Understanding the pomology of the planar cordon tree architecture in apple.

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Abstract

Future Orchard Planting Systems (FOPS) is a radical new concept for orchard systems aimed at doubling the productivity of New Zealand orchards across key fruit sectors. The programme incorporates new orchard configurations using a two-dimensional planar tree architecture designed to harness ≥ 85% seasonal radiation when fully-grown. Metrics to manage fruit density, fruit quality and return bloom have not yet been calibrated for new planar tree designs. Additionally, the understanding around the light environment of this new two-dimensional system is unknown. Therefore, four and five-year-old planar cordon trees of 'Royal Gala' and 'Scifresh' (Jazz™) were used in 2018 and 2019 to investigate relationships between the final crop density (fruit no/cm^2 BCA) and the light environment on yield and fruit quality at harvest.

Individual fruit weights from each branch unit were quantified at harvest using an electronic weight sizer and Invision system (Compac New Zealand). Branch unit fruit density present after hand thinning ranged from 1.8 to 13.5 fruit/cm^2 BCA in 2018 and 2.5 to 28 fruit/cm^2 BCA in 2019. Crop densities in the upper range were nearly five times that typically used for branch units in conventional tall spindle trees. As crop density increased, fruit weight did not change. A simple linear correlation suggests that for both cultivars the relationship between fruit weight and crop density was weak, with r^2 values ranging from 0.004 to 0.108 in 2018 and 0.024 to 0.248 in 2019. Fruit density did not affect fruit size below 28 fruit/cm^2 BCA. However, there was evidence of reduced return bloom at the closer, 1.5 m row spacing for 'Scifresh' only in 2018.

Light measurements at 5 different heights in the planar canopies were completed over four complete replicate days during January 2019. Light readings were recorded using a LI-COR data logger and 'Palmer' sensors fixed onto a vertical steel rod placed within the tree. Light irradiance ranged from approximately 60 to 1419 µmol/m^2/s in the middle of the day. A simple regression suggested that light energy received at each position was higher in the top of the canopy compared to the bottom, with r^2 values of 0.979 for 'Royal Gala' and 0.965 for 'Scifresh'. A typical level of light in this planar canopy would reach 12% at the bottom, 32% in the middle and 60% at the top in terms of percentage of total incoming radiation. Leaf area index at a whole tree level (uprights as well as the cordon) within the planar cordon system (Vertical canopy only) ranged from 3.1 – 4.0 at the 1.5 m spacing and 2.6 – 3.1 at the 2.0 m row spacing, consequently producing high yields at 132-159 t/ha at 1.5 m (planting density of 2222 trees/ha) and 115-121 t/ha at 2.0 m row spacing (planting density of 1667 trees/ha) for 'Royal Gala' and 'Scifresh'. Fresh fruit weight, dry matter content, red colour and specific leaf weight increased with increasing height in the canopy. These fruit quality

attributes also showed positive correlations with the daily light integral (mol/m^2). We discuss the implications of these findings for yield and fruit quality optimisation within this planar cordon planting system.

It was concluded that crop loading metrics for this planar cordon training system differ in comparison to the conventional tall spindle design. The light environment increased with canopy height and successfully supported the production of high quality fruit in terms of fruit size, colour and dry matter content. Future work directions may include quantifying the performance of this system at full canopy development as well as assessing the internal quality of fruit grown on a 2D planar cordon training system.

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1 Introduction and literature review

1.1 The New Zealand pipfruit industry

1.1.1 History

Pipfruit is crucial to the New Zealand economy, with total production of 568,000 tonnes in 2018 and increasing (Lee-Jones et al., 2018). In 2018, 377,000 tonnes was exported, 73,300 tonnes is supplied to the domestic market and the remaining 120,000 tonnes is used for processing or juice (Lee-Jones et al., 2018). The vast majority of fruit grown is exported to international markets, in particular the Northern Hemisphere including, Asia (39%), Continental Europe (26%), Americas (13%), UK and Ireland (13%), Middle East (5%) and the Pacific (2%) (FreshFacts, 2018). The major apple growing regions in New Zealand include Hawkes Bay (4746 ha), Nelson (2400 ha) Otago (427 ha) and Canterbury (312 ha).

From 1991, the pipfruit industry operated under an export monopoly, held by ENZA Ltd until October 2001, when it was deregulated by the NZ government. Deregulation lead to a reduction in the number of orchards (21%), planted hectares (34%) and pack houses/cool stores (54%) (FreshFacts, 2001, 2018), but an increase in exporters (to 80, though varying in size) (FreshFacts, 2018) from 2001 to 2018. The industry remained financially stable until the 2004-2005 seasons where it took a down turn with a rise in the world supply and a high NZ$ exchange rate. The main cause being, falling consumption in key markets, global overproduction, new varieties taking time to perform but mainly the uncertainty around the industry structure transition (CoriolisResearchLTD, 2006). Since 2005, conducive growing seasons (frost free, no hail, etc.) and rising market demand created positive momentum within the industry, which has now developed a reputation for consistently producing high quality apples globally (Dobbs, 2006).

1.1.2 Sustainability/resource use

In production systems of apple, sustainability focus by the New Zealand apple industry is placed on land use and resource use. The most effective way of increasing the level of sustainability in New Zealand orchards is by increasing productivity off the same land area with more efficient use of resources (land, water, nutrients and labour). This may refer to the production per hectare, the reduction of inputs used or the utilisation of class one land. Intensive apple production systems reduce row width, allowing more trees to be planted per hectare. This is accompanied with changes in tree architecture in the form of 2D (see section1.2.3) which would ultimately support the development of automation. The amount of class one soils in New Zealand is becoming increasingly limited, especially with New Zealand's growing population, the need for housing continues to grow (StatsNZ, 2017). The New Zealand apple industry is increasingly using highly intensive planting systems (trees/ha) not only for sustainability but to enable increases in orchard productivity.

1.1.3 Labour

As high intensity plantings become more prominent and fruit production increases, regions where major apple production occurs (stated above) will increasingly suffer due to a shortage of skilled labour (Eyles, 2019). There is increasing demand for a large number of skilled workers every year to successfully manage the crop being produced, which predominately includes activities such as pruning, thinning and most importantly harvest (as the window of opportunity for harvest is very small and requires high labour numbers). The reason demand for labour is increasing is due to an increasing crop and a low regional unemployment rate (5.6%) (MinistryofSocialDevelopment, 2018). The Hawkes Bay apple industry is rising by ca. 100 permanent jobs per year and requires approximately 5400 seasonal workers during the growing season (NZAPI, 2019). The next biggest limitation is associated to the suitability of planting systems to robotics and advanced mechanical engineering, an idea to suppress the current labour shortage. Technology and automation is constantly progressing, with desire within the industry to have automated machines completing tasks such as harvesting, pruning and thinning.

1.2 Orchard training systems, tree density and designs.

1.2.1 Tree and orchard designs

1.2.1.1 International

Throughout the history of apple production, there has been progression from a large umbrella-shaped canopy at low planting densities (270 trees/ha) to a single leader tree (S. Tustin, 2000). Modern apple orchards are grown with a three-dimensional tree structure with wide inter-row spacing's (3 to 5 m) and planting densities ranging from 840 - 5328 trees/ha (Corelli et al., 1989; Palmer et al., 2002; Terence L. Robinson et al., 1991; Tustin et al., 2001; Verheij et al., 1973). To date, there have been a number of limitations associated with the three-dimensional system including light interception (LI) (Palmer et al., 2002), light distribution throughout the canopy (Verheij et al., 1973) and leaf area index (LAI) (Tustin et al., 2001) during early establishment, leading to a low cumulative yield as a young orchard (Terence L. Robinson et al., 1991).

In the late 1990's, a new planting system called the Tall Spindle was developed at Cornell University, New York, using a combination of the Slender Spindle, the Vertical Axis and the Super Spindle systems (Table 1). It uses high tree densities (2500-3300 trees per ha) with replaceable branching units (Terence L Robinson et al., 2006). This system became popular and the average planting densities within orchards around the world began to increase. The change to higher densities was made possible with dwarfing rootstocks (Ferree et al., 2003; Jones, 1971; John W. Palmer et al., 1997; van Hooijdonk, 2009). Trees are smaller, meaning they can be planted closer, therefore achieve more efficient, earlier LI and yield with a better return on investment (Patricia S Wagenmakers, 1995; Patricia S. Wagenmakers et al., 1995).

The planting densities and tree architecture are two of the most pronounced changes within the development of tree canopies for improved production efficiency (Terence L. Robinson et al., 1991). The original large umbrella shaped system was planted at 270 trees/ha globally, now considered a low planting density which consequently led to low production potential and minimal light interception (Terence L. Robinson et al., 2014; S. Tustin, 2000). There have since been a number of tree designs and planting densities developed to increase an orchards ability to capture light and maintain high yield and quality. Table 1 represents a few commonly used training systems around the world as well as their common planting densities.

1.2.1.2 New Zealand

In the 1960s, orchards were typically planted on very vigorous rootstocks (Northern Spy, M.12 and M.16) that required wide row spacing's (6m x 6m), which were very typical for apple production all over the world (S. Tustin, 2000). With the adoption of renewal pruning on the McKenzie Central Leader tree design on MM.106 'semi-dwarfing' rootstock, orchard systems started to change as the tree height reduced from 6 m to 4.5 m and planting densities increased from 270 to 580 trees/ha. The adoption of the MM.106 semi dwarfing rootstock led to developments in tree architecture that improved efficiency, mainly in terms of light interception. In the 1980's, the Vertical Axe and Slender Pyramid structures were widely used throughout New Zealand. By 1990, intensive orchard systems research was expanding and planting densities had increased up to 2000 trees per ha with Slender spindle management as dwarfing M.26 and M.9 rootstocks became readily available (S. Tustin, 2000).

In 2019, the NZ apple industry now uses a wide range of different planting systems. Growers in New Zealand (and most growing regions around the world) are better suited to the 'tall spindle' planting system, a system designed with combined inspiration from the slender spindle and vertical axe (S.

Tustin et al., 2008). It can provide high cumulative yields (**up to 54 t/ha** in the first 2 years in New Zealand (John W. Palmer et al., 1997) and, **up to 150 t/ha** in the first 5 years in Australia on M.9 rootstock (James et al., 2011), high light penetration (48-81% on outer sections from bottom to top of the tree) (Narayan Bhusal et al., 2017) leading to better fruit quality (size and colour) (Barritt et al., 1991; J. E. Jackson, 1980; J. W. Palmer, 1989; T. L. Robinson et al., 1989) and improved labour efficiency (T. L. Robinson et al., 2014).

1.2.2 Rootstocks

The physiological role of the rootstock is to provide nutrients, water (Valverdi et al., 2019) and hormones (Tworkoski et al., 2015) to the tree, necessary for productivity. The choice of the appropriate rootstock can enable a grower to control scion vigour, making it possible to facilitate the training or adoption of a chosen training system (Ferree et al., 2003). Many rootstocks have been developed for the intensification of orchards and also for disease resistance (Ferree et al., 2003). In the 1990s, New Zealand was introduced to dwarfing rootstocks. From then, orchard systems have become more intensive with significantly higher planting densities with the favoured adoption of the M.9 rootstock released from East Malling Research Station in England (Ferree et al., 2003). Dwarfing apple rootstocks reduce scion vigour by restricting the uptake and transport of nutrients, such as nitrogen, phosphorus and potassium to the scion (Jones, 1971) and restrict the movement of water (root hydraulic conductivity in dwarfing rootstock - M.27 = 2.34 kg/m.s, semi dwarfing – MM.106 = 5.89 kg/m.s) from the root to the scion (Atkinson et al., 2003). The size control of apple trees using dwarfing rootstocks enabled great planting densities increasing light interception by the canopy and throughout the canopy (Tustin et al., 2001). By reducing the size and vigour of trees using dwarfing rootstocks, canopies become much easier to work with, when completing management practices such as thinning, pruning and harvesting (James et al., 2011).

Since the 1960s, the New Zealand apple industry has used intermediate density plantings predominately grafted on rootstocks such as MM.106 (van Hooijdonk, 2009). These rootstocks proved to be very productive under New Zealand conditions with an almost ideal growing condition providing a long growing season with high solar radiation and adequate winter chilling (Palmer et al., 2002). However, additional intermediate density planting rootstocks such as 'Northern Spy' and M.793 or dwarfing rootstocks including M.9, M.26 and Mark have also been used extensively throughout the New Zealand apple industry (S. Tustin, 2000; van Hooijdonk, 2009).

Table 1. Training systems used throughout the world. The positives and negatives and the corresponding planting densities (Terence L. Robinson et al., 2014)

Training System	Density (trees/ha)	Rootstock	Advantages	Disadvantages	Photo
Tall Spindle	2500-3300	• M.9 • G.41 • G.11	• High early production • High mature yields • Labour efficient • High fruit quality	• High labour cost	
Solaxe	1500-2500	• M.9	• Control of excessive vigor • High production • Low alternate bearing	• Shading • Space wasted • High labour cost	
Bi-axis	1800-2500	• M.9	• Low tree cost/ha • High yields • High quality • Low vigor	• Requires a 2 stem tree from the nursery.	
Super Spindle	5000-6000	• M.9 • G.41 • G.11	• High tree densities • Early production • Simple pruning • High fruit quality • Adaptable to platform	• High investment • Excessive vigour • Not profitable to lower densities	
Precision V-Trellis	2500-5000	• M.9	• High tree density • Systemized pruning • Cost effective • Reduced sunburn	• Costly trellis • Complicated management	
Fruiting wall.	2500-3300	• M.9 • M.27	• Mechanical pruning • Reduction of costs • High yield • High quality	• Small fruit • Excessive vigor	

1.2.3 Future orchard planting system development

Orchard planting systems are most commonly grown in a three-dimensional manner in the form of a slender spindle, vertical axe, slender pyramid or tall spindle, all over the world. Two dimensional canopies are a product of more recent developments made in orchard production systems, particularly in the United States (Figure 1). Scientists at The New Zealand Institute of Plant and Food Research, Hawkes Bay, are developing a new two-dimensional canopy, known as the planar cordon (S. Tustin & van Hooijdonk, 2016) (Figure 3 and 5). A trial orchard was designed to increase LI by reducing the interow width, using a narrow 2-D planar cordon tree structure. In 2017, the system reached 63% of light interception in its fourth leaf (Breen et al., 2017). Two-dimensional planting systems have the opportunity to increase LI which in turn could double the yield potential for current orchards when extrapolating the LI and yield relationship data presented by (Palmer et al., 2002).

It was a part of the design process to create a tree that had the ability to distribute light with numerous light wells created by long thin branching units with small dard-like fruiting sites (Figure 9). The long vertical fruiting branch units are intended to have fruiting structures small and dispersed spatially to create the light wells and keep LAI within the limits understood to be optimum throughout the entire canopy. However, it is currently unknown how light is distributed throughout a planar canopy and how this influences fruit quality. Because the planar cordon is new, research is needed to understand the physiological and pomological factors including crop load and light distribution to understand the efficiency and practicality of this system.

Generally, the success or performance (in terms of yield, LI or fruit quality responses) of other two-dimensional training systems has not been demonstrated scientifically in the literature, but rather through industry application and empirical evidence. The most developed 2D systems include the 2D (vertical structure with horizontal branches), Washington V and the planar cordon (FOPS).

