (41)	9	-	-	-
			Medium	80 (40)		-	-	-
			High	27 (26)		-	-	-
Tasman	Brightwater	1070	Low	139 (54)	38	24	67	0.25–0.60
			Medium	70 (43)		-	-	-
			High	18 (23)		-	-	-

*1 mm of water=10 m^3 ha^{-1}.
Ψ Values estimated using the regression function of the linear phase of segmented regression (see Figures 13 and 14).

In addition to linear regression, quantile regression was performed to explore different values of the response variable, instead of only the average, to give a complete picture of the relationships between the proportion of fruiting buds and irrigation amounts. An example of a range of quantile regressions is shown in (Appendix Figures A10) and a summary of coefficients (intercept and slope) are shown in (Appendix Figures A11–13). Results of quantile regression analysis showing the low (25^{th} percentile) and high (50^{th}/60^{th} percentile) risk tolerance to fruit bud loss are presented in Table 5. Productive irrigation correlated well with each of the estimated survival irrigation; R^2 of 0.92, 0.78 and 0.92 for Survival (average), low risk tolerance and high risk tolerance categories, respectively. Quantile regression equations for each site and soil type are presented in Appendix Table A1.

4 Conclusions

This study undertook the development of a simple fruit tree model (APSIM-STRUM) and ascertained its performance in predicting the dynamics of soil moisture, fruit biomass, radiation interception and tree transpiration. The model was then used to evaluate effect of water stress on the productivity of an apple orchard in the following season (estimated fruiting bud density) based on 30 years of climate data from two North Island and four South Island sites, providing a range of weather conditions.
A range of irrigation regimes (based on progressive withholding of irrigation during the season) and three soil types varying in water holding capacity were included in the evaluation. The conclusions drawn from the predictions are:

- The model predicted varying amounts of water stress from withholding irrigation. The response to irrigation regimes was influenced by weather and soil conditions.
- Water stress had a negative impact on fruit bud density; the risk of fruit bud loss was associated with drier sites with low water retention soils.
- The influence of climatic and soil factors on fruiting bud density implies irrigation requirements for orchards will vary depending on the site.
- Based on the irrigation schedule implemented in this study and assuming that loss of fruiting buds should be kept below 10% of the target post-pruning numbers, the model estimated per season irrigation requirements of 0–371 mm (0–3710 m^3 ha^{-1}) for productive orchards and 0–255 mm (0–2550 m^3 ha^{-1}) for apple rootstock survival, depending on soil type and location.
- There was wide variation in irrigation over the 30-year period of evaluation and an alternative (quantile) analysis indicated rootstock survival irrigation requirements of 0–226 mm (0–2260 m^3 ha^{-1}) and 339 mm (0–3390 m^3 ha^{-1}) at high and low risk tolerance levels, respectively. Details for individual locations and soil types are provided in Table 5.

5 Acknowledgements

We are very grateful to Brent Clothier and Paula Ibell for providing expert advice and review of the literature.

6 References

Allen RG, Pereira LS, Raes D, Smith M 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. . FAO.

Andrews PK, Chalmers DJ, Moremong M 1992. Canopy-air temperature differences and soil water as predictors of water stress of apple trees grown in a humid, temperate climate. J Am Soc Hort Sci 117(3): 453-458.

Anjum SA, Ashraf U, Zohaib A, Tanveer M, Naeem M, Ali I, Tabassum T, Nazir U 2017. Growth and developmental responses of crop plants under drought stress: a review. Zemdirbyste-Agriculture 104(3): 267-276.

Atkinson CJ, Policarpo M, Webster AD, Kuden AM 1998. Drought tolerance of apple rootstocks: production and partitioning of dry matter. Plant Soil 206(2): 223-235.

Bai T, Li Z, Song C, Song S, Jiao J, Liu Y, Dong Z, Zheng X 2019. Contrasting drought tolerance in two apple cultivars associated with difference in leaf morphology and anatomy. American Journal of Plant Sciences 10(5): 709-722.

Behboudian MH, Dixon J, Pothamshetty K 1998. Plant and fruit responses of lysimeter-grown 'Braeburn' apple to deficit irrigation. J Horticult Sci Biotechnol 73(6): 781-785.

Berman ME, DeJong TM 1996. Water stress and crop load effects on fruit fresh and dry weights in peach (Prunus persica). Tree Phys 16(10): 859-864.

Blanco-Cipollone F, Prieto MH, Vivas A, Lledo S, Monino MJ 2020. Controlled deficit irrigation in late Japanese plum: intense deficit versus late deficit

Riego deficitario controlado en ciruelo Japones de ciclo tardio: deficit intenso frente a deficit tardio.

Boland A, Ziehri A, Beaumont J 2002. Guide to Best Practice in Water Management: Orchard Crops . Murray-Darling Basin Commission, State of Victoria, Department of Natural Resources and Environment, Melbourne.

Boretti A, Rosa L 2019. Reassessing the projections of the World Water Development Report. NPJ Clean Water 2: 30.

Brown HE, Huth NI, Holzworth DP, Teixeira EI, Zyskowski RF, Hargreaves JNG, Moot DJ 2014. Plant Modelling Framework: Software for building and running crop models on the APSIM platform. Environ Model Software 62: 385-398.

Caspari HW, Behboudian MH, Chalmers DJ 1994. Water use, growth, and fruit yield of 'hosui' Asian pears under deficit irrigation. J Amer Soc Hort Sci 3: 383-388.

Chalmers DJ, Mitchell PD, van Heek L 1981. Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. J Amer Soc Hort Sci 106: 307-312.

Chandel JS, Chauhan JS 1990. Effect of rootstocks and soil moisture stress on growth and vigour of apple (Malus domestica Borkh.) cv. Starking Delicious. Punjab Hort J 30(1-4): 162-170.

Chartzoulakis K, Patakas A, Kofidis G, Bosabalidis A, Nastou A 2002. Water stress affects leaf anatomy, gas exchange, water relations and growth of two avocado cultivars. Sci Hortic 95(1/2): 39-50.

Chauhan PS, Sud A, Sharma LK, Mankotia MS 2005. Studies on the Effect of Micro-irrigation Levels on Growth, Yield, Fruit Quality and Nutrient Assimilation of Delicious Apple. Acta Hort 696: 193-196.

Chenafi A, Monney P, Arrigoni E, Boudoukha A, Carlen C 2016. Influence of irrigation strategies on productivity, fruit quality and soil-plant water status of subsurface drip-irrigated apple trees. Fruits 71(2).

Clothier BE, Green S, Hall A 2014. Root architecture, root dynamics, tree water-use and drought in apple trees. A Plant & Food Research report prepared for: Hawkes Bay Regional Council. Milestone No. 56019. Contract No: 30433. Job code: P/443015/04. PFR SPTS No 9346.

DeJong TM 2022. Energy capture and carbon assimilation. In: Wilford S, McCann E, eds Concepts for understanding fruit trees. CABI Concise: CABI International. p. 4-17.

Doltra J, Oncins JA, Bonany J, Cohen M 2007. Evaluation of plant-based water status indicators in mature apple trees under field conditions. Irrig Sci 25(4): 351-359.

Ebel RC, Proebsting EL, Evans RG 1995. Deficit irrigation to control vegetative growth in apple and monitoring fruit growth to schedule irrigation. HortSci 30(6): 1229-1232.