The 2D vertical structure (Figure 1) consists of seven or eight equally spaced layers of horizontally orientated branches positioned in opposite directions off a central vertical trunk axis, up to a canopy height of approximately 3 m. Row spacing in the 2-D typically varies from 2.4 to 3 m (S. Tustin, van Hooijdonk, et al., 2016). Light interception ranges from 50 to 70% at full maturity, with yields ranging from 100-124 t/ha. The Washington V is similar to the 2D system with horizontal branches but instead of being vertically orientated, it is grown in a V formation. Light interception and yield properties have not been studied in this system. Branches are positioned in an orderly manner, improving the light environment and creating a manageable, simple canopy that is easy to prune, thin and harvest.

The planar cordon structure is designed to harvest high light levels supporting the production of high volumes of high quality fruit. It consists of two cordons positioned at opposite directions on a single root system, accompanied by 10 vertical branching units. The total cordon length is 3 m with each vertical branching unit spaced 30 cm apart. The canopy is designed to reach 3 m in height and is spaced 3 m between trees. The row spacing has been set in the trial orchard at 1.5 m and 2.0 m (S. Tustin & van Hooijdonk, 2016). The advantage of the planar cordon structure is its ability to create controlled short shoots which enable large light wells (structural gaps in the canopy between uprights which allow light flow) throughout the canopy. Similarly to the 2D and Washington V, it provides measurable branching units which makes crop loading easy to set and accurate (planar cordon: fruit/cm2 BCA, 2D and Washington V: fruit per unit branch length).

Additionally, the development of a planar cordon canopy takes away a lot of the branching complexity, allowing spray deposits to be distributed efficiently throughout the entire canopy.

To harness the benefits of the narrow row space, adaptation of conventional machinery will be required to fit down the rows for activities such as spraying, mowing and harvesting.

Figure 1. 2D system example used in 'Royal Gala' apple (S. Tustin, van Hooijdonk, et al., 2016)

1.3 Effect of light in apple production

1.3.1 Light interception, photosynthesis and dry matter production

Photosynthetic active radiation (PAR) designates the spectral range of solar radiation (from 400-700nm) that photosynthetic organisms are able to use as the driving force for biomass production via its effect on photosynthesis (Ferree et al., 2003). Maximum net photosynthesis occurs at 900 to 1100 µmol/m^2.s (Rom, 1991) (refer chapter 4). High light interception correlates with high dry matter (DM) production, but DM is not always automatically translated into increasing yield of marketable fruit (Rom, 1991). Fruit growth is the result of several factors including, the inherent demand (relative sink strength) of the fruit (demand for cell division and expansion growth), carbon assimilation by the source leaves (source strength), and the resulting allocation to the organ in question (Bairam et al., 2019). This partitioning of resources (nutrients, carbohydrates and water) into fruit instead of other growing organs is a complex phenomenon that is controlled by light (Ferree et al., 2003) and vigour/cropping balance within the tree. Light influences the production of large quantities of high quality fruit in two ways; the first being its ability to supply the energy stored in the tree, in a chemical form as carbohydrates, the second being its influence on the physical development of the trees structure (Ferree et al., 2003).

J. Palmer (2002) found that total tree dry matter is strongly related to light interception. Total tree dry matter can reach 26 t/ha depending on cultivar and as stated earlier, light interception and tree age. This study found that approximately 70% of the total tree dry matter is made up of harvested fruit, 12% from the tree structure (wood) and the remaining is made up of leaf, fruitlet thinnings and flowers in three different cultivars (‘Royal Gala’, ‘Braeburn’ and ‘Fuji’). Concluding that a 70% harvest index can be achieved for mature trees on dwarfing rootstocks under New Zealand’s high light environment (Palmer et al., 2002). Top orchards within the industry now produce yields of 110 t/ha in ‘Royal Gala’ and 130 t/ha for ‘Scifresh’ and ‘Scilate’ (AgFirst, 2019).

1.3.2 Limitation of light

Plant productivity in terms of yield per ha depends on the proportion of incoming radiation intercepted by plants (Palmer et al., 2002). That light energy is then absorbed by the leaf tissues and converted into plant biomass from photosynthate produced during photosynthesis (Monteith, 1977; J Palmer, 2007). Current three-dimensional orchard systems at full maturity are limited to 55-60% light interception, which ultimately restricts production potential to yields just exceeding 100 t/ha (Palmer et al., 2002). The three-dimensional nature of tall spindle trees can increase the amount of shading within the inner parts the canopy if tree structure and vigour are not managed appropriately (N. Bhusal et al., 2016; S. Tustin et al., 1989; Patricia S. Wagenmakers, 1991).

Direct light occurs mainly on clear sky days when the light from the sun hits directly onto the outer canopy whereas indirect/diffuse light is most common on an overcast day but can also be created by shading within the tree (JW Palmer, 1977). To reduce shading, the tree architecture must be altered so high levels of sunlight penetrate from the top to the bottom of the canopy.

1.3.3 Importance of light interception and distribution in orchard systems.

Two approaches have been used to improve light distribution in apple canopies. One is to use tree forms to allow light penetration from small openings between branches, used in structures such as tall spindle or multi-leader systems (Terence L. Robinson et al., 1991). Coinciding with this, increases in tree height will increase LI, particularly in these triangular shaped systems (Corelli et al., 1989). However, in a three-dimensional structure, tree height should not exceed the row width, otherwise shading from neighbouring trees becomes problematic (Willaume et al., 2004). The second approach is to allow a thin plane of foliage to intercept light (Terence L. Robinson et al., 1991). Finally, if the leaf area index (LAI) is held constant, increasing the tree height will improve light distribution throughout the canopy (Corelli et al., 1989).

The amount of sunlight captured by the leaf area of the canopy has a significant influence on the photosynthesis and transpiration of apple trees (Lakso, 1981). There are a number of factors when optimising light interception. It does not only depend on the density and spread of the foliage but also the direction and size of neighboring trees within an orchard (Corelli et al., 1989; E. Jackson, 2011). Ultimately, light distribution throughout the canopy plays an important role when it comes to affecting flowering, fruit size and colour (Hirst et al., 1990; J. E. Jackson, 1970). Studies have shown the requirement for light levels above a critical minimum of approximately 25-30% incoming radiation for the production of high quality fruit (Heinicke, 1964; J. Jackson et al., 1971; J. E. Jackson et al., 1977; Seeley et al., 1980). However, many factors are to be considered when comparing literature, for example environmental conditions and method of measurement. A common trend in the literature shows how light levels increase with canopy height and around the outer proportions of the three-dimensional canopies (S. Tustin et al., 1989). P. Wagenmakers (1991) showed that light interception increased from 20% of incoming radiation to 80% from the middle of the tree to the outer portion of the tree however, fruit quality (in terms of fresh weight, colour or dry matter content) was not measured (Patricia S. Wagenmakers, 1991).

Tustin et al (1989) measured the photosynthetic photon flux density (PPFD) profiles for within canopy positions in the Ebro-Espallier trellis of 'Granny Smith' and looked at the influence light had on fruit quality. This system involved a trellis containing multiple horizontal branches layered on top of each other. The results showed that instantaneous PPFD was typically 50 µmol/m^2/s and rarely exceeded 400 µmol/m^2/s for the three lowest trellis layers at noon ± 2 hours. Open-sky instantaneous PPFD levels, for the same time ranged between 500 and 2200 µmol/m^2/s. Mean fruit weight (MFW) and specific leaf weight (SLW) decreased down the layers of the trellis which coincided with declining PPFD levels (MFW from top to bottom; 183 g to 109 g; SLW, 100 g/m^2 to 60 g/m^2) (S. Tustin et al., 1989).

Previously reported literature (Hirst et al., 1990; J. E. Jackson, 1970; S. Tustin et al., 1989; Patricia S. Wagenmakers, 1991) does not describe detailed methodology around sensor positioning and placement. Among the literature it is assumed that the methodology in light measurements varies due to differences in equipment, although one aspect that seems to remain the same is a horizontal sensor placement. N. Bhusal et al (2019) measured the distribution of light at different parts of a tall spindle canopy by holding a probe horizontally at a desired height. The probe contained a total of 80 sensors, spacing 1 cm apart (N. Bhusal et al., 2016). Apart from this paper, the lack in information regarding sensor positioning makes it hard to compare results with potentially different methodologies between papers.

From assessment of the apple literature, there is currently very limited data presented showing the light energy captured in an apple canopy at a daily level. The majority of the literature describes the light environment through a proportion of incoming radiation, which is often an average over few readings in a day or a season (Barritt et al., 1991; N. Bhusal et al., 2016; J. W. Palmer et al., 1992; T. L. Robinson et al., 1989; S. Tustin et al., 1988; Wunsche et al., 2000). From this it is hard to distinguish exactly what level of energy (PPFD and daily light integral) is being captured at different heights in the canopy and how this influences fruit quality in terms of fruit size, colour, dry matter (refer to chapter 4).

After reviewing the literature, it is clear that there are many knowledge gaps related to the light relations in apple canopies. Light profiles of a 2D apple canopy presented as total energy received (µmol/m^2/s) and how this directly influences fruit quality in terms of fruit size, colour and dry matter is unknown.

1.4 Effect of crop loading in apples

Crop load is often defined as a quantitative parameter used by the industry to control fruit density, which often describes the number of fruit per tree. Crop load is often expressed in terms of fruit per trunk cross-sectional area (fruit/cm^2 TCA), as this gives a reference to tree size and the crop load potential of that tree (S. Tustin et al., 2015). The main objective of managing crop load is to remove a proportion of fruitlets during thinning to improve fruit size and colour, and to ensure sufficient return bloom in the following season. Removing part of the crop early in the growing season is the most effective way to do this (Racskó, 2006). Optimal crop loads differ between different cultivars under different growing conditions, however an overall optimal crop load ranges from 8-12 fruit/cm^2 TCA (Castro et al., 2015; McArtney et al., 1996; Racskó, 2006). Crop loading influences fruit yield, quality parameters, tree vigour (canopy extension growth during the growing season) and return bloom (rate of flowering in the following season) (Jakopič et al., 2013; Meland, 2009; Racskó, 2006; T. Robinson et al., 2012). The optimal crop load is a fruiting density that allows the majority of the crop to meet market requirements (colour, size, dry matter and firmness) while also having the ability to produce consistent yields annually.

Castro et al (2015) looked at crop densities ranging from 2 to 17 fruit/cm^2 TCA and found that fruit weight declined from 130 g to 93 g, red skin colour declined from 72% to 48% from low to high fruit densities in 'Eva' apples (Castro et al., 2015). Additionally, trees cropped to 6, 8, 10 and 12 fruit per cm^2 TCA showed with increasing crop load, yield increased, but mean fruit weight decreased in 'Fuji' apple (Jakopič et al., 2013). Meland (2009) looked at the influence of crop load on return bloom and found that trees cropped at 2 fruit/cm^2 TCA had a significantly greater return bloom (106 flower clusters per tree) compared to trees cropped at 8 fruit/cm^2 TCA (13 flower clusters per tree). The results from this study were consistent with the other literature in terms of fruit weight and ground colour (background colour of the fruit) (MFW; declined from 175 g at low crop density to 128 g at a higher fruit density, ground colour declined from 5.3 at low crop density to 4.2 at a higher fruit density (unit- ground colour score 1-9, 1 being dark green and 9 being bright yellow)) (Meland, 2009).

As stated earlier, the majority of the literature based their crop loading studies on a fruit per TCA basis. Ultimately, the TCA is not a branching unit and therefore it makes sense for cropping accuracy to base crop loading decisions on an individual branch basis i.e. per unit of branch cross-sectional area (BCA). Crop loading studies at a branch unit level (base cross-sectional area, BCA) are limited and only originated in 1995 from Lauri along with the development of the 'mafcot' wheel, used as a tool to standardise spur extinction (fruit density management technique) (Lauri et al., 1995). In 2009, Tustin then looked at the concept of regulating floral bud distributions within the tree, in order to manipulate fruit set and early fruit development to more optimally use dry matter resources. By setting bud densities of 5 or 6 buds per cm^2 BCA, 35% of floral buds failed to set fruit compared with 57% on unmodified trees (S. Tustin et al., 2012). van Hooijdonk (2014) was the first to measure both bud regulation and fruit density on a branch unit level. All branches were thinned to a fruit density of 5 fruit/cm^2 BCA, however the study found that fruit on bud pruned trees were significantly larger (10-15 g through 3 consecutive seasons) than the control (van Hooijdonk et al., 2014). K. Breen (2016) looked at the difference between artificial spur extension (ASE – bud thinning) and unmodified trees in terms of differing bud loads between 2, 4, and 6 buds/cm^2 BCA which at harvest equated to fruit densities of 3.3 to 5.2 fruit/cm^2 BCA. The results showed that in both ASE and unmodified trees, fruit at lower densities were significantly larger (ASE =184 g, Unmod = 169 g) than fruit at higher densities (ASE =170 g, Unmod = 156 g) (Breen et al., 2016).

The development of fruiting buds can be influenced by a number of different factors including but not limited to; light quality, fruit set, type of branch, rootstocks, pruning techniques and the application of growth regulators (Jonkers, 1979).

The standard practice for crop load management within the global apple industry is generally application of chemical thinners followed by hand thinning. Hand thinning is one of the major costs to growers annually as it is a direct cost due to labour. When chemical thinning became available, growers saw it as an easy way to reduce labour costs. Chemical thinning can be effective however, it can easily provide unpredictable and inconsistent responses every year in terms of return bloom and fruit set (Greene et al., 1990; T. L. Robinson et al., 2011). This, along with the increasing consumer concern when using any chemical substance, is creating room for precision management practices for crop loading.

Earlier literature has generally measured crop load at a whole tree level (fruit number per cm^2 of TCA), mainly when describing a three-dimensional tree (Jakopič et al., 2013; Meland, 2009; Racskó, 2006; T. Robinson et al., 2012). However, the development of 2D planar cordon structures will allow crop loading strategies to become more concentrated on a branch unit level (fruit number per cm^2 of BCA) and therefore more reliable in terms of yield predictions.

There is a knowledge gap around how to manage the crop load of two-dimensional systems, in particular the planar cordon system. With a completely new tree architecture, it is unknown what crop loading metrics would be suited to this canopy. Thus, we set out to examine the relationship between different crop loading levels at a branch and tree unit basis and its response to fruit quality in terms of fruit size and colour.

1.5 Research Objectives

The objective of this research was to understand the pomological performance of new planar cordon orchard canopies because limited knowledge exists. Crop load metrics and canopy light distribution properties were elucidated for their impacts on fruit quality.

Specific objectives were to:

1) Quantify the relationships between tree and branch unit crop loads and fruit size, quality and return bloom in a planar cordon orchard.

2) Understand and quantify the light environment within a planar cordon orchard and determine how light relationships impact leaf properties and fruit quality traits.

2 General methods

2.1 Experimental site

The experimental tree material used for this thesis is part of a long-term productivity trial within the Future Orchard Planting System (FOPS) programme (MBIE contract C11X1310). The trial was established in 2014. The study within this thesis occurred during the 2017-2018 and 2018-2019 growing seasons, and the trees were 4 and 5 years old respectively.

This experiment was conducted at the Plant and Food Research Ltd (PFR), Hawke's Bay Research Centre, Havelock North, New Zealand. The soil was a silty loam over clay which is categorised as being deep, poorly drained, stoneless with an unlimited potential rooting depth (LandcareResearch, 2019).

2.2 Tree propagation and planting

The trial was established using purpose-grown, winter bench-grafted bi-axis nursery trees. One-year-old 'M9' rootstock stools were bench-grafted with cultivars 'Royal Gala' and 'Scifresh' (commercially known as 'Jazz TM') in August 2013 and grown from scion lateral buds as bi-axis nursery trees for one season in the nursery, at the end of which, trees had two primary stems each approximately 1.3 to 1.5 m in length (van Hooijdonk & Tustin, 2015). The nursery trees (Figure 2) were lifted after one season and planted at the PFR Hawke's Bay Research Centre, Crosses Road Research Orchard.

Figure 2. Left: bi-axis 'Scifresh'/Jazz™ apple trees on 'M9' rootstock at 20 October 2013 in the nursery prior to staking. Right: strong growth of trees being trained up a temporary bamboo structure in January 2014. Source: (van Hooijdonk & Tustin, 2015).

2.3 Experimental Orchard Design

The experimental planting systems study was designed to compare two row spacings (1.5 m and 2 m inter-rows) and two tree designs (vertical and vee cordon (Figure 3). The trial site had a total of six rows with each treatment row being guarded on either side by a similarly planted row at the same spacing and cultivar (Figure 4). The tree design treatments were grown in plots of 3 trees that were randomised along the rows within each row spacing plot. The treatment structure was a 2 (row spacing) x 2 (tree design) factorial layout set out in a split plot design. Trees were planted at 3 m apart along the row, with plots of each cultivar used as a replicate so that each cordon canopy type was represented by four replicates, two training systems per row spacing for each of 'Royal Gala' and 'Scifresh' cultivars. The rows were orientated from NW to SE and trees were planted so that the two axes aligned along the row direction (Figure 6).

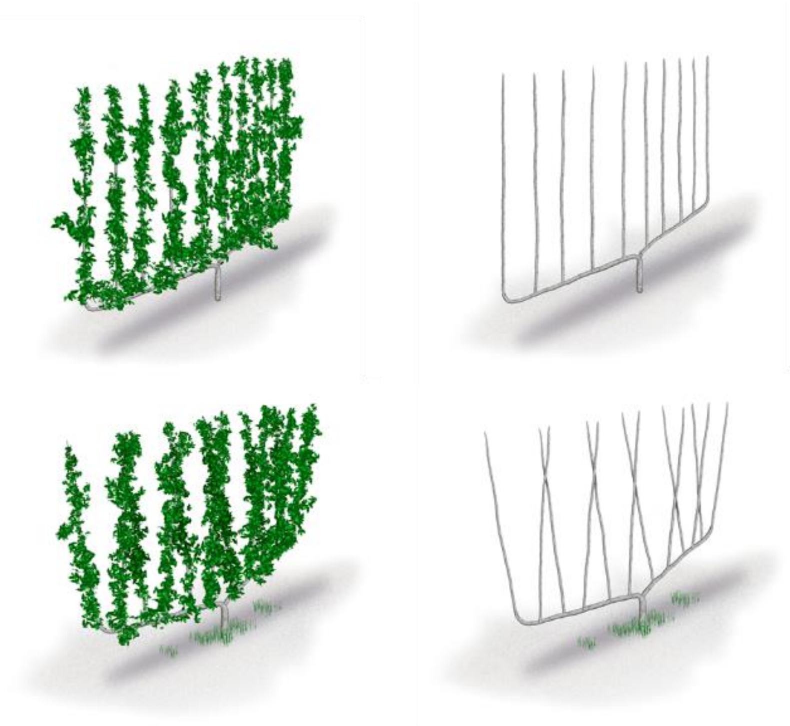


Figure 3. Diagrammatic image of Vertical (top) and Vee (bottom) canopies planted in prototype II research trials at the PFR, Hawke's Bay Research Centre, Crosses Road orchard. Graphic source: Tony Corbett, PFR.

Plan of Apple Prototype II planar cordon planting systems Trial July 2014

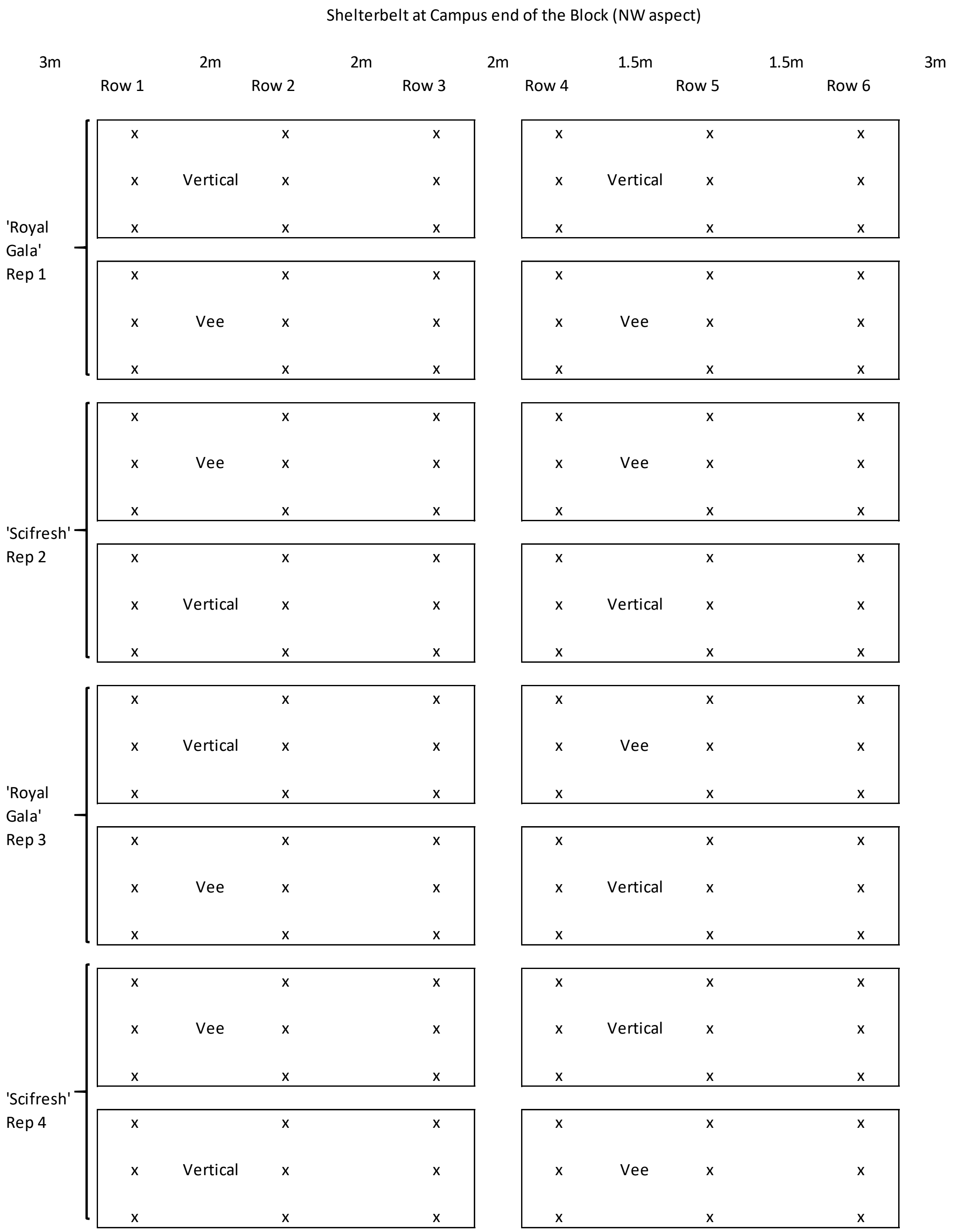


Figure 4. Experimental orchard design using a 2 (row spacing) x 2 (tree design) factorial layout set out in a split plot design. The design comprises two cultivars ('Royal Gala' and 'Scifresh'). Within each cultivar there are two treatments: row spacing (1.5 m and 2.0 m) and tree design (Vertical and Vee). The trial comprises four true replicates. There are six rows each made up of 24 trees. Rows two and five are measurement rows guarded by adjacent rows of the same row spacing. The tree design treatment was randomly assigned to plots across each row spacing.

2.4 Young tree training

Trees were planted at 3.0 m apart in the row and secured to a vertical five-wire trellis, initially maintaining the cordon axes at approximately 45° angles from vertical to a height of 1.5 m (Figure 5). The cordon was established by bending the two axes in opposite directions along the row leaving a final angle of approximately 15° above the horizontal so that the end of the cordon was higher than the inner cordon (Figure 5). After tying the cordons down, the ends were tipped to a downward facing bud at 1.35 m. The top buds were removed with a knife, and a notch was placed above the remaining buds to stimulate budbreak where a vertical branch was required. Once branches (only taken off the side of the cordon) reached 30 cm long, they were trained up bamboo stakes with regular taping using a ‘max tapener’ (Figure 6). Uprights were trained 30 cm apart in the vertical tree design and 50 cm apart on the same side, being 25cm apart between alternating uprights in the Vee tree design (Figure 6). Uprights were regularly taped and tied to bamboo sticks for structural support. The Vertical tree design had 10 uprights while the Vee had 12.

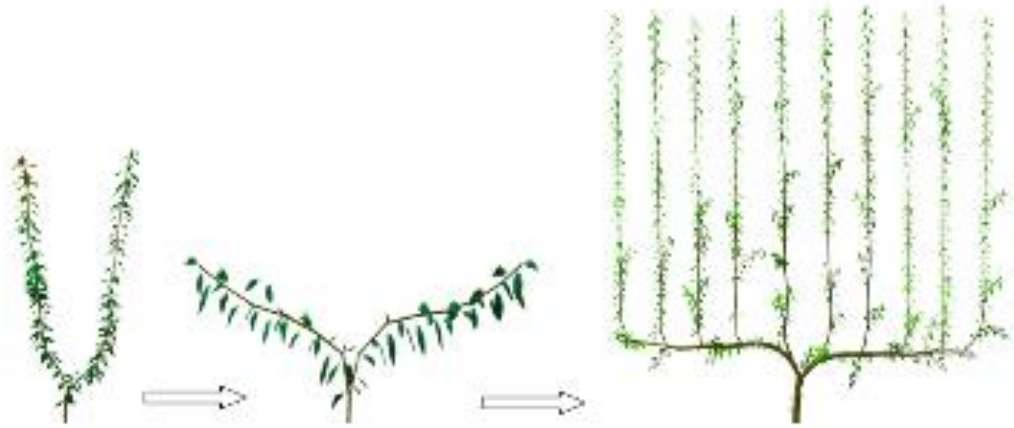


Figure 5. Pictorial example of the vertical planar cordon progression from the time of planting (left), bending down of the cordon (middle) and growing of the uprights (right) in the orchard. The cordon was initially grown near vertically to reach 1.35m in length on each side before bending down to a resting angle of 15^{o} angle (Source: Ben van Hooijdonk).

Figure 6. Initial setup of the Vertical (top) and Vee (bottom) tree design treatments with examples of all structural support including wires and bamboo stakes in year 1 from planting. Row width within this Figure is 2 m. Photo taken March (2015) in the first leaf. (Photo source: Ben van Hooijdonk)

2.5 Cultivars studied

2.5.1 'Royal Gala'

The original 'Gala' apple tree was bred from a cross between a 'Golden Delicious' and 'Kidd's Orange Red'. 'Royal Gala' is a sport of 'Gala', which was first patented in 1977 by the Stark Brothers Nurseries and Orchards (Ten Hove, 1977). 'Royal Gala' was more successful because of improved red skin colour. However, because 'Royal Gala' is a sport of 'Gala', it can exhibit reversion, a mutation causing morphological differences in which the skin reverts from green to red typical of the original 'Gala' (El-Sharkawy et al., 2015). 'Royal Gala' is an early variety harvested from early to late February and can be distinguished by its bold, red striped appearance. It has very thin skin allowing for a crisp, sweet flesh (Ten Hove, 1977; WaimeaNurseries, 2019). Overall, its appearance and eating qualities have made 'Royal Gala' a premium product globally.

Figure 7. 'Royal Gala' at harvest. Foreground and background are displayed from a side and top angle. Red colour percentage must be ≥66% for A-grade export (Snaith, 2010).

2.5.2 'Scifresh'

'Scifresh' was commercialised in April 2004 and trademarked as Jazz™. It is a cross between 'Braeburn' × 'Royal Gala' and, which was originally bred in New Zealand by HortResearch (now Plant & Food Research) in 1985 (White, 2002).

'Scifresh' has similar characteristics to a 'Braeburn' being crisp and juicy. Its colour has flushes of red over background shades of green, yellow and orange. 'Scifresh' has been successful as a new variety because of its attractive appearance, categorised by its striped red bi-colour appearance and excellent eating quality after long-term storage (Figure 8).

'Scifresh' has become one of the more successful apple varieties in terms of quantity sold and produced. It is grown under a license from T&G Global. In 2018, New Zealand produced 55,331 tonnes of 'Scifresh' from 807 ha, 37,885 tonnes of that met export requirements and was sold overseas (NZAPI, 2018).

Figure 8. 'Scifresh' fruit, highlighting its appearance and colour at harvest. 'Scifresh', commercialised in April 2004 and trademarked as Jazz™. Characterised by its flushes of dark red over background shades of green. Photo source: (Shaw, 2006).

2.6 Experimental tree management

Winter pruning of planar cordon trees occurred annually in July. The cordon section of the tree was pruned to ensure there were no branches within the row, in reach of tractors. Uprights were pruned to ensure there was plenty of gaps between fruiting dards for light throughout the canopy. This meant cutting out extended shoots longer than 40 cm, especially shoots growing along the row between uprights that block the light well. After pruning, uprights comprised mostly of spurs and dards (Figure 9). In the first few years, crop load was minimised to ensure plant growth was optimised. Nutrient applications, irrigation and pest and disease management were completed by the Field Research Network (FRN) team at PFR, Hawkes Bay, as per commercial practice. The trial block was irrigated through a permanent sprinkler system (using Netafim sprinklers) controlled by the orchard staff. Irrigation was based on AgFirst soil monitoring which often occurred Monday, Wednesday and Friday for approximately two hours during the growing season. Yield increases from season to season continue to increase as the trees are yet to reach their full maturity. The trees are at approximately 60% of their full canopy development in 2018 and 80% in 2019.

Figure 9. Example of a planar cordon vertical 'Scifresh' tree after pruning in 2019 (year 6). Following pruning, each upright is composed of mostly short shoots (spurs and dards). This along with the vertical orientation and spacing of the uprights allows light penetration into the bottom of the tree.

2.7 Flowering

Return bloom was measured in (2018 and 2019) by recording the number and type of floral buds (i.e. spurs and terminals) within the canopy after pruning. In 2018, bud break occurred on the 1/9/18 and 14/9/18 for ‘Scifresh’ and ‘Royal Gala’, respectively. Return bloom measurements were recorded on the 27/9/18. In 2019, bud break occurred on the 6/9/19 and 17/9/19 for ‘Scifresh’ and ‘Royal Gala’, respectively. Return bloom measurements were recorded on the 15/11/19. Working systematically through each individual upright and cordon, the total number of floral buds were counted (15/11/19) and categorised into either spur or terminal buds (Figure 10) for each upright and cordon. Axillary floral buds were not counted as they had been removed as a part of normal crop load management.