Ebel RC, Proebsting EL, Evans RG 2001. Apple tree and fruit responses to early termination of irrigation in a semi-arid environment. HortSci 36(7): 1197-1201.

English MJ, Musick JT, Murty VVN 1990. Deficit irrigatiion. In: Hoffman GJ, Howell TA, Solomon KH, eds Management of farm irrigation systems. American Society of Agricultural Engineers: MI. p. 630-663.

Failla O, Cocucci SM, Treccani CP 1987. Effect of different water deficits on fruit and vegetative growth of apple trees

Poster. Agrometeorology 2nd International Cesena Agricultura Conference, Cesena, 8-9 October 1987: 387-388.

FAO 2012. Crop yield and response to water https://www.fao.org/3/i2800e/i2800e08.pdf [accessed Mar 2023].

Fernandez JE, Cuevas MV 2010. Irrigation scheduling from stem diameter variations: a review. Agric For Met 150(2): 135-151.

Fernandez RT, Perry RL, Flore JA 1997. Drought response of young apple trees on three rootstocks: growth and development. J Am Soc Hort Sci 122(1): 14-19.

Freshfacts 2021. New Zealand's horticultural exports https://www.freshfacts.co.nz/files/freshfacts-2021.pdf [accessed Mar 2023].

Genard M, Huguet JG 1996. Modeling the response of peach fruit growth to water stress. Tree Phys 16(4): 407-415.

Goldhamer DA 1997. Regulated deficit irrigation for California canning olives. 3rd International Symposium on Olive Growing, Sep 22-26, Khania, Greece 10.17660/ActaHortic.1999.474.76. p. 369-372.

Goodwin I, McClymont L, Green S 2022. The effects of water deficits on fruit cracking and sunburn damage in 'Cripps Pink' apple. Acta Hort 10.17660/ActaHortic.2022.1335.52(1335): 421-428.

Green S, McNaughton K, Wunsche JN, Clothier B 2003a. Modeling light interception and transpiration of apple tree canopies. Agron J 95(6): 1380-1387.

Green SR, McNaughton KG 1997. Modelling effective stomatal resistance for calculating transpiration from an apple tree. Agric For Met 83(1-2): 1-26.

Green SR, Vogeler I, Clothier BE, Mills TM, van den Dijssel C 2003b. Modelling water uptake by a mature apple tree. Aust J Soil Res 41(3): 365-380.

Green SR, Hodson A, Barley M, Benson M 2013. Development and testing of the CropIRLog irrigation calculator for trees and vines. A report prepared for the Hawke's Bay Regional Council.

Hewett EW 1976. Irrigation of apple-trees in Nelson. N Z J Agric Res 19(4): 505-511.

Intrigliolo DS, Reig C, Mesejo C, Bonet L, Ferrer P, Soler E 2011. Usefulness of stem dendrometers as continuous water stress indicators of loquat tree water status. Acta Hort 887: 149-154.

Jackson JE, Parry MS, Stephens CP 1981. Intensification of tree fruit production: Current constraints, relevant research and an alternative system strategy for the 1980s. Acta Hortic 114: 399-406.

Kalcsits L, Valverdi N, Reid M 2022. Timing of water limitations affect source to sink differences in delta13C composition in apple. Acta Hort 10.17660/ActaHortic.2022.1335.54(1335): 437-443.

Katimbo A, Rudnick DR, DeJonge KC, Lo TH, Qiao X, Franz TE, Nakabuye HN, Duan JM 2022. Crop water stress index computation approaches and their sensitivity to soil water dynamics. Agric Wat Manag 266.

Khaembah EN, Brown HE, Zyskowski R, Chakwizira E, de Ruiter JM, Teixeira EI 2017. Development of a fodder beet potential yield model in the next generation APSIM. Agric Sys 158: 23-38.

Khorsand A, Rezaverdinejad V, Asgarzadeh H, Majnooni-Heris A, Rahimi A, Besharat S, Sadraddini AA 2021. Linking plant and soil indices for water stress management in black gram. Sci Reps 11(1).

Kucukyumuk C, Yildiz H, Meric MK 2020. The response of Braeburn apple to regulated deficit irrigation. Tarim Bilimleri Dergisi 26(2): 154-163.

Landsberg JJ, Jones HG 1981. Apple orchards In: Kozlowski TT, ed. Water deficit and plant growth. Elsevier Science: New York, NY, USA. p. 419–469.

Lo Bianco R 2019. Water-related variables for predicting yield of apple under deficit irrigation. Hort 5(8).

Lopez G, Girona J, Marsal J 2007. Response of winter root starch concentration to severe water stress and fruit load and its subsequent effects on early peach fruit development. Tree Phys 27(11): 1619-1626.

Lopez G, Behboudian MH, Girona J, Marsal J 2014. Yield and quality responses of deciduous fruit trees to drought and strategies for its mitigation. In: Theron K, ed. Acta Hort. p. 221-227.

Marsal J, Mata M, Arbones A, Campo Jd, Girona J, Lopez G 2008. Factors involved in alleviating water stress by partial crop removal in pear trees. Tree Phys 28(9): 1375-1382.

Mihaljevic I, Vuletic MV, Simic D, Tomas V, Horvat D, Josipovic M, Zdunic Z, Dugalic K, Vukovic D 2021. Comparative study of drought stress effects on traditional and modern apple cultivars. Plants 10(3).

Miller SA, Smith GS, Boldingh HL, Johansson A 1998. Effects of water stress on fruit quality attributes of kiwifruit. Ann Bot 81(1): 73-81.

Mills TM, Behboudian MH, Tan PY, Clothier BE 1994. Plant water status and fruit quality in 'Braeburn' apples. HortSci 29(11): 1274-1278.

Mills TM, Behboudian MH, Clothier BE 1997a. The diurnal and seasonal water relations, and composition, of 'Braeburn' apple fruit under reduced plant water status. Plant Sci 126(2): 145-154.

Mills TM, Clothier BE, Behboudian MH 1997b. The water relations of 'Braeburn' apple fruit grown under deficit irrigation. In: Chartzoulakis KS, ed. Acta Hort. p. 385-392.

Mitchell PD, Chalmers DJ 1982. The effect of reduced water-supply on peach-tree growth and yields. J Am Soc Hortic Sci 107(5): 853-856.

Mohamed AZ, Osroosh Y, Peters RT, Bates T, Campbell CS, Ferrer-Alegre F 2020. Monitoring water status in apple trees using a sensitive morning crop water stress index. Irrigat Drain 70(1): 27-41.

Moñino MaJ, Blanco-Cipollone F, Bodelón OG, Prieto MaH, Vivas A 2020. Evaluation of different deficit irrigation strategies in the late-maturing Japanese plum cultivar 'Angeleno'. Agric Wat Manag 234.

Moriana A, Orgaz F, Pastor M, Fereres E 2003. Yield responses of a mature olive orchard to water deficits. Journal of the American Society for Horticultural Science 128(3): 425-431.

Mpelasoka BS, Behboudian MH, Green SR 2001. Water use, yield and fruit quality of lysimeter-grown apple trees: responses to deficit irrigation and to crop load. Irrig Sci 20(3): 107-113.

Naschitz S, Naor A 2005. The effect of crop load on tree water consumption of 'Golden Delicious' apples in relation to fruit size: An operative model. J Am Soc Hort Sci 130(1): 7-11.