Figure 10. Example of floral spurs (left) and a terminal floral bud (left) in ‘Scifresh’ apple trees, spring 2018.

2.8 Harvest timing and criteria

Harvest occurred in February and March of 2018 & 2019. Three select colour picks occurred on 14/02/18, 21/02/18, 01/03/18 in 2018 and 28/02/19, 06/03/19, 13/03/19 in 2019 for ‘Royal Gala’. ‘Scifresh’ was harvested in three picks in 2018 (5/3/18, 12/3/18, 20/3/18) and two picks in 2019 (18/3/19, 26/3/19 March). Commercial colour standards were used: ≥40% for ‘Scifresh’ (Turners&Growers, 2005) and ≥ 66% for ‘Royal Gala’, which are the minimum colour that is required for export quality fruit. Harvest 1 began when 30% fruit had sufficient blush coverage and an starch pattern index (SPI) of 1.6-4 (1.6-2.5 – RG and 2-4 ‘Scifresh’), minimum fruit firmness (FF) of 7-8 kg-f and total soluble solid (TSS) of >10.5 in ‘Royal Gala’ and >12 in ‘Scifresh’ (Turners&Growers, 2005). Fruit from each tree were picked into crates/bags, however the methodology differed between sub-sections of the study (see Chapters 3 and 4)

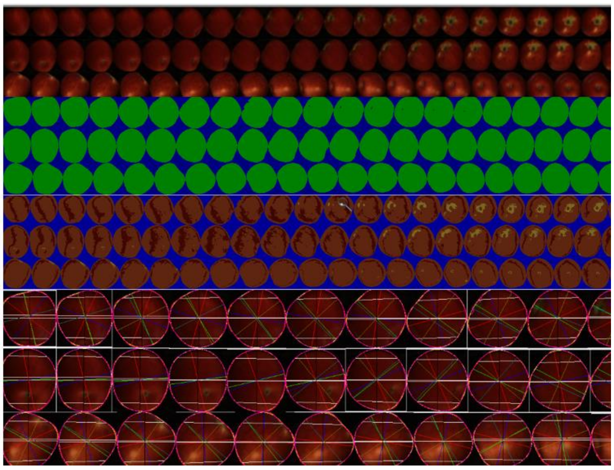
2.9 Measurement of fruit yield and quality

2.9.1 Quantification by grading

After each harvest, colour and size of each fruit was electronically measured using an automated weight sizer with InVision (COMPAC, New Zealand) (Figure 11). Each tree and tree part (cordon, individual upright or height) was run as a separate batch through the grader. With INVISION, multiple photos were taken by three different cameras to capture every angle of each fruit (Figure 12). The grader was set to run at approximately 50% of its maximum speed to ensure fruit imaging was optimised for high accuracy.

Figure 11. Compac grader in use during the 2019 harvest of 'Scifresh'. Multiple photos are taken by three different cameras to capture every angle of each fruit. The grader was set to run at approximately 50% of its maximum speed to ensure fruit imaging was optimised for high accuracy. Above: loading zone. Below: Fruit after passing through the InVision system.

High colour	Fresh weight (g)	RBC (%)	Volume
	190.6 g	97.1%	203



Low colour	Fresh weight (g)	RBC (%)	Volume
	140.1 g	48.4%	150

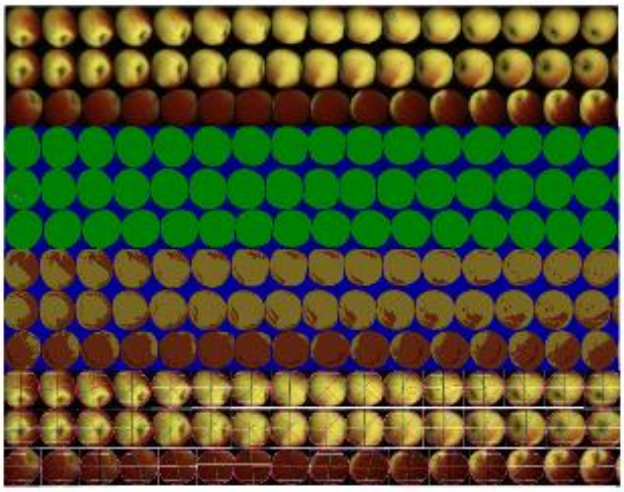


Figure 12. Left: Example of fruit weight, red blush coverage (RBC%) and volume for examples of a low (bottom) and high coloured (top) 'Scifresh' apple quantified using COMPAC grading technology. The left image shows how the grader identifies the shape, volume and colour of the fruit. It first looks for the edges (pink line) and then takes several diameter measurements (red, green and blue lines) to determine this (seen in the first two series of images). In the third series illustrates, how the grader determines what colour it identifies on the fruit (dark red, light red and background colour). All three series of information are derived from the same photos taken of the fruit on the right, and transforms them to give us individual fruit data. Right: Example of fruit weight, red blush coverage (RBC%) and volume for examples of a low (bottom) and high colour (top) 'Scifresh' quantified using COMPAC grading technology.

2.9.2 Near Infra-red analysis (NIR) of fruit dry matter content

2.9.2.1 Operation

A portable near infrared analyser (NIR; Felix F-750) was used to measure fruit dry matter content non-destructively. The NIR combines near-infrared spectroscopy and chemometric analysis to estimate quality metrics in fruit (Zhang et al., 2019). Each measurement shines near infrared wavelengths (800-1000 nm) of light into the apple flesh. When the light hits the apple, it is either reflected, absorbed or transmitted, creating a spectrum that reflects the chemical composition of the fruit sample. In summary, NIR measures the interaction of light with molecules within the fruit generating spectra. Spectra is then correlated to quality traits of interest obtained by destructive measurement of fruit (Jha et al., 2010; Nturambirwe et al., 2019; Zhang et al., 2019). Correlation of spectra with destructive measurements of fruit quality (i.e. dry matter content) is then used to develop a prediction model to measure fruit quality non-destructively.

2.9.2.2 Building a prediction model for fruit dry matter content (%)

Before NIR was used to measure fruit dry matter content non-destructively, a prediction model was created using the F-750 Model Building Software. The F-750 bases its chemometric analyses upon the user-created Model. To create this model, 100 fruit were sampled by taking spectral images (Figure 11). A range of fruit representing different maturities were used. Each fruit was measured twice at opposite sides of the fruit (Figure 14) and at three different temperatures (5 °C, 12 °C and 20 °C). A circle was drawn on the fruit where the measurement was taken to ensure this position remained the same for each temperature recording (Figure 13). These samples were then measured for their dry matter content using a 26x40mm core taken from the same position that NIR spectra were measured. Fresh weight of flesh sample cores were weighed immediately using a 3 decimal place balance (Electrotech Mettler AE200, New Zealand). Samples were then dried in a dehydrator (HYDRAFLOW ezi dri Ultra 1000FD, New Zealand) for more than 48 hours at (60°C) to a constant weight. Once fully dry, all samples were weighed to obtain their dry weight. Percentage dry matter content was calculated by dividing the final dry weight by the initial fresh weight ×100.

2.9.2.3 Non-destructive measurement of fruit dry matter content using NIR

In chapter four, fruit dry matter content was measured for each fruit by taking a reading on each side of the fruit (the reddest area – blush, and the lightest area – green) at a temperature range of 5-10°C. The sampled fruit were placed in coolstore at 0.5°C directly after harvest until the NIR measurements were ready to be completed (approximately 3-4 days). The readings were then transferred from the Felix to Excel spreadsheet for further analysis.

Figure 13. Example of Scifresh' fruit used for NIR Model creation in 2019. The sample included measurements of 100 fruit of different maturities and red blush coverage. Each fruit was measured twice on opposite side of the fruit and marked to repeat the measurement at three different temperatures (5 ^{o}C, 12 ^{o}C and 20 ^{o}C). After the NIR readings were taken, the sampled area of the fruit was used to measure destructively the dry matter content.

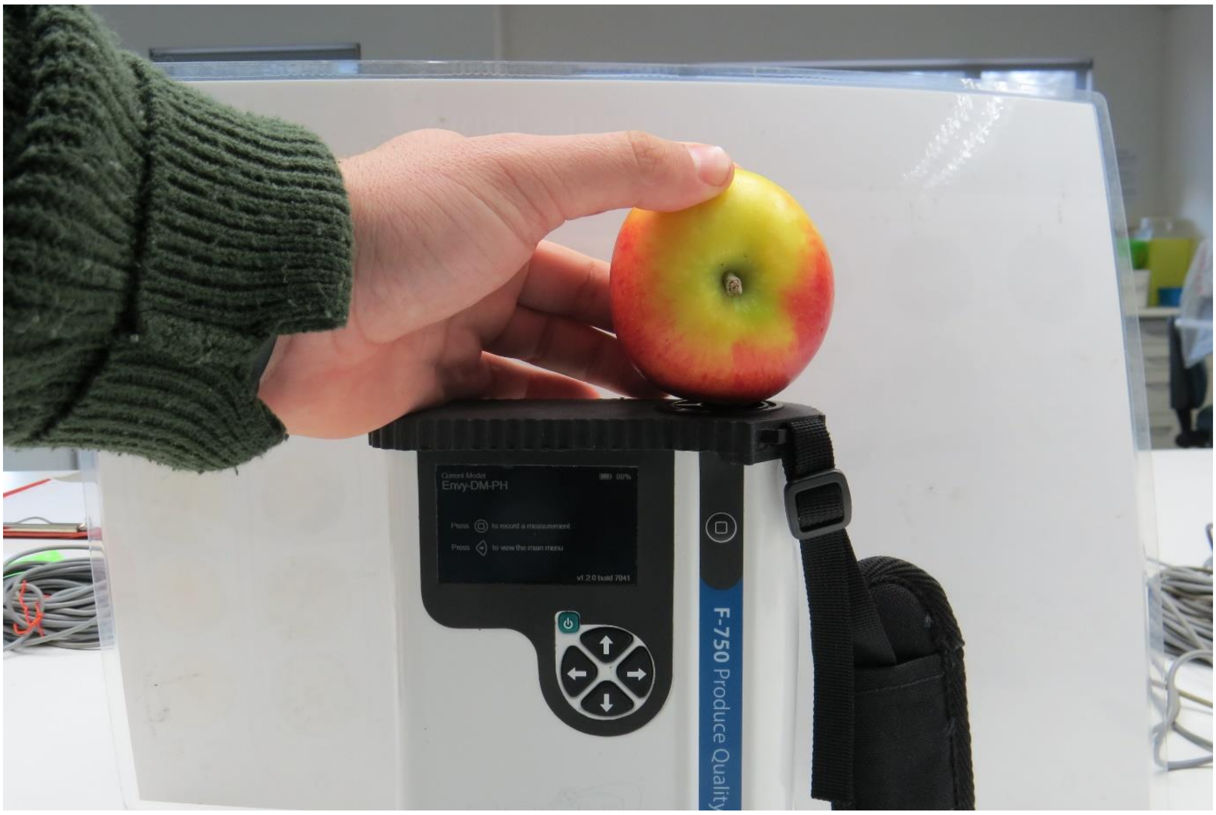


Figure 14. Example of NIR taking a dry matter reading on a 'Scifresh apple' Measurements were taken directly after harvest in 2019 only. Two measurements were taken on opposing sides of the fruit (blush and non-blushed sides).

3 Fruit density management in planar cordon apple trees

3.1 Introduction

Increase in total growth and productivity of any agricultural system is dependent on the interception of total seasonal radiation (Monteith, 1977; Murchie et al., 2009; Palmer et al., 2002). Orchard productivity is limited by the ability to capture light due to wide inter-row spacing, reducing the yield potential per ha (S. Tustin et al., 2014). In current orchard training systems, light interception is maximised at 55-60% of the total seasonal radiation which is limited by wide inter-row spacings for machinery access, reducing the amount of plant canopy per unit of land area. This level of light interception limits orchards to maximum yields of approximately 100 t/ha by using a linear regression developed by (Palmer et al., 2002). This study suggests that an upper limit of 169 t/ha could be achieved at 90% light interception. To reach this potential, different orchard designs are required, especially in terms of row spacing (narrower inter-rows) and tree architecture (planar trees for machinery access). These results have inferred that there is significantly more production potential to be gained than what is seen in current apple orchards.

The Future Orchard Planting System program (FOPS) was a long-term study that is aimed to redesign orchards by using narrower interrows to increase light interception (>85% of total incoming radiation) and consequent yield (up to 170 t/ha). This idea should be achieved by reducing the inter-row spacing (to 2 m or 1.5 m from the commonly used 3.5 m in a tall spindle system) and developing a planar canopy (S. Tustin et al., 2018).

The FOPS program is now in its 6th year and has brought a paradigm shift to the way we think about apple production within the industry. The results have shown with alterations in orchard design, total light interception can be increased significantly. Results from the five year old planar cordon trees in the FOPS program showed that, seasonal maximum light interception with 'Royal Gala' was 81% to 84% at the 1.5 m row spacing (1667 trees/ha) and 71% to 74% at the 2.0-m row spacing (2222 trees/ha). The range in seasonal maximum light interception with 'Scifresh' was 82% to 86% for the 1.5-m row spacing, and 71% to 76% for the 2.0-m row spacing. The tall spindle comparison at 2.0 m row spacing reached only 44% maximum light interception, all in their fifth year from planting (S. Tustin et al., 2019).

The development of planar canopies or any new canopy development requires research to gain knowledge around crop management and system performance. Currently, crop management practices for a two–dimensional planar cordon system, in terms of crop loading are unknown. The literature is limited and with the rapid advancements in robotics and automation, it is important to fully understand the crop load and fruit quality relationships a two-dimensional tree canopy possesses.

This chapter is focused on crop loading because of how essential it is to yield, fruit size, quality, profitability and reducing biennial bearing (Castro et al., 2015; Embree et al., 2007; Jakopič et al., 2013; McArtney et al., 1996; Meland, 2009; Racskó, 2006; T. Robinson et al., 2012). The presence or absence of fruit in any perennial crop has a major effect on the sink-source relationship (sources being the parts of the plant where net fixation of carbon dioxide occurs, and sinks being the sites where assimilates are stored or used) and therefore the photosynthetic performance and growth response of trees (Wünsche et al., 2005). Given the scarcity of information regarding the two-dimensional planar cordon canopies, how crop load impacts fruit quality attributes and its effect on return bloom were elucidated over two consecutive seasons.

The present crop loading metrics for tall spindle trees range from 10-12 fruit/cm^2 TCA depending on cultivar (Castro et al., 2015; Elfving et al., 1993; Embree et al., 2007; McArtney et al., 1996; Wright et al., 2006). A hypothesis of the current study is that this metric will differ for planar cordon canopies because of the different branch architecture (long and thin branches) and altered light environment.

As stated in the literature review, the standard practice for estimated crop loads is done on a per tree basis using TCA. Commercially, a select few trees are counted and then fruit numbers are adjusted. From there, management are able to give broad rules to thinners in the hope of reaching target crop loads. However, as trees age the relationship between TCA and crop load becomes less reliable as the rate of trunk growth differs to the rate of change in crop potential. Trees only require six branches per metre of tree canopy height (S. Tustin et al., 2015). This is the minimum number of branches needed to maximise orchard light interception and production potential. Ultimately, the TCA is related to the trunk of the tree which is not a branching unit and therefore it makes physiological sense to base crop loading decisions on an individual branch basis (fruit bearing wood) i.e. fruit number per unit of branch cross-sectional area (BCA). Within the literature, it is unclear if there is any relationship between the TCA and the sum of the BCA in apple canopies. For tall spindle trees on dwarfing rootstocks, the optimal fruit density per branch lies between 4 and 6 fruit per cm^2 BCA (Breen et al., 2016).

Crop loading metrics are currently unknown for planar cordon systems, particularly their effects on fruit set/return bloom, fruit yield and quality.

The main objective of this research was to quantify the relationships between tree and branch unit fruit densities and fruit size, colour, yield and return bloom, necessary to inform commercial management of planar cordon orchards.

A hypothesis was that fruit size, quality and return bloom of planar cordon trees would decline as fruit density increased, which has been a typically response measured in previous apple crop loading studies in 3D trees of various designs (Castro et al., 2015; Embree et al., 2007; McArtney et al., 1996; Wright et al., 2006).

3.2 Materials and methods

3.2.1 Crop loading and hand thinning

For all general and background methodology refer to section (2 -general methods).

In spring of 2017 and 2018, the basal cross-sectional area (BCA) of individual uprights was measured using the mafcot wheel (Figure 15) for all trees within the trial. Axillary flowers throughout the canopy were removed shortly after bud break. Fruit clusters on the cordons were thinned to singles, spaced 15-20 cm apart after fruit drop. On each upright, fruit were thinned to primarily a single fruit per bud in the lower half of the tree. Fruiting buds were left with two fruit primarily in the top half of the tree when fruit were large and were accompanied by a large supporting leaf area (i.e. bourse shoot > 10 cm long). All fruit sites were spaced approximately 15-20 cm apart between clusters. Some axillary flowers were kept in the top part of each upright for the following season's flower buds (i.e. in the zone of one-year old wood). In this zone of one-year-old wood, an axillary fruit was carried on approximately every second flower cluster. In 2018 following hand thinning, the fruit number retained on each upright was counted and a mafcot wheel (Figure 15) was used to measure the basal cross-sectional area of each upright. In 2019, crop load was increased further in an attempt to increase yield and understand relationships between fruit density, fruit size and colour. The thinning process was as described for 2018, however, upper limit fruit densities of each upright was based on spatial arrangement of fruit with good light environment for both cultivars. The TCA of each tree was measured 20 cm above the graft union while dormant in winter of 2017 and 2018. No chemical thinners were applied during both years of this trial.

Figure 15. Crop loading 'mafcot wheel'. Used to measure the branch base cross-sectional area of each individual vertical branch quickly and effectively.

3.2.2 Harvest planning:

During harvest, fruit were colour picked over 2-3 harvests within a 14-day window as previously described (section 2.8).

During the 2018 and 2019 season, all fruit were harvested by individual upright, each having a corresponding bag, labelled with identifiers of upright position, tree and treatment. Cordon fruit were harvested into crates to distinguish them from upright fruit. Component tree parts including cordon and uprights were run over a weight sizer as separate batches (see section 2.9.1).

3.2.3 Statistical analysis

The experiment was a split plot design with four treatments (2 m Vertical, 2 m Vee, 1.5 m Vertical and 1.5 m Vee) replicated by six trees per treatment (section 2.3). The main effects (row spacing (RS) and tree design (TD)) were factorially arranged. In this study, only trees in the measurement rows were used for analysis and all fruit within the trial were measured. In sections 3.3.6 and 3.3.7, crop load categories were separated into a nominally low (<8 fruit/cm^2 BCA), moderate (8-12 fruit/cm^2 BCA) and high crop density (>12 fruit/cm^2 BCA). Cultivars were analysed separately. Data were analysed by one-way and two-way ANOVA using the analysis of variance procedure in GenStat (18th Edition, VSN International, UK). Mean separations were made using the LSD test at *P*=0.05 for the yield data.

3.3 Results

3.3.1 Relationship between tree trunk cross-sectional area and tree total branch cross-sectional area.

Figure 16 shows the relationship between trunk cross-sectional area (TCA) and the total branch cross-sectional area (BCA) of individual trees. The data shows a polynomial relationship for both 'Royal Gala' and 'Scifresh' across two seasons, suggesting that as the TCA increases, the overall BCA for all uprights and droppers combined, increases also. 'Royal Gala' had a higher r^2 meaning a tighter/more precise response relationship than 'Scifresh' (r^2 'Royal Gala' = 0.7535, 'Scifresh' = 0.6038). The r^2's presented are their respective regression coefficients.

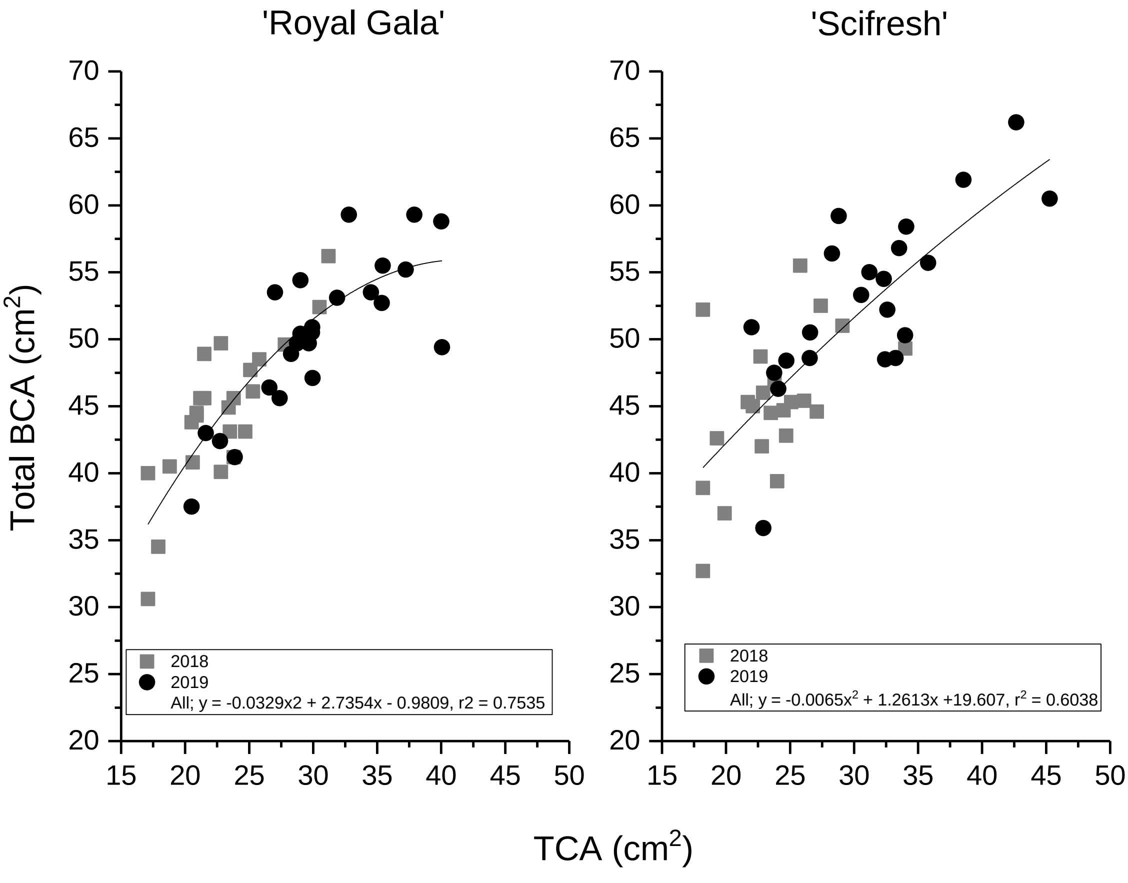
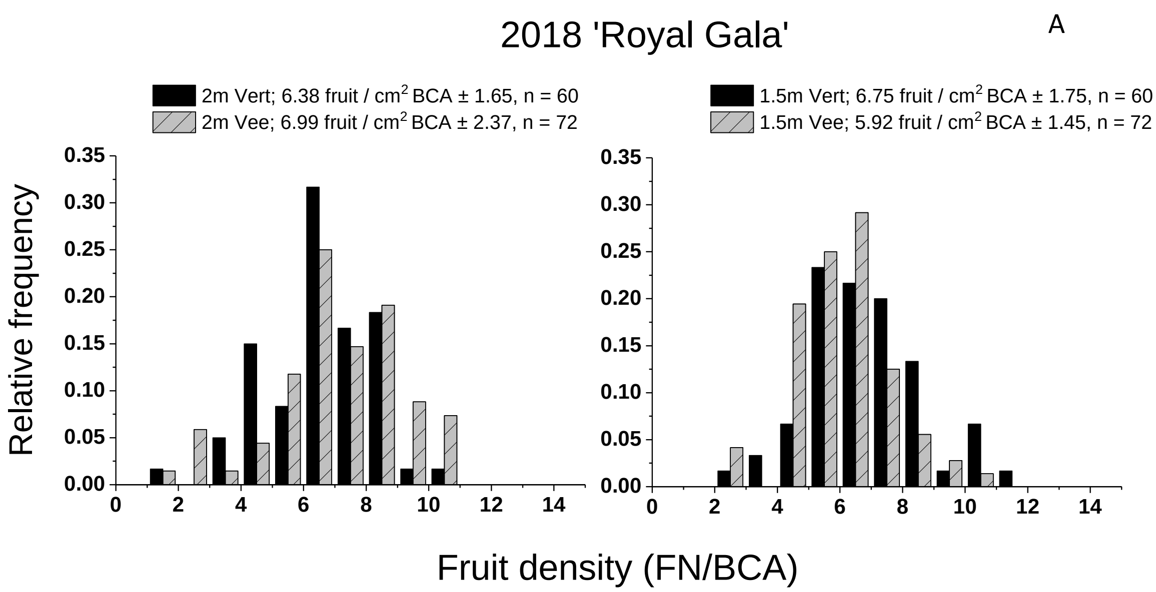


Figure 16. Relationship between trunk cross-sectional area (TCA) and total BCA (base cross-sectional area) of 'Royal Gala' and 'Scifresh' uprights in planar cordon apple trees grown on M9 rootstocks during the 2018 and 2019 seasons. The trunk cross-sectional area is made up of the sum of each cordon area (cm²). Total BCA is made up of the total branch cross-sectional area across all uprights and droppers throughout the canopy.

3.3.2 Distributions of upright fruit density

Relative frequency distributions of the crop load ranges achieved for each cultivar and year are shown in Figures 17 and 18. In 2018, uprights of ‘Royal Gala’ achieved crop loads ranging from 1 to 11 fruit/cm^2 BCA with an average of 6.5 fruit/cm^2 BCA, whereas uprights of ‘Scifresh’ achieved crop loads ranging from 4 to 14 fruit/cm^2 BCA with an average of 8.1 fruit/cm^2 BCA. In 2019, uprights of ‘Royal Gala’ achieved crop loads ranging from 4 to 28 fruit/cm^2 BCA with an average of 12.4 fruit/cm^2 BCA, whereas uprights of ‘Scifresh’ achieved crop loads ranging from 2 to 23 fruit/cm^2 BCA with an average of 9.4 fruit/cm^2 BCA. Uprights have a wide range of fruiting densities because of the natural variation and cropping ability of each upright at thinning.

Throughout 2018 and 2019, there were no interactions seen between the four treatments in terms of fruit density. However, with ‘Royal Gala’ in 2019, the average fruit density of 13.5 fruit/cm^2 BCA at the 1.5 m row spacing was significantly greater than 11.3 fruit/cm^2 BCA at the 2.0 m row spacing (p-value = 0.011). This was the opposite for ‘Scifresh’ as the uprights at the 2.0 m row spacing had a greater average fruit density than the 1.5 m row spacing at 9.99 and 8.87 fruit/cm^2 BCA, respectively (p-value = 0.05). The main effect of tree design in both ‘Royal Gala’ and ‘Scifresh’ between the Vertical and Vee canopies in the 2018 and 2019 seasons was not significantly different (p-value >0.05).



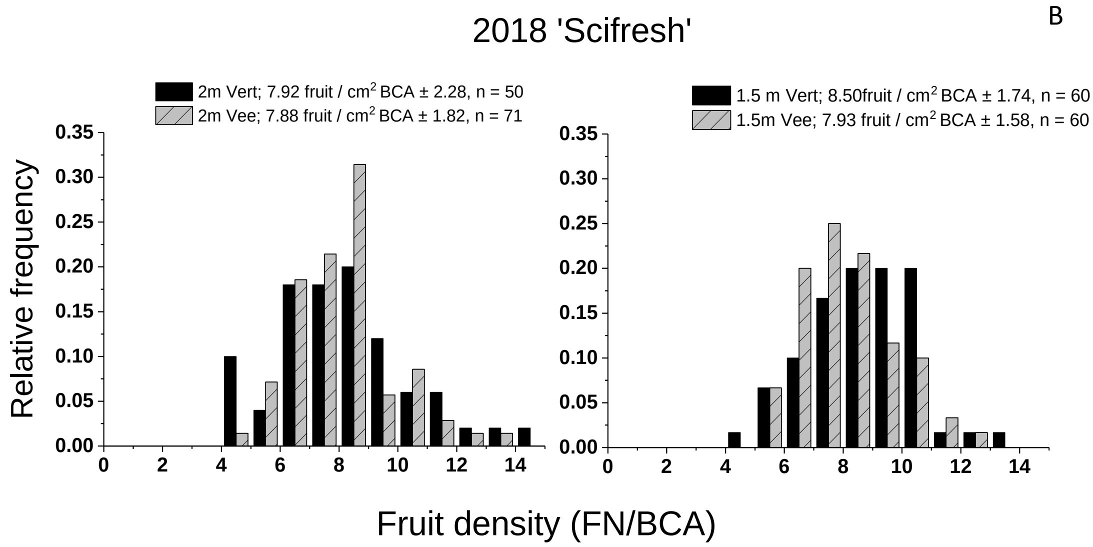
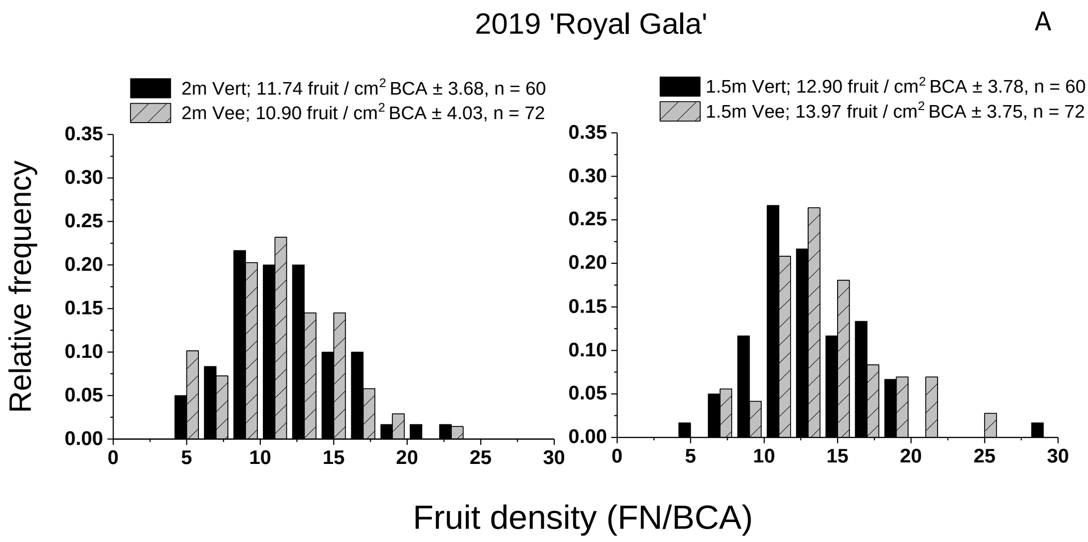


Figure 17. Fruit density distribution for 'Royal Gala' (A) and 'Scifresh' (B) apple in 2018, from 1.5 m and 2.0 m row spacing treatments trained with Vertical and Vee tree structures. Trees, grown on a bi-axis planar cordon planting system trial in their fourth year from planting. Annotated data are the mean crop load (fruit / cm² BCA), standard deviation and n-value (number of observations). Fruit density expressed as FN/BCA (fruit number/base cross-sectional area).