Naschitz S, Naor A, Genish S, Wolf S, Goldschmidt EE 2010. Internal management of non-structural carbohydrate resources in apple leaves and branch wood under a broad range of sink and source manipulations. Tree Phys 30(6): 715-727.

NIWA 2020. Climate database-NIWA. http://cliflo.niwa.co.nz/. http://cliflo.niwa.co.nz/. [accessed April 2023].

O'Connell MG, Goodwin I 2007. Responses of 'Pink Lady' apple to deficit irrigation and partial rootzone drying: physiology, growth, yield, and fruit quality. Aust J Agric Res 58(11): 1068-1076.

Patten K, Nimr G, Neuendorff E 1989. Fruit doubling of peaches as affected by water stress 10.17660/ActaHortic.1989.254.53. International Society for Horticultural Science (ISHS), Leuven, Belgium. p. 319-322.

Proebsting EL, Jr., Middleton JE, Mahan MO 1981. Performance of bearing cherry and prune trees under very low irrigation rates. J Am Soc Hort Sci 106(2): 243-246.

Rahmati M, Gholam Hossein D, Génard M, Bannayan M, Azizi M, Vercambre G 2015. Peach water relations, gas exchange, growth and shoot mortality under water deficit in semi-arid weather conditions. PLoS ONE 10(4).

Reid M, Lee K 2020. Water deficit timing affects physiological drought response, fruit size, and bitter pit development for 'honeycrisp' apple. Plants 9: 874.

Ritter A, Munoz-Carpena R 2013. Performance evaluation of hydrological models: Statistical significance for reducing subjectivity in goodness-of-fit assessments. J Hydrol 480: 33-45.

Ruiz-Sanchez MC, Egea J, Galego R, Torrecillas A 1999. Floral biology of 'Bulida' apricot trees subjected to postharvest drought stress. Ann Appl Biol 135(2): 523-528.

Ruiz-Sanchez MC, Domingo R, Castel JR 2010. Deficit irrigation in fruit trees and vines in Spain. Span J Agric Res 8(Special issue (S2)): S5-S20.

Silber A, Naor A, Cohen H, Bar-Noy Y, Yechieli N, Levi M, Noy M, Peres M, Duari D, Narkis K et al. 2019. Irrigation of 'Hass' avocado: effects of constant vs. temporary water stress. Irrig Sci 37(4): 451-460.

Smith P, Smith JU, Powlson DS, McGill WB, Arah JRM, Chertov OG, Coleman K, Franko U, Frolking S, Jenkinson DS et al. 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81(1-2): 153-225.

Syvertsen JP 1985. Integration of water stress in fruit trees. HortSci 20(6 (1)): 1039-1043.

Teixeira EI, Brown HE, Michel A, Meenken E, Hu W, Thomas S, Huth NI, Holzworth DP 2018. Field estimation of water extraction coefficients with APSIM-Slurp for water uptake assessments in perennial forages. Field Crops Res 222: 26-38.

Thompson RB, Gallardo M, Valdez LC, Fernandez MD 2007. Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors. Agric Wat Manag 88(1-3): 147-158.

Torrecillas A, Domingo R, Galego R, Ruiz-Sanchez MC 2000. Apricot tree response to withholding irrigation at different phenological periods. Sci Hortic 85(3): 201-215.

Tustin DS, Breen KC, van Hooijdonk BM 2022. Light utilisation, leaf canopy properties and fruiting responses of narrow-row, planar cordon apple orchard planting systems-A study of the productivity of apple. Sci Hortic 294.

Vosnjak M, Mrzlic D, Hudina M, Usenik V 2021. The effect of water supply on sweet cherry phytochemicals in bud, leaf and fruit. Plants (Basel) 10(6).

Wang D, Gartung J, Zhang H 2020. Long-term productivity of early season peach trees under different irrigation methods and postharvest deficit irrigation. Agric Wat Manag 230.

Wojcik D, Marat M, Marasek-Ciolakowska A, Klamkowski K, Buler Z, Podwyszynska M, Tomczyk PP, Wojcik K, Treder W, Filipczak J 2022. Apple autotetraploids-phenotypic characterisation and response to drought stress. Agron 12(1).

Wright DEJ, Cline JA, Earl HJ 2019. Physiological responses of four apple (Malus * domestica Borkh.) rootstock genotypes to soil water deficits. Can J Plant Sci 99(4): 510-524.

Yang W, Pallas B, Durand JB, Martinez S, Han M, Costes E 2016. The impact of long-term water stress on tree architecture and production is related to changes in transitions between vegetative and reproductive growth in the 'Granny Smith' apple cultivar. Tree Phys 36(11): 1369-1381.

Zuazo VHD, Lipan L, Rodriguez BC, Sendra E, Tarifa DF, Nems A, Ruiz BG, Carbonell-Barrachina AA, Garcia-Tejero IF 2021. Impact of deficit irrigation on fruit yield and lipid profile of terraced avocado orchards. Agron Sustain Dev 41(5).

Appendices

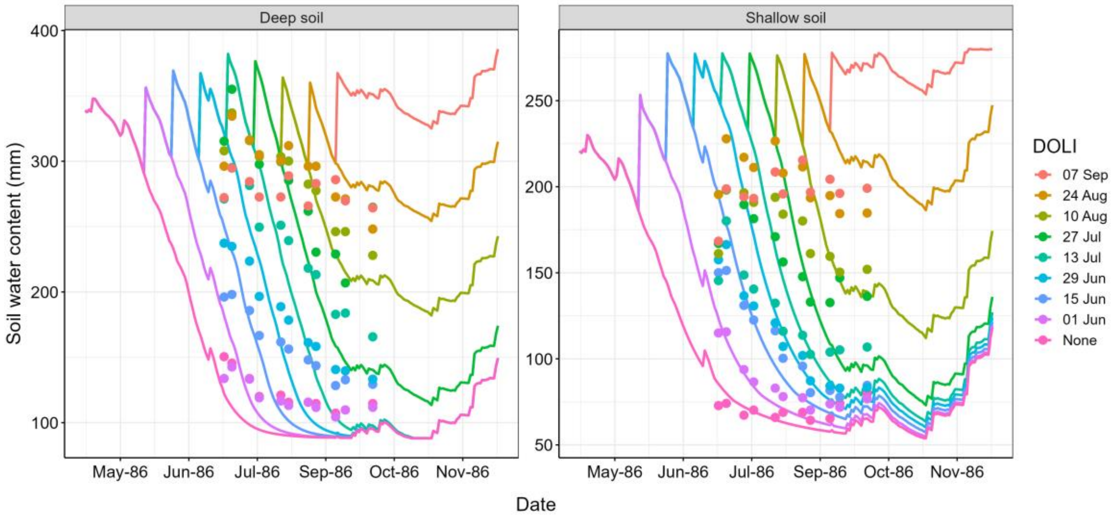

Figure A1. Measured (symbols) and predicted (lines) of soil moisture dynamics in apple orchards with different soil depths and under different irrigation management in Prosser, USA. DOLI=date of last irrigation, None=no applied irrigation. Trees were irrigated between 01 June and 07 September 1986. Data source: Ebel et al. (2001).