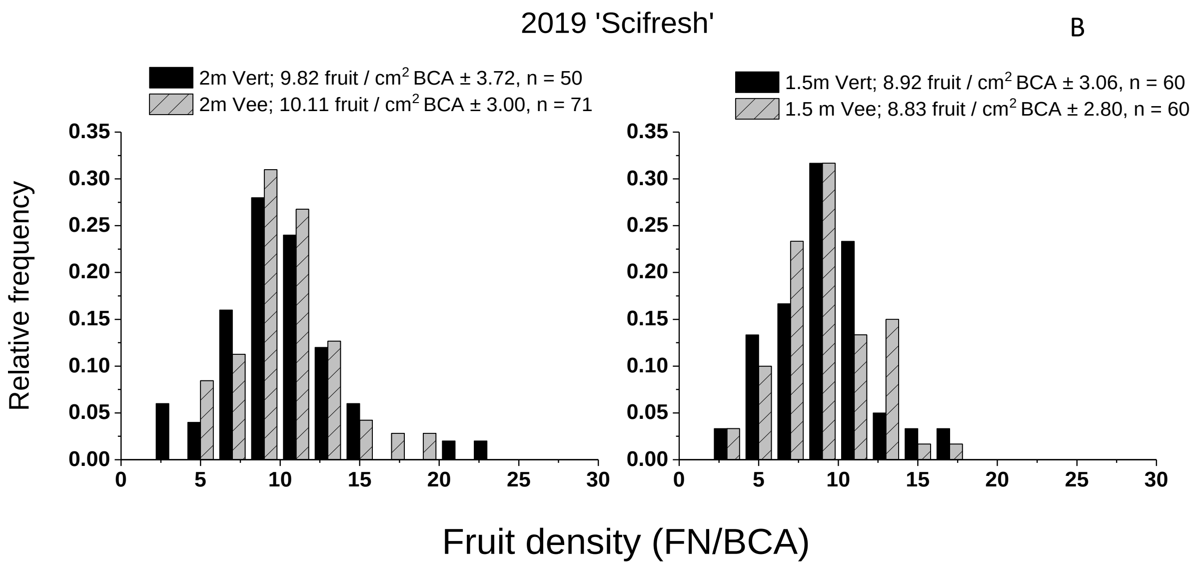


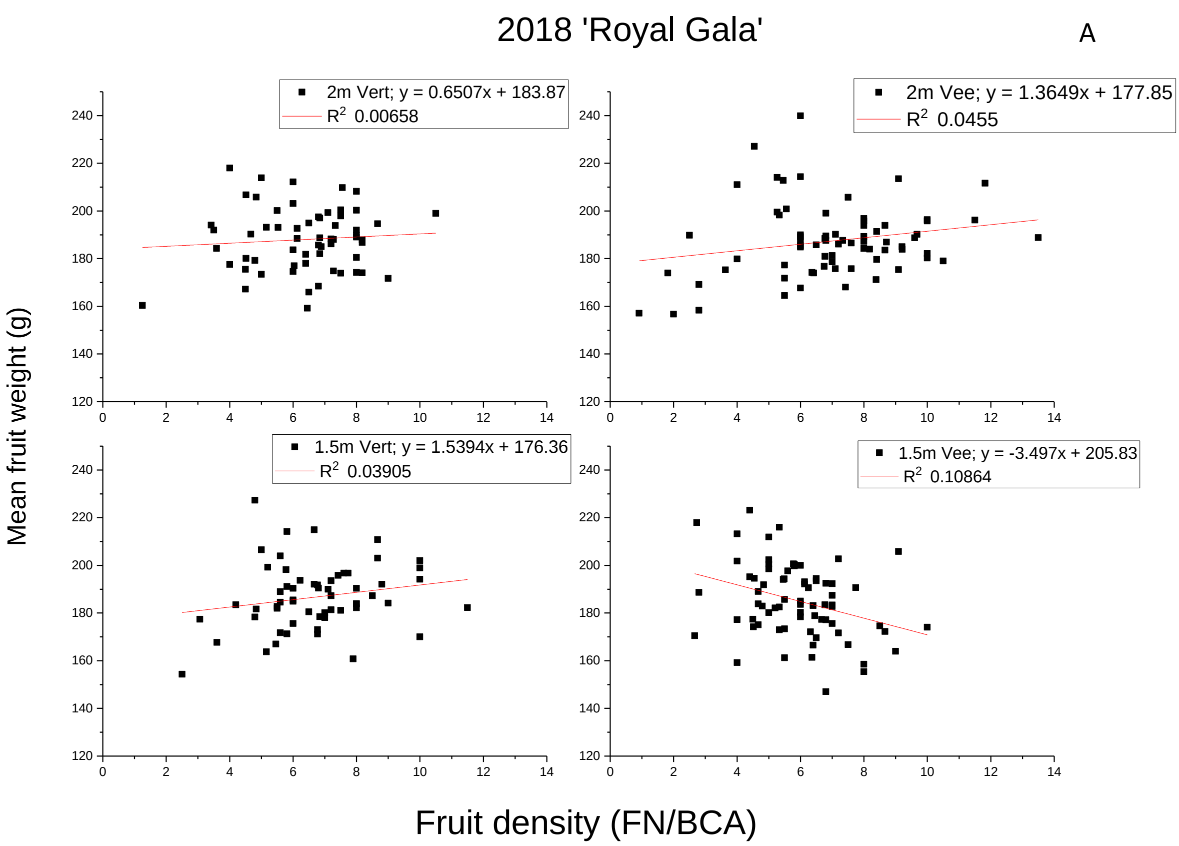
Figure 18. Fruit density distribution for 'Royal Gala' (A) and 'Scifresh' (B) in 2019, from 1.5 m and 2.0 m row spacing treatments trained with Vertical and Vee tree structures. Trees, grown on a bi-axis planar cordon planting system trial in their fifth year from planting. Annotated data are the mean fruit density (fruit / cm² BCA), standard deviation and n-value (number of observations). Fruit density expressed as FN/BCA (fruit number/base cross-sectional area).

3.3.3 Effect of upright fruit densities (crop load) on mean fruit weight

Fruit densities of individual uprights for 'Royal Gala' ranged from (0.9 – 13.8 fruit/cm^2) in 2018 (Figure 19). The four plots show a weak correlation between fruit density and mean fruit weight among all treatments. According to the r^2 values, the plots only explain, at best, 10% of the variation. Generally, mean fruit weight (MFW) does not decrease with fruit density. However, there was a relationship at the 1.5 m Vee where fruit density increased from 2-10 units, mean fruit weight decreased by 20 g (Figure 19).

For 'Scifresh', the results also show only a weak correlation between fruit density and MFW for each of the four treatments in 2018 with only ≤5% of the variation explained. Uprights at all densities produced fruit with weights from 140-240g. Fruit density levels were targeted at 10-11 fruit/cm^2 BCA for 'Scifresh' in 2018. This gave a fruit density range of 2.6 – 14 fruit/cm^2 BCA for individual uprights among the four treatments (Figure 19).

3.3.3.1 2018



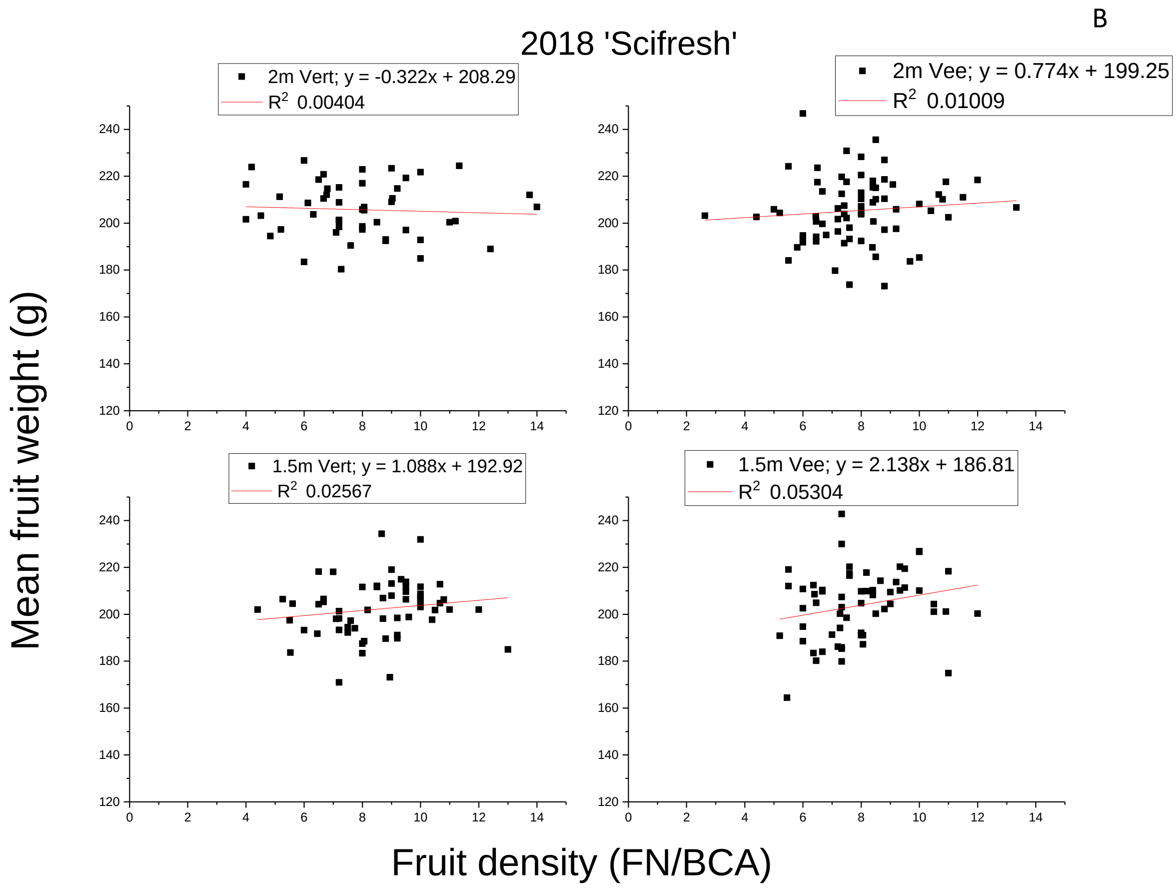
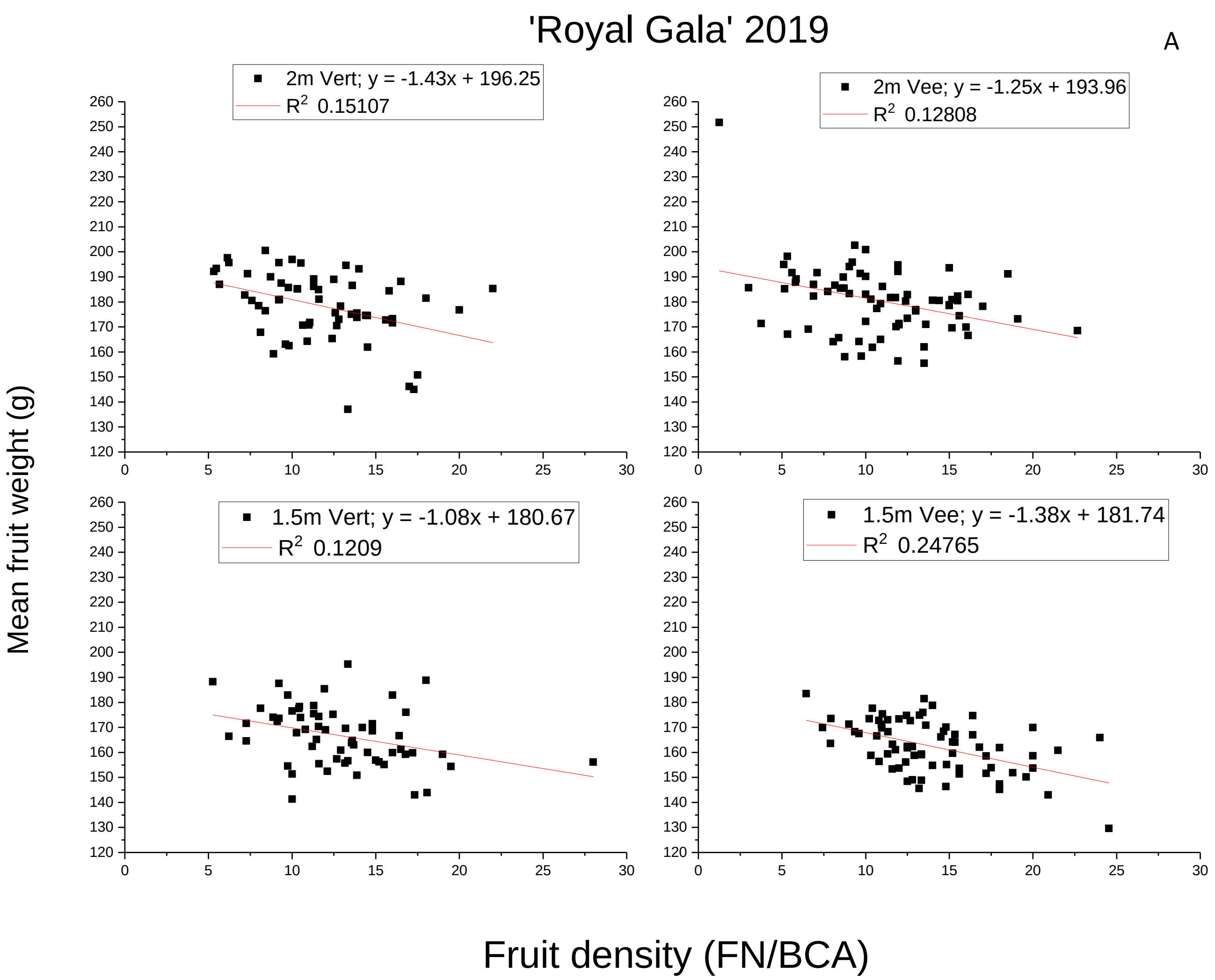


Figure 19. Relationships between fruit density of individual branch units (fruit number (FN) per basal cross-sectional area (BCA)) and mean fruit weight (g) at harvest (February 2018) for 4-year-old planar cordon 'Royal Gala' (A) and 'Scifresh' (B) trees on M9 rootstock grown at 1.5 m or 2 m inter-row spacings and trained as Vertical or Vee canopies. Each plot is annotated with a relative treatment description, relationship equation and the r^2 value.

3.3.3.2 2019

In 'Royal Gala', there was a large spread of crop density per upright ranging from 1 to 28 fruit/cm^2 BCA (Figure 20). A negative trend occurred with MFW of each individual treatment decreasing as fruit density increased. However, r^2 values of each treatment regression suggest the relationship was not strong, with only 12 to 25% of the variation explained (r^2 values; 0.151, 0.128, 0.120, 0.247) (Figure 20).

In 'Scifresh', correlations between fruit density and MFW suggests that there was a weak relationship that was highly variable, showing that when fruit density increased the MFW stays constant on an upright level. The r^2 values were below 0.08 for all four of the treatments (r^2; 0.02, 0.06, 0.07, 0.06). The MFW ranged from approximately 160-220g at crop densities ranging from 2 to 23 fruit/cm^2 BCA.



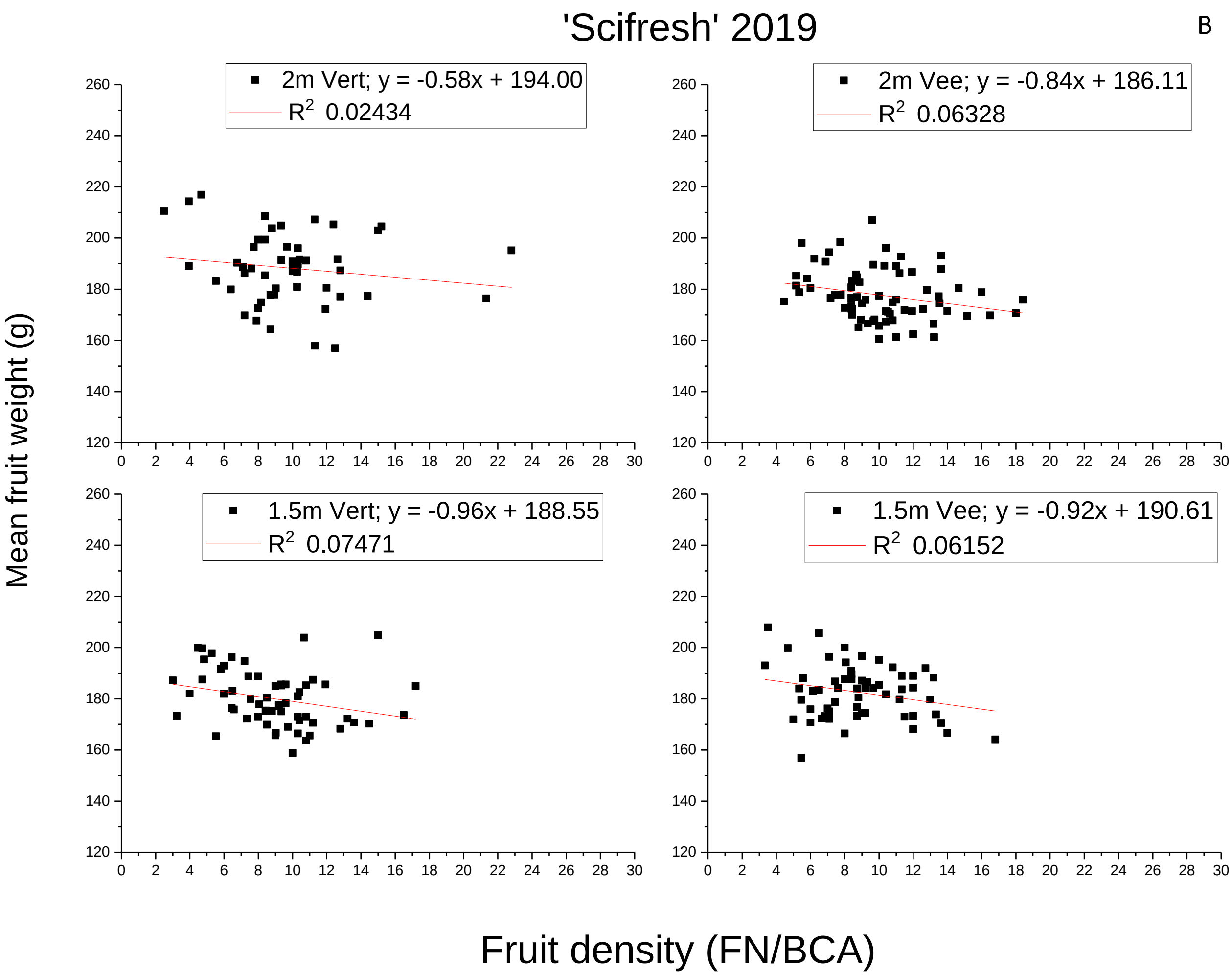
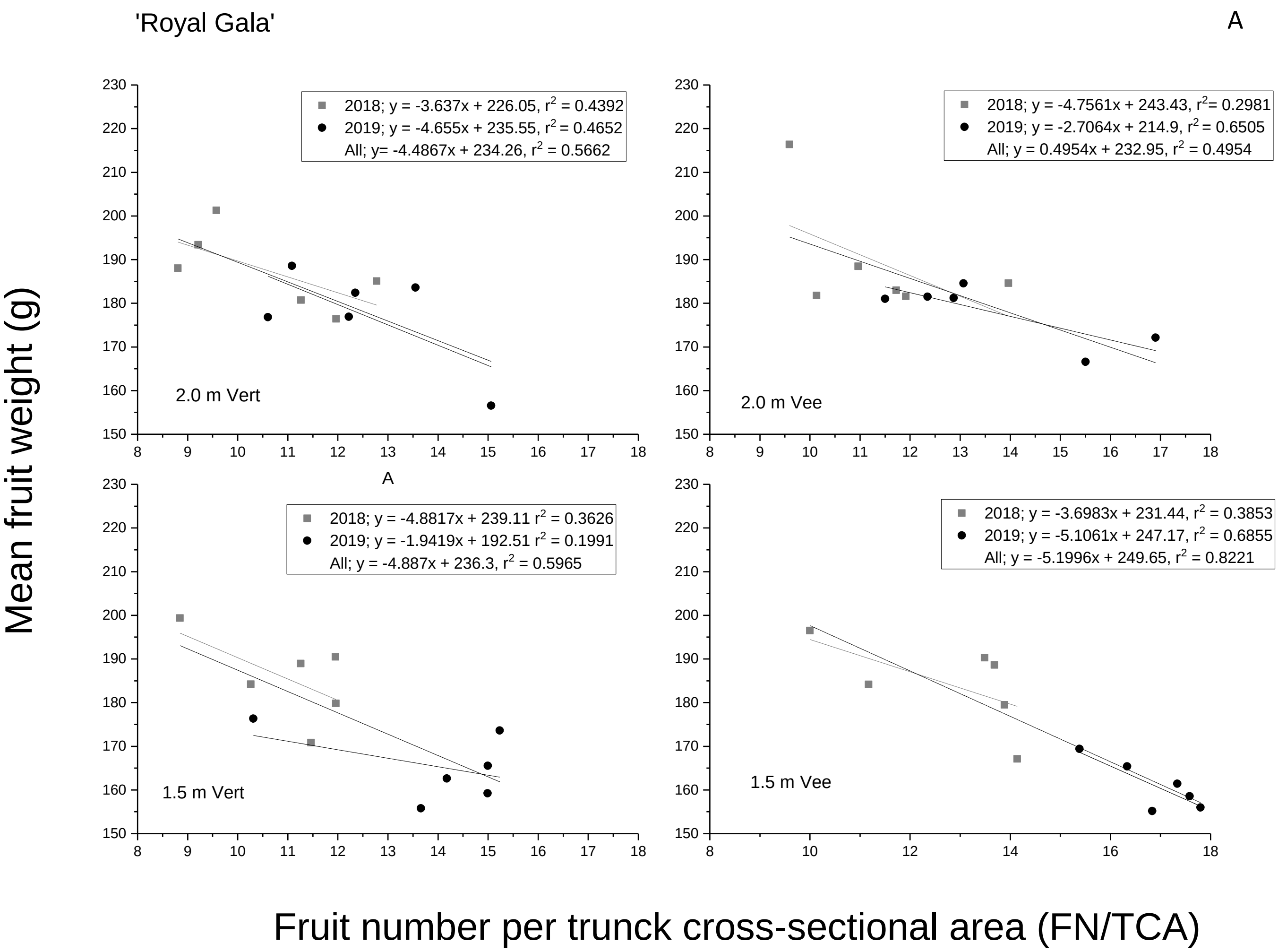


Figure 20. Relationships between fruit density of individual branch units (fruit number (FN) per basal cross-sectional area (BCA) and mean fruit weight (g) at harvest (February 2019) for 5-year-old planar cordon 'Royal Gala' (A) and 'Scifresh' (B) trees on M9 rootstock grown at 1.5 m or 2 m inter-row spacings and trained as Vertical or Vee canopies. Each plot is annotated with a relative treatment description and the r^2 value.

3.3.4 Relationship between tree TCA and tree mean fruit weight at harvest

In 'Royal Gala', the 2018 data showed that on a TCA basis the fruit densities were relatively similar between trees (Figure 21). This was dependent on tree design as the Vee canopy had two extra uprights, so the fruit number per TCA was slightly more. The vertical canopy carried an average of 10.6 fruit/cm^2 TCA in the 2 m spacing and 10.9 fruit/cm^2 TCA in the 1.5 m row spacing. The Vee canopy carried slightly more at 11.3 fruit/cm^2 TCA at 2 m and 12.7 fruit/cm^2 TCA at the 1.5 m row spacing. The response of MFW to fruit density per unit TCA was similar with the 2019 'Royal Gala' data. Overall the 'Royal Gala' data is showing a negative relationship between fruit density and MFW at a tree level.

The fruit density x mean fruit weight relationship for 'Scifresh' suggests a significant seasonal effect. 'Scifresh' showed no difference in fruit density (fruit number per TCA) between the 2018 and 2019 seasons. This may be attributed to the light flowering intensity in the 2019 season. In all four treatments, the data shows that the MFW in 2018 was greater than that in 2019 at 199 g and 178 g, respectively. R^2 values for fruit density (at a whole tree level) and MFW relationships range from 0.0041 to 0.7089 in 2018 and 0.3018 to 0.8774 in 2019 (Figure 21).



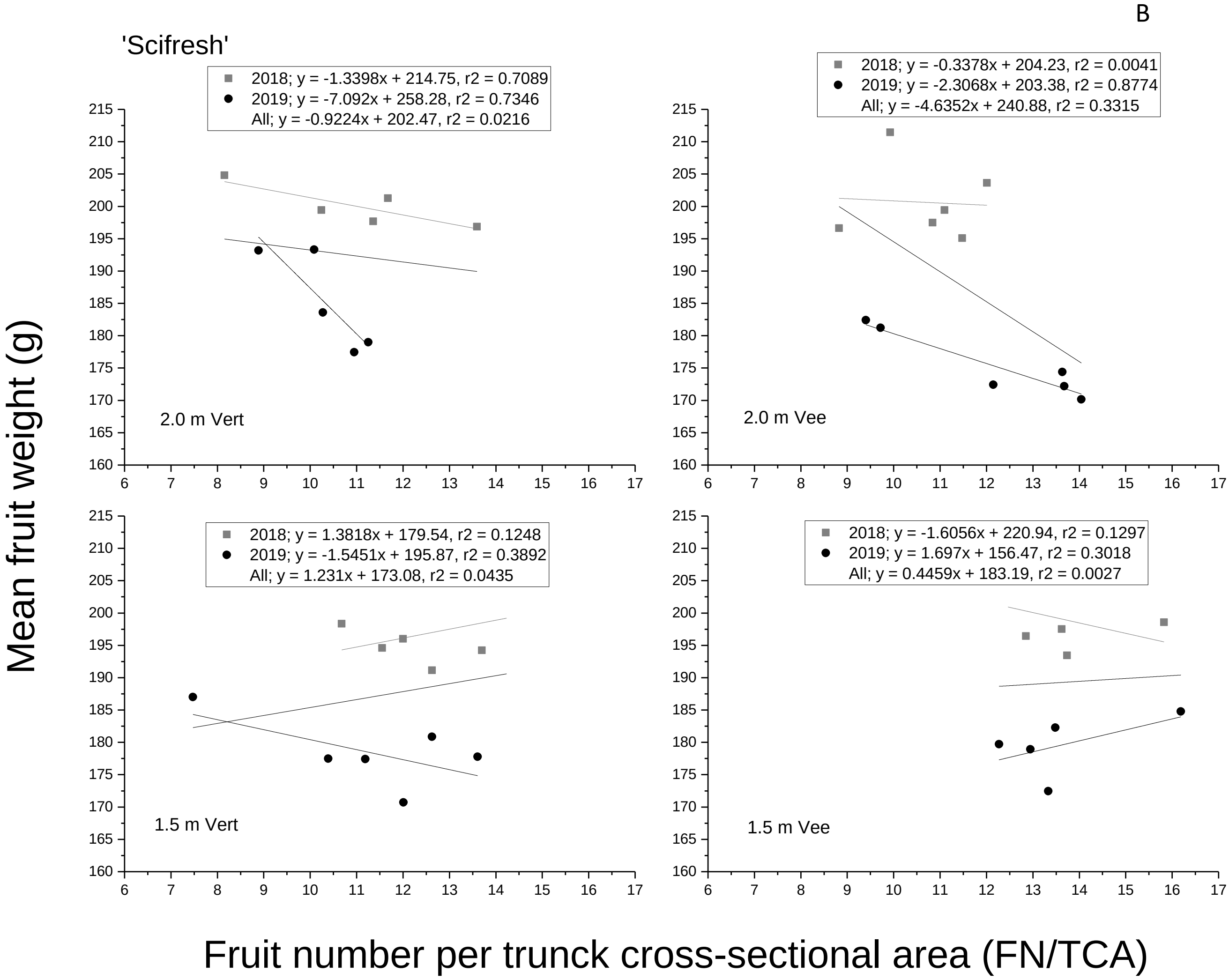
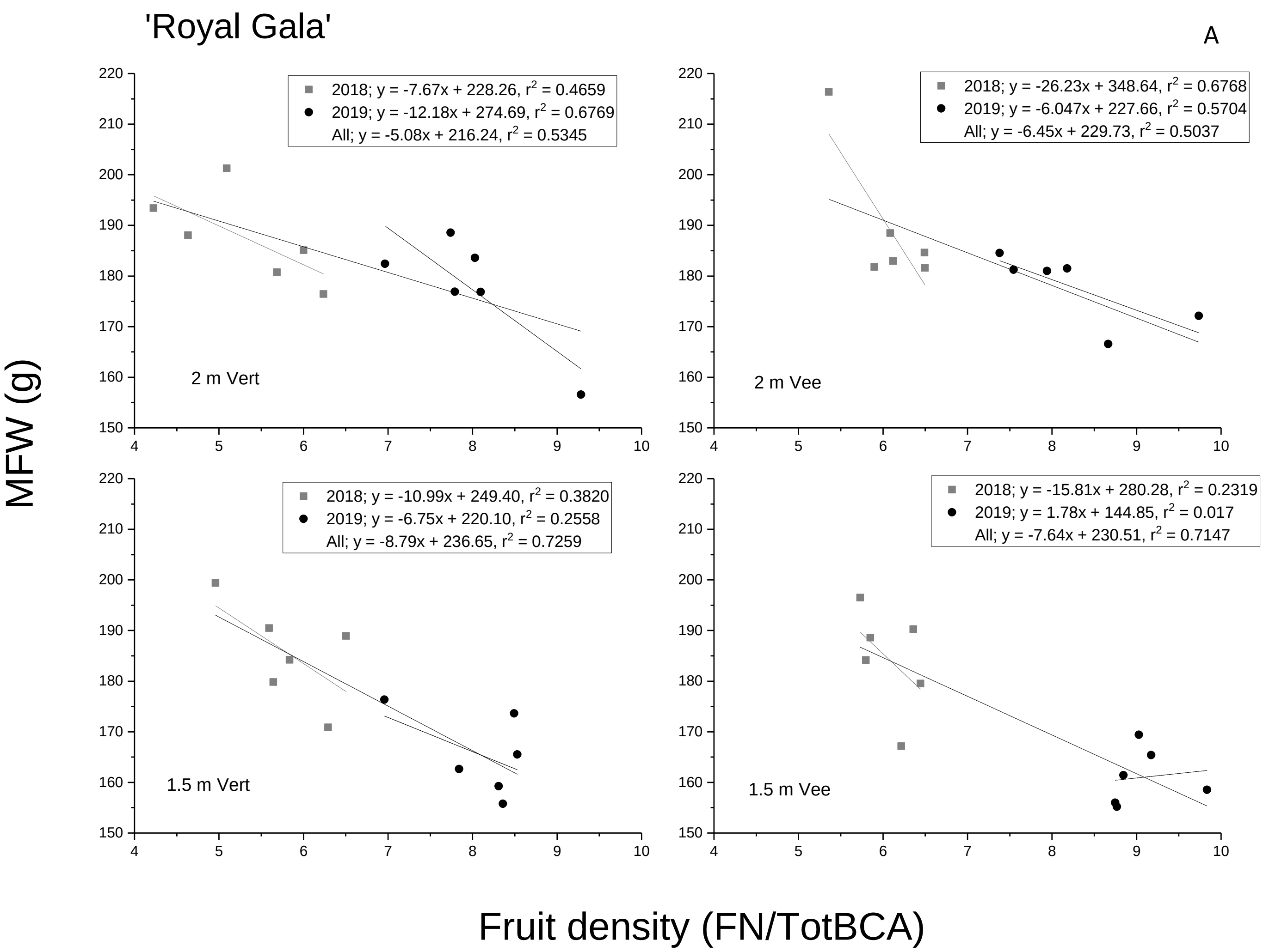