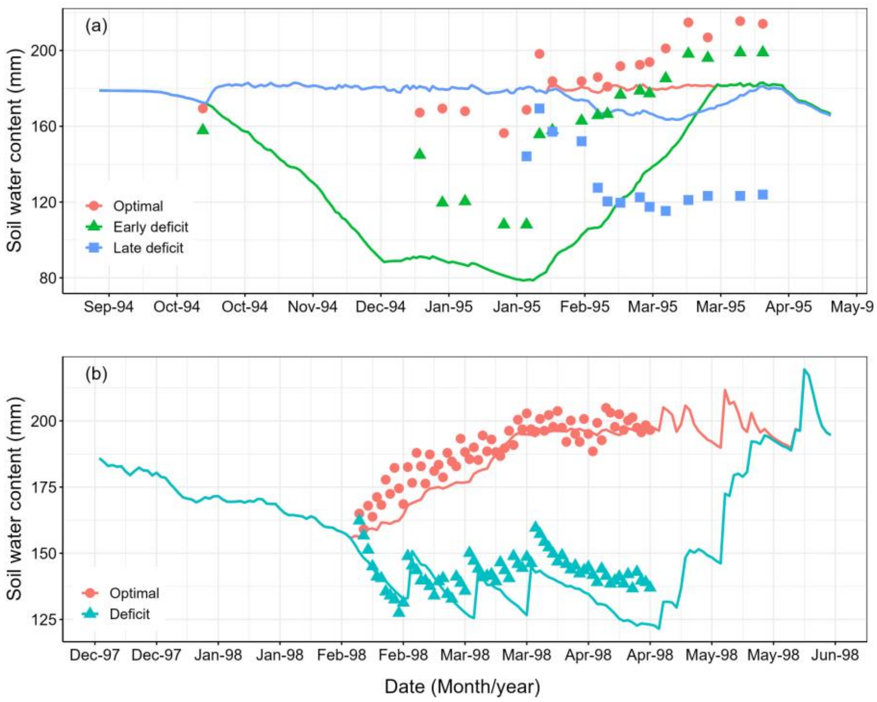

Figure A2. Measured (symbols) and predicted (lines) changes in soil moisture content in lysimeters in Palmerston North, New Zealand. Measurements were based 4-year-old apples trees planted in lysimeters (one tree per lysimeter) and assigned to different irrigation regimes: optimal, early deficit and late deficit in 1994 (a) and optimal and deficit in 1997 (b). Experiment details are reported by Mills et al. (1997a) and Mpelasoka et al. (2001).

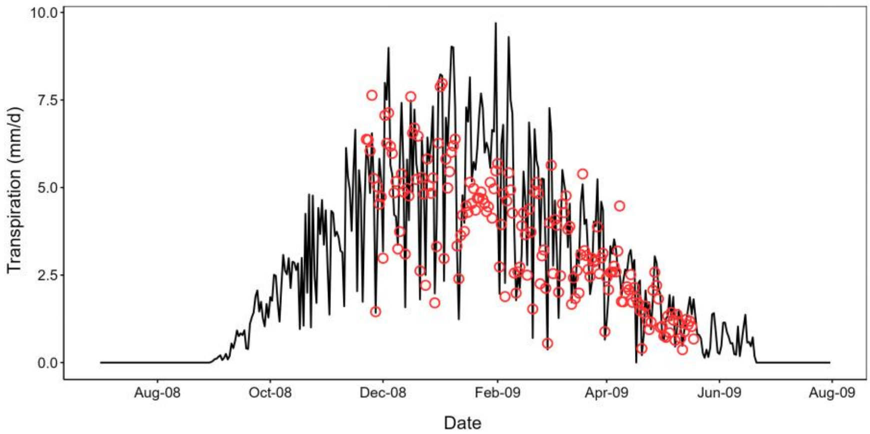

Figure A3. Measured (symbols) and predicted (lines) transpiration for dwarf apples. Data source: Green et al (2013).

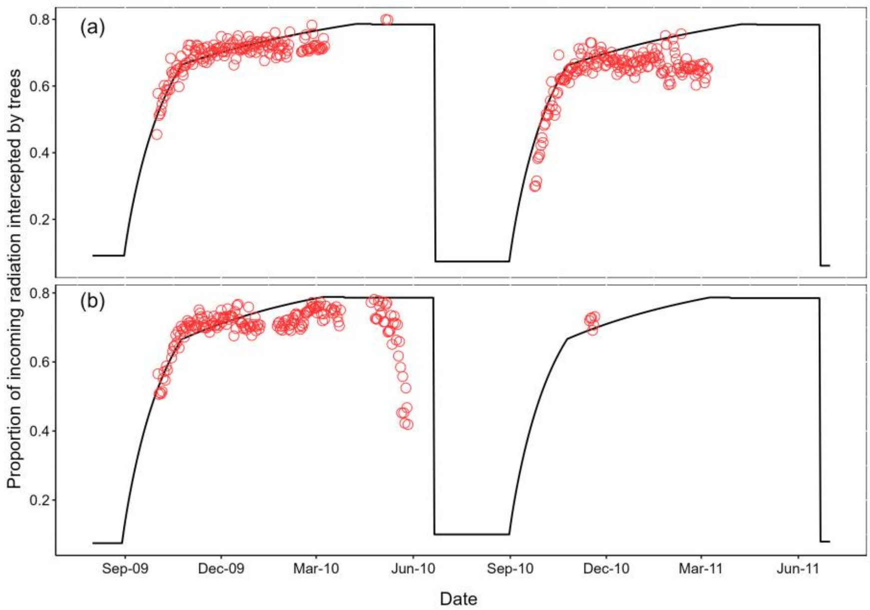

Figure A4. Measured (symbols) and predicted (lines) proportion of incoming radiation intercepted by (a) dwarf and (b) tall apple trees. Data source: Green et al (2013).

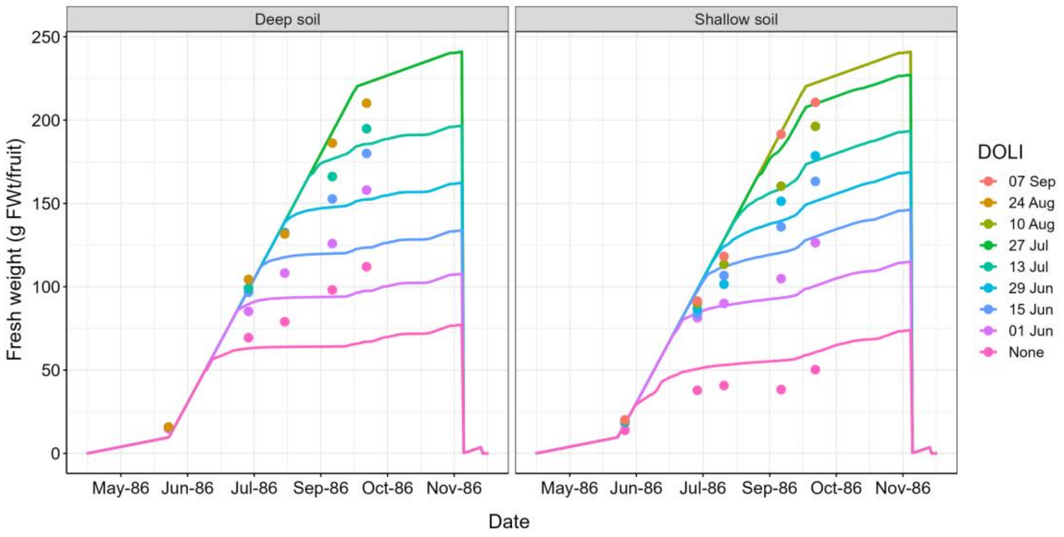

Figure A5. Measured (symbols) and predicted (lines) of fruit weight of apples growing in orchards with different soil depths and under different irrigation managements in Prosser, USA. DOLI represents date of last irrigation; None represents no applied irrigation. Trees were irrigated between 01 June and 07 September 1986. Data source: Ebel et al. (2001).

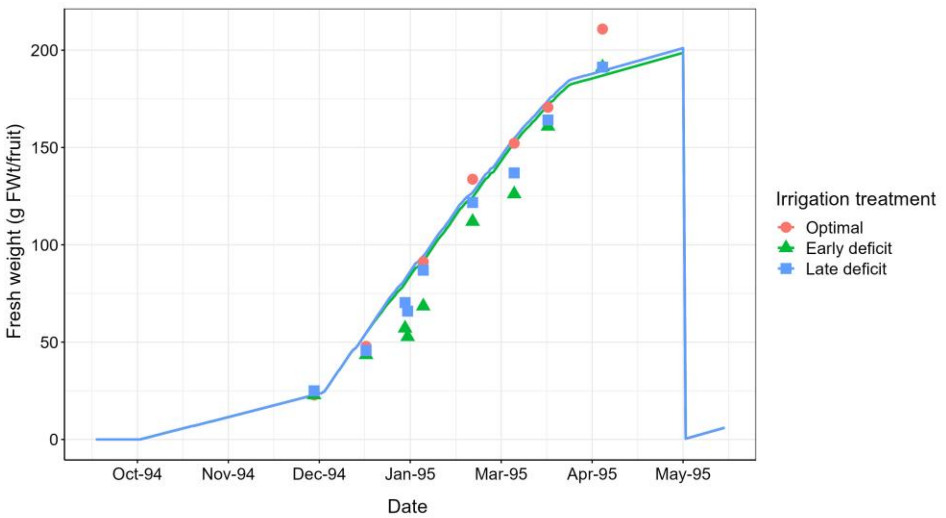

Figure A6. Measured (symbols) and predicted (lines) of fruit weight of apples growing in lysimeters under different irrigation managements in Palmerston North, New Zealand. Data source: Mills et al. (1997a).

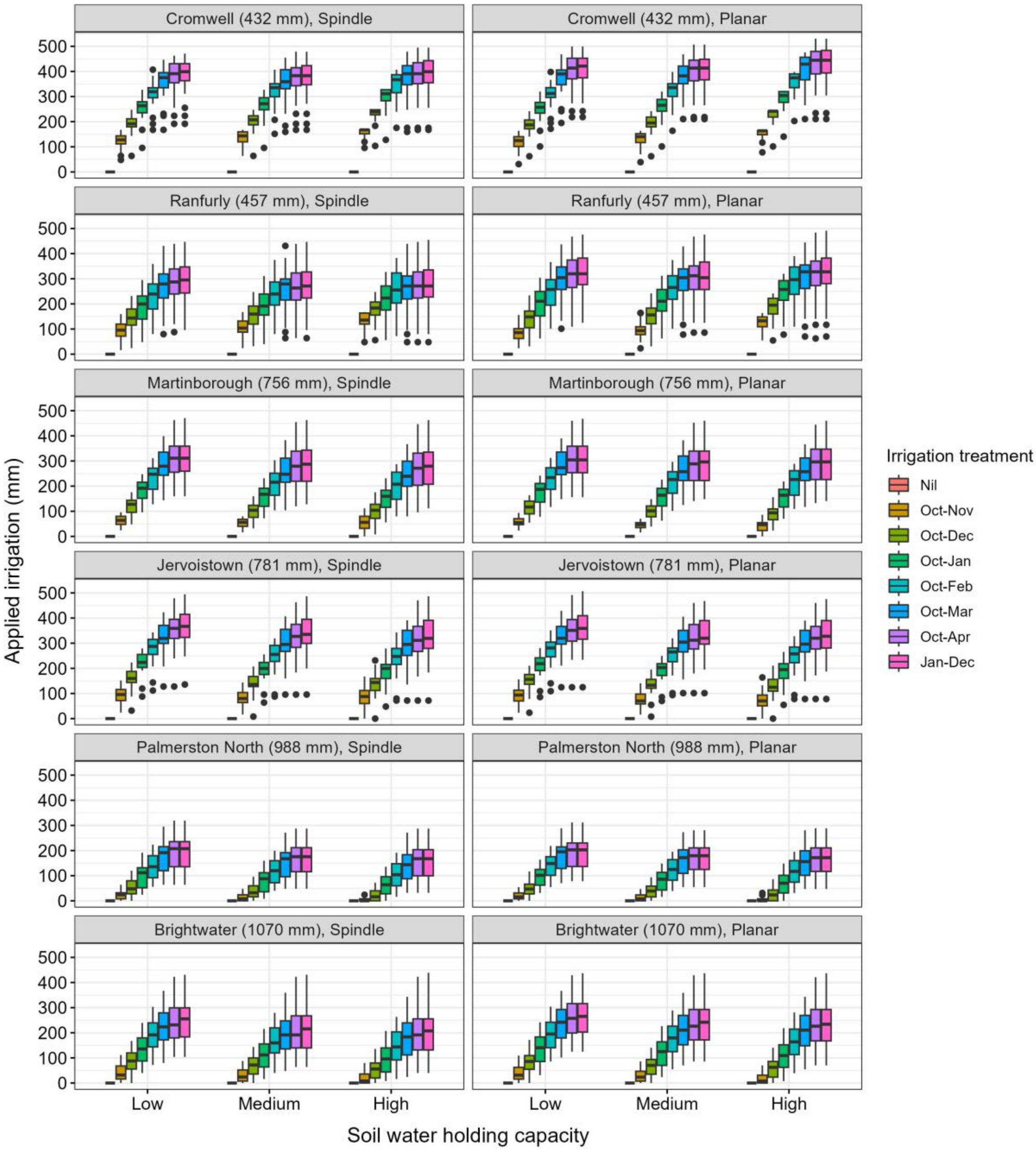

Figure A7. Boxplots showing annual total applied irrigation predicted by STRUM-APSIM for apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation managements and weather conditions (determined by location). Orchard design (spindle and planar) were included in simulations. Results are based on simulations running continuously for 30 (1985–2014) years.

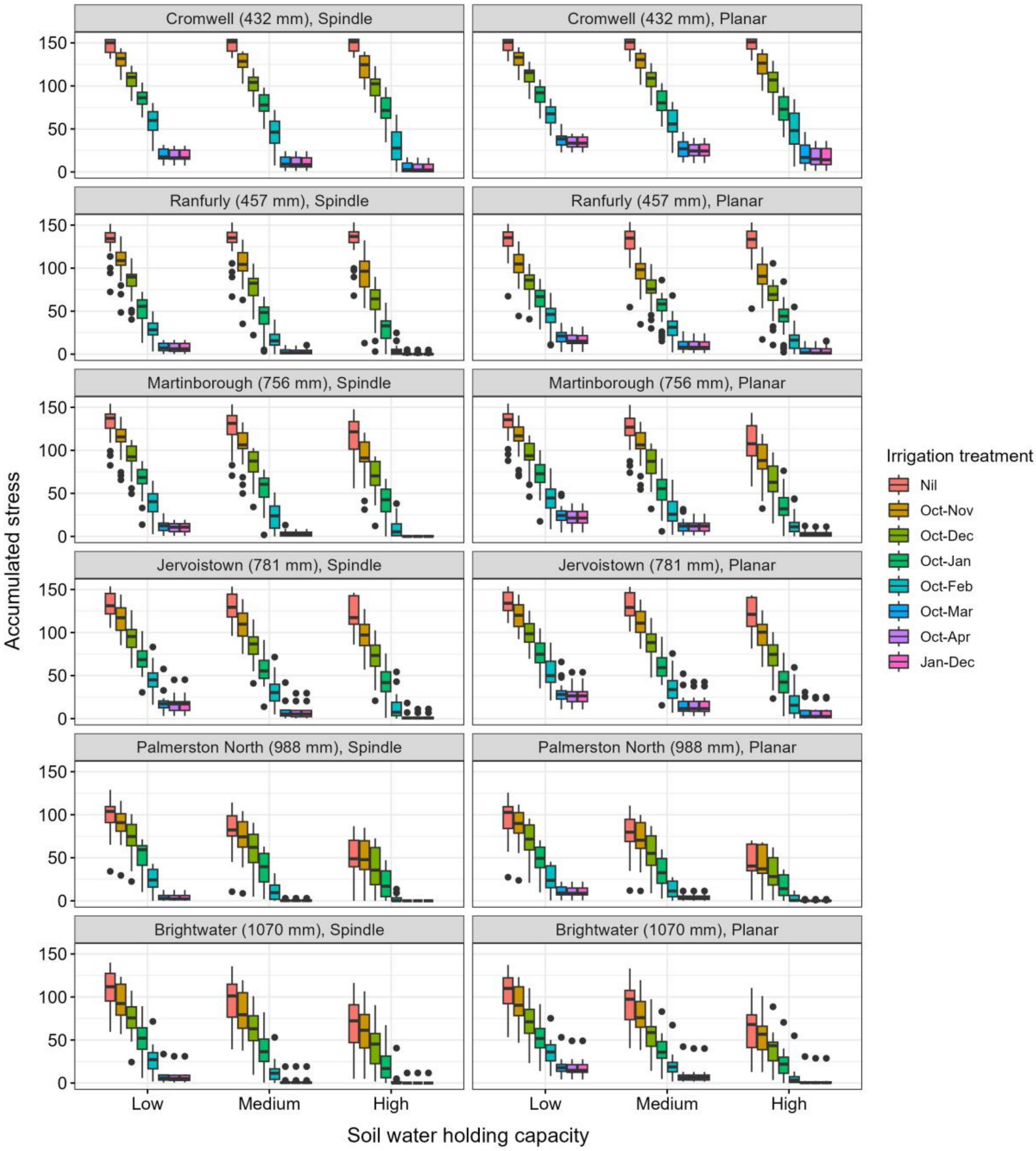

Figure A8. Boxplots showing STRUM-APSIM-estimated water stress accumulated during the season for apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation managements and weather conditions (determined by location). Orchard design (spindle and planar) were included in simulations. Results are based on simulations running continuously for 30 (1985–2014) years.

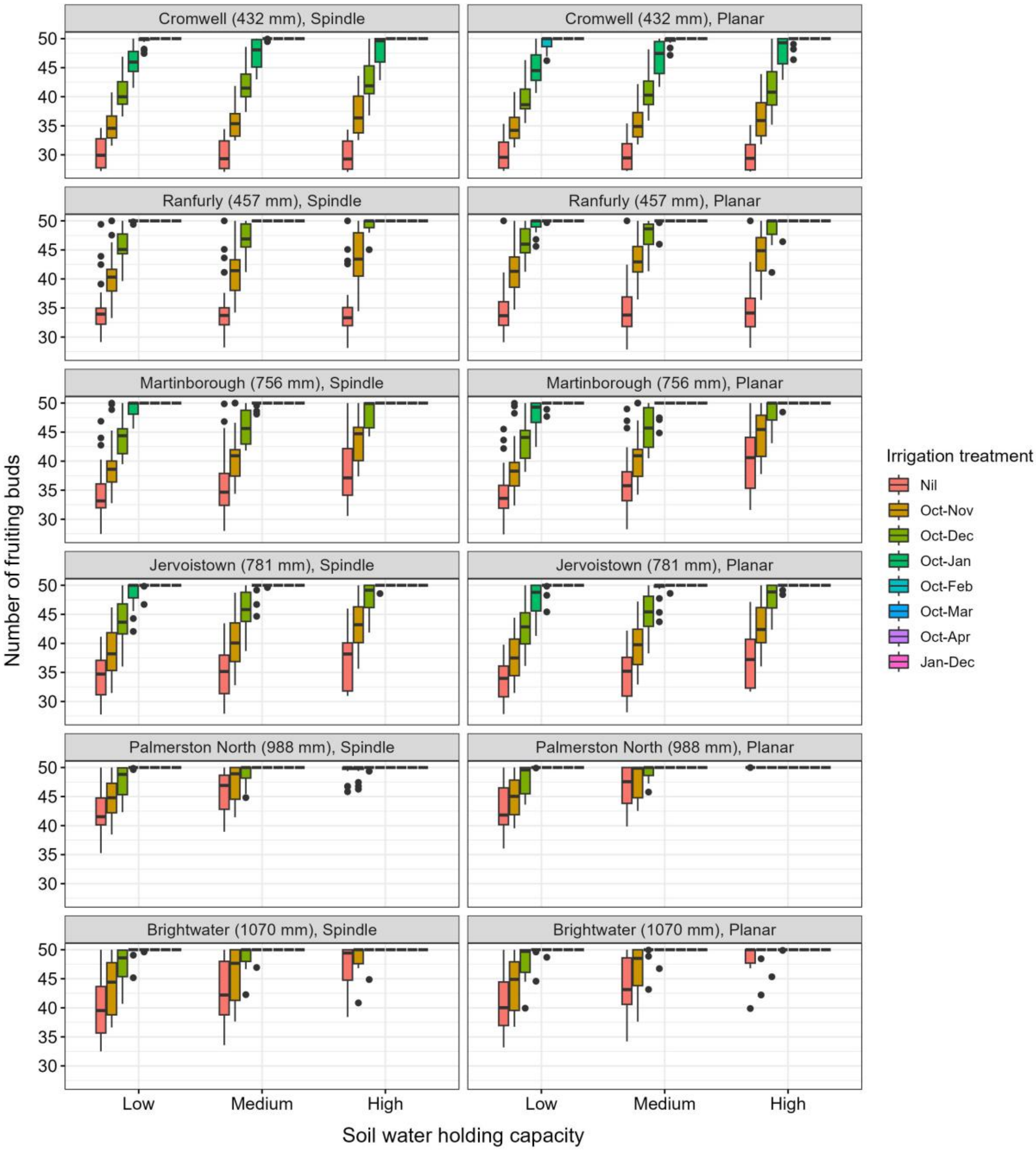

Figure A9. Boxplots showing STRUM-APSIM-estimated effect of irrigation management on the number of fruiting buds for apple orchards established on different soil types (low, medium and high water holding capacity) and subjected to different irrigation managements and weather conditions (determined by location). Orchard design (spindle and planar) were included in simulations. Results are based on simulations running continuously for 30 (1985–2014) years. Note: colours of some irrigation treatments (Oct–Mar, Oct–Apr, Jan–Dec) do not appear on the graph because they resulted in nil loss of fruiting buds.

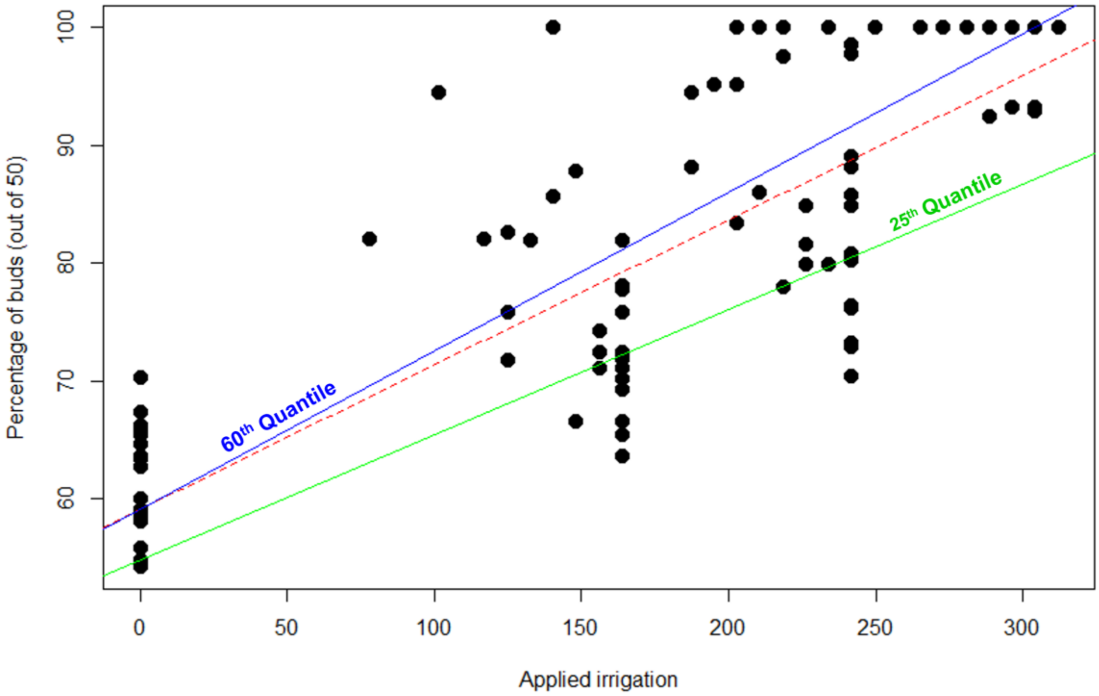

Figure A10. Ordinary least squares (dotted line) and quantile (25th and 60th) regressions of percentage buds against applied irrigation values estimated by APSIM-STRUM for apple orchards established at Cromwell on high water holding capacity soils.

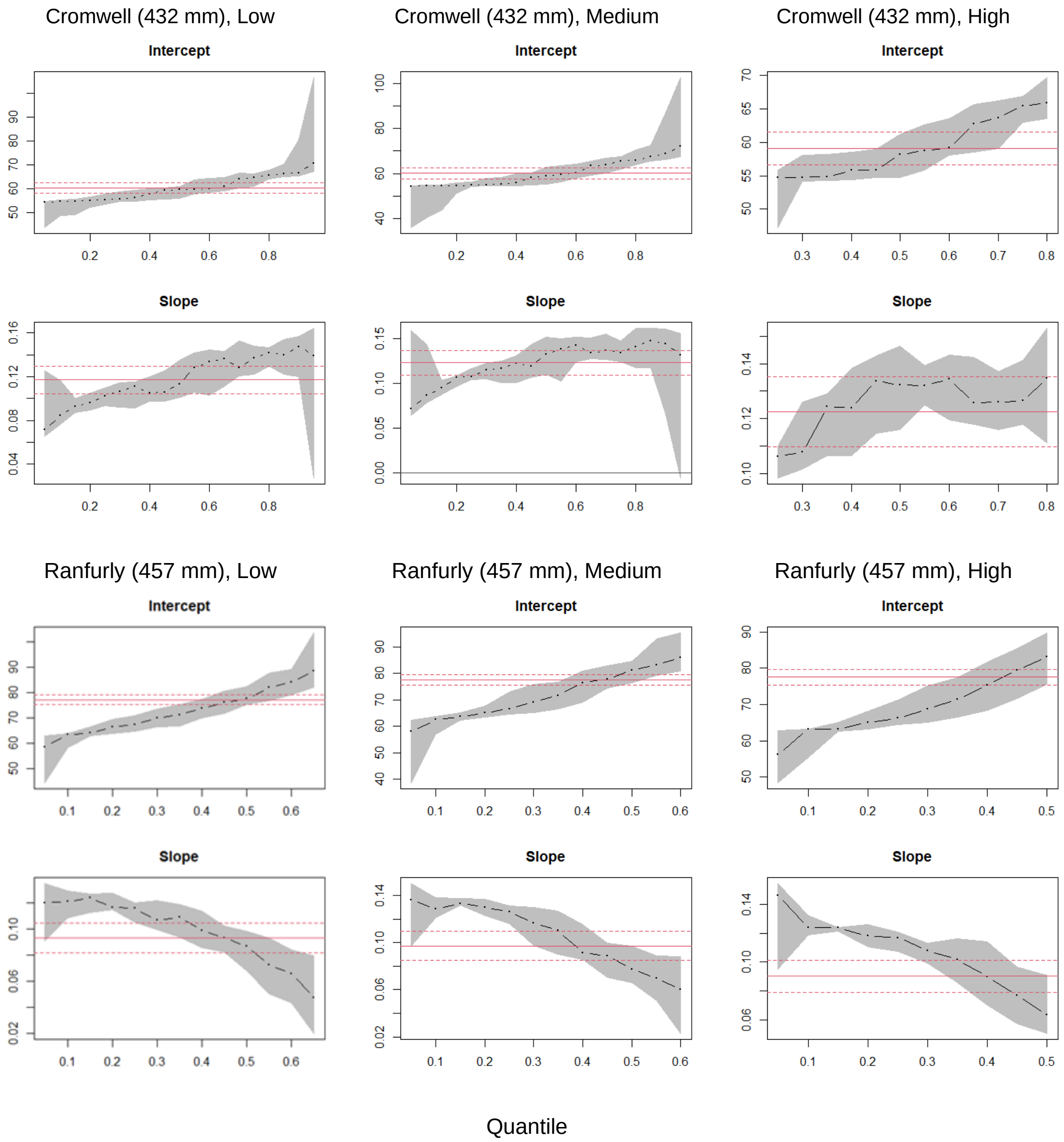

Figure A11. Estimated coefficients with 95% confidence intervals from quantile regression analysis (percentage of buds ~ applied irrigation) for data predicted by APSIM-STRUM for apple orchards established on soils with low, medium and high water holding capacity at Cromwell and Ranfurly.

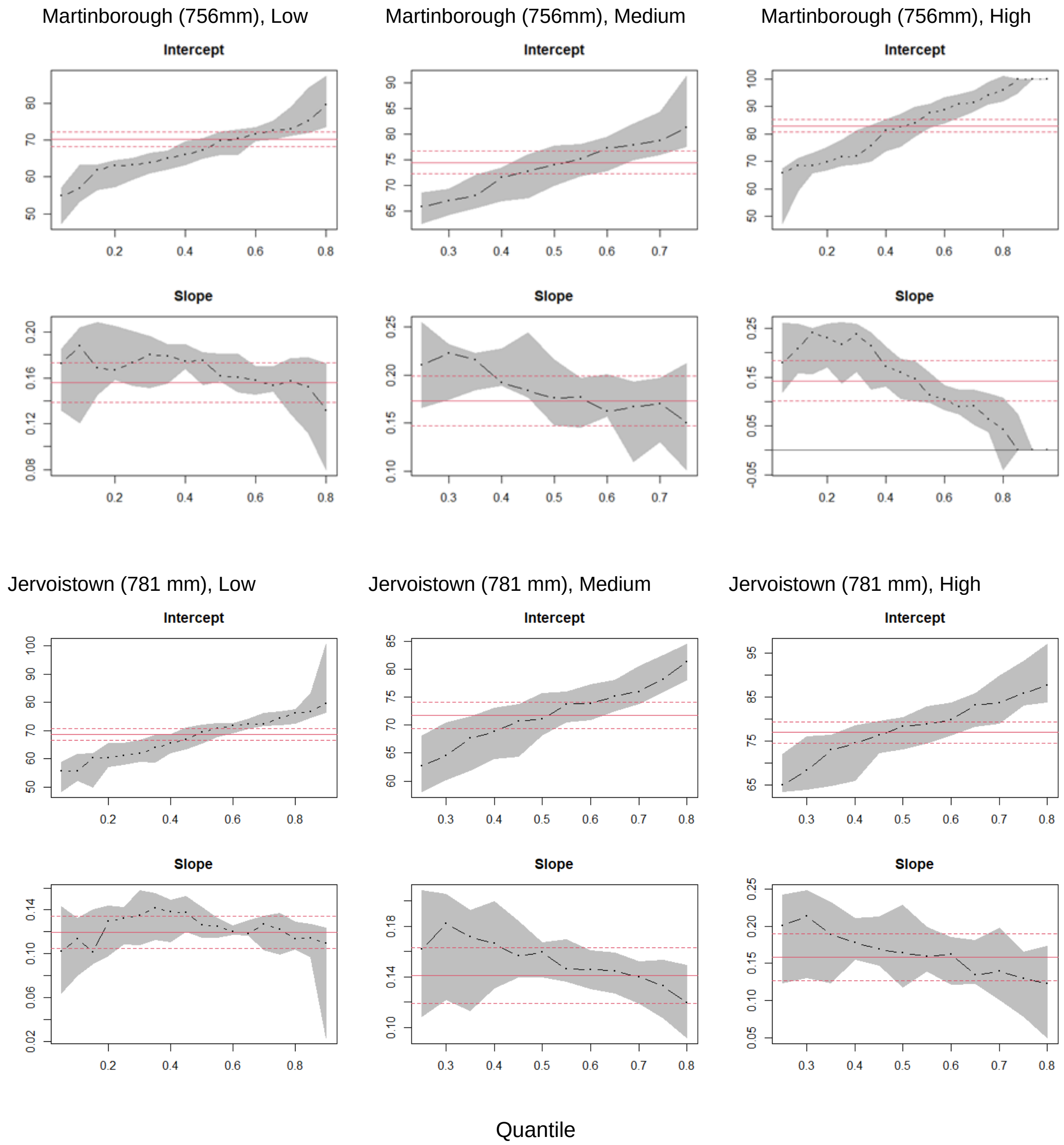

Figure A12. Estimated coefficients with 95% confidence intervals from quantile regression analysis (percentage of buds ~ applied irrigation) for data predicted by APSIM-STRUM for apple orchards established on soils with low, medium and high water holding capacity at Martinborough and Jervoistown.

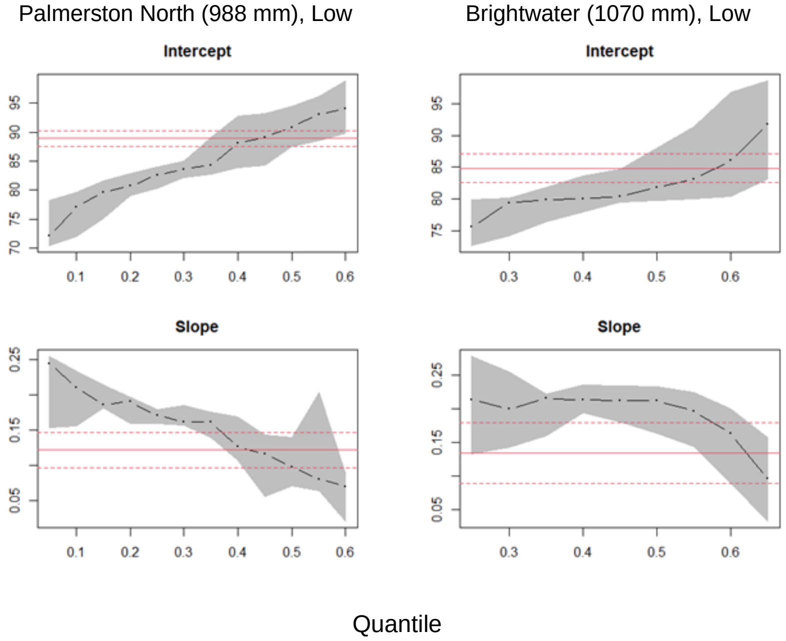

Figure A13. Estimated coefficients with 95% confidence intervals from quantile regression analysis (percentage of buds ~ applied irrigation) for data predicted by APSIM-STRUM for apple orchards established on soils with low, medium and high water holding capacity at Palmerston North and Brightwater.

Table A1. Quantile regression equations for percentage buds against applied irrigation values estimated by APSIM-STRUM for apple orchards established on soils with low, medium and high water holding capacity at different New Zealand locations. VCSN represents Virtual Climate Network. In the equation, Y is the percentage of buds and X is the amount of irrigation in mm.

		Regression equation	
VCSN station	Soil water holding capacity	25th quantile	60th quantile
Cromwell	Low	Y = 0.10242X + 55.3	Y = 0.13335X + 59.9
	Medium	Y = 0.10757X + 55.0	Y = 0.14215X + 60.1
	High	Y = 0.10622X + 54.8	Y = 0.13433X + 59.1
Ranfurly	Low	Y = 0.11628X + 67.3	Y = 0.06603X + 84.0
	Medium	Y = 0.12604X + 66.6	Y = 0.06036X + 85.9
	High	Y = 0.11698X + 66.2	Y = 0.06337X + 83.2*
Martinborough	Low	Y = 0.17291X + 63.2	Y = 0.15790X + 71.7
	Medium	Y = 0.21042X + 65.9	Y = 0.16219X + 77.2
	High	Y = 0.21644X + 71.6	Y = 0.10384X + 88.8
Jervoistown	Low	Y = 0.13233X + 61.2	Y = 0.12049X + 71.8
	Medium	Y = 0.16190X + 62.7	Y = 0.14573X + 73.9
	High	Y = 0.20068X + 65.0	Y = 0.16214X + 79.8
Brightwater	Low	Y = 0.21370X +75.7	Y = 0.16275X +86.0

*Equation based on the 50th quantile

A smart
green
future.
Together.