Figure 21. Effect of fruit density at a whole tree level (fruit number (FN) per truck cross-sectional area (TCA)) on mean fruit weight (g) at harvest of 'Royal Gala' (A) and 'Scifresh' (B) in 2018 and 2019 seasons. Fruit were harvested from the bi-axis planar cordon planting system on an M9 rootstock in February of both seasons. Each plot is annotated with a relative treatment description (row spacing x tree design) and the r^2 value.

3.3.5 Relationship between tree total BCA and tree mean fruit weight at harvest

The total BCA (totBCA) is the sum of all the upright and dropper (cordon branches) BCA's. In 'Royal Gala' the 2018 data showed that on a total BCA basis the fruit densities were similar between trees, only differing by, at most, 2 fruit/cm^2 BCA (Figure 22). The Vertical canopy carried an average of 5.31 fruit/cm^2 totBCA in the 2 m spacing and 5.80 fruit/cm^2 totBCA in the 1.5 m row spacing. The Vee canopy carried slightly more at 6.07 fruit/cm^2 totBCA at 2 m and at the 1.5 m row spacing. In 2019, the Vertical canopy carried an average of 7.98 fruit/cm^2 totBCA in the 2 m spacing and 8.08 fruit/cm^2 totBCA in the 1.5 m row spacing. The Vee carried slightly more at 8.24 fruit/cm^2 totBCA at 2 m and 9.07 fruit/cm^2 totBCA at the 1.5 m row spacing. Overall the 'Royal Gala' data is showing a negative relationship between totBCA fruit density and MFW at a tree level. R^2 values for fruit density (at a whole tree level) and MFW relationships range from 0.2319 to 0.6768 in 2018 and 0.017 to 0.6769 in 2019 (Figure 22).

The crop loading data from 'Scifresh' suggests a significant seasonal effect. Unlike 'Royal Gala', 'Scifresh' showed no difference in fruit density between the 2018 and 2019 seasons. In all four treatments, the data shows that the MFW in 2018 was greater than that in 2019. The Vertical canopy carried an average of 5.58 fruit/cm^2 totBCA in the 2 m spacing and 6.65 fruit/cm^2 totBCA in the 1.5 m row spacing. The Vee carried 6.00 fruit/cm^2 totBCA at 2 m and 6.41 fruit/cm^2 totBCA at the 1.5 m row spacing. In 2019, the Vertical canopy carried an average of 6.16 fruit/cm^2 totBCA in the 2 m spacing and 6.13 fruit/cm^2 totBCA in the 1.5 m row spacing. The Vee carried slightly more at 7.76 fruit/cm^2 totBCA at 2 m and 6.72 fruit/cm^2 totBCA at the 1.5 m row spacing. Overall the 'Scifresh' data for 2018 and 2019 is showing a negative relationship between fruit density and MFW at a tree level. R^2 values for fruit density (at a whole tree level) and MFW relationships range from 0.017 to 0.5289 in 2018 and 0.1212 to 0.5963 in 2019 (Figure 22).


'Royal Gala'
A
MFW (g)
2018; y = -7.67x + 228.26, r2 = 0.4659
2019; y = -12.18x + 274.69, r2 = 0.6769
All; y = -5.08x + 216.24, r2 = 0.5345
2 m Vert
2018; y = -26.23x + 348.64, r2 = 0.6768
2019; y = -6.047x + 227.66, r2 = 0.5704
All; y = -6.45x + 229.73, r2 = 0.5037
2 m Vee
2018; y = -10.99x + 249.40, r2 = 0.3820
2019; y = -6.75x + 220.10, r2 = 0.2558
All; y = -8.79x + 236.65, r2 = 0.7259
1.5 m Vert
2018; y = -15.81x + 280.28, r2 = 0.2319
2019; y = 1.78x + 144.85, r2 = 0.017
All; y = -7.64x + 230.51, r2 = 0.7147
1.5 m Vee
Fruit density (FN/TotBCA)

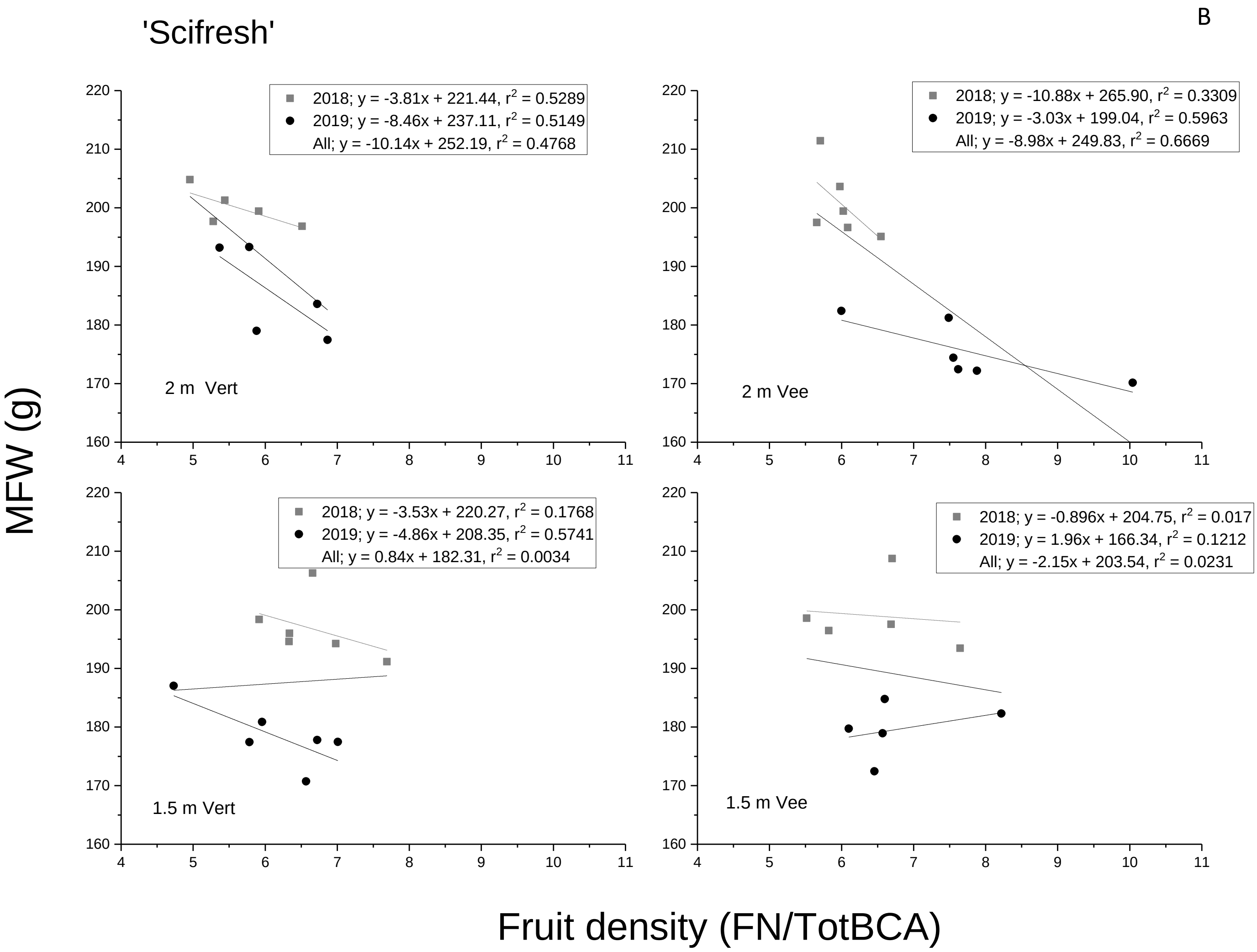


Figure 22. Effect of fruit density at a whole tree level (fruit number (FN) per total branch cross sectional area (TotBCA)) on mean fruit weight (MFW) (g) at harvest of 'Royal Gala' (A) and 'Scifresh' (B) in 2018 and 2019 seasons. Fruit were harvested from the bi-axis planar cordon planting system on an M9 rootstock in February of both seasons. Each plot is annotated with a relative treatment description (row spacing x tree design) and the r^2 value.

3.3.6 Fruit density categories and their effect on fruit size

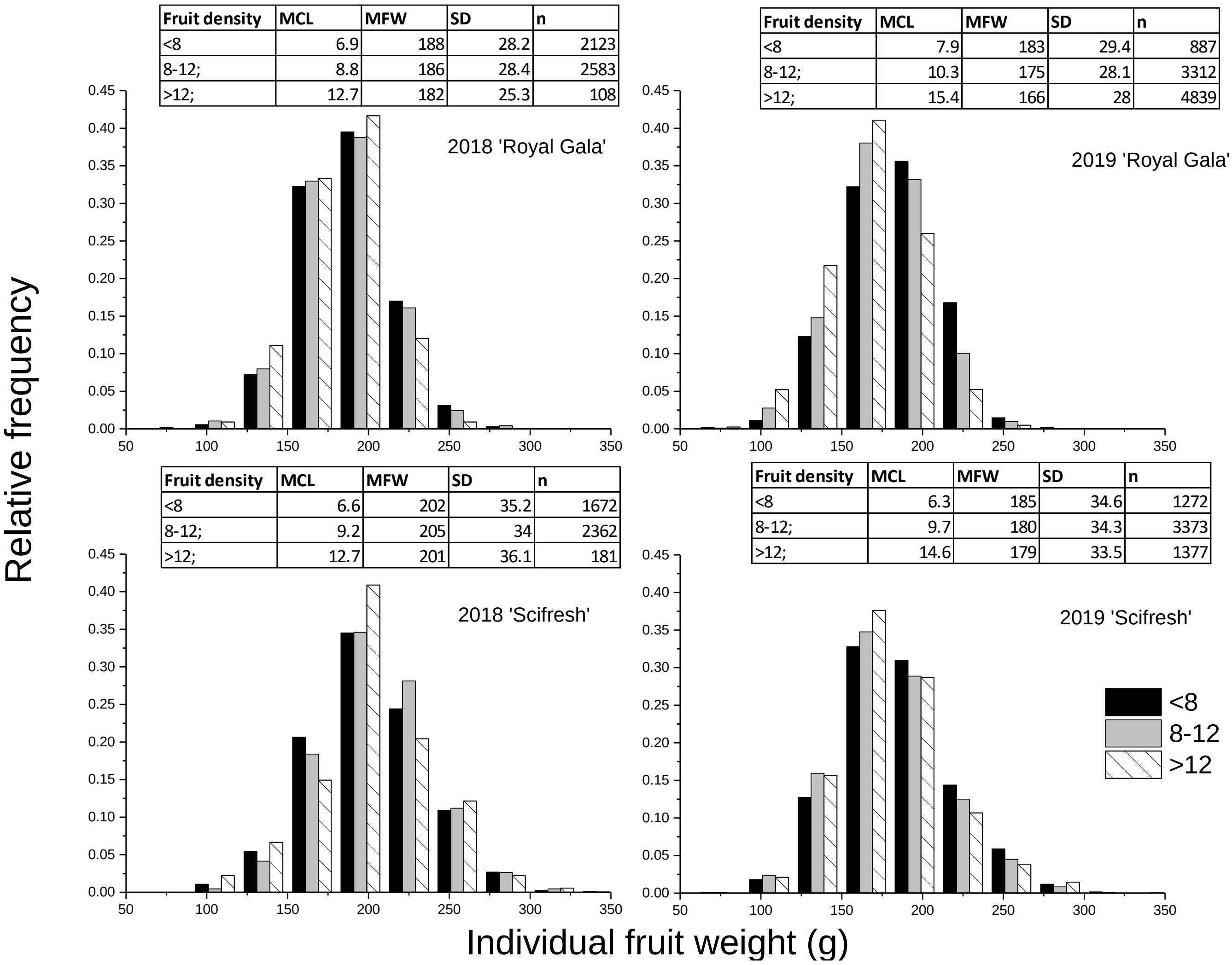
In an attempt to discover how fruit density effects fruit size, fruit were analysed for a response to three different levels of fruit density. Being able to differentiate between nominally low, moderate and high fruit densities will give an understanding around at what point fruit quality is being affected. The three upright fruit density categories are less than 8 fruit/cm^2 BCA, 8 to 12 fruit/cm^2 BCA and greater than 12 fruit/cm^2 BCA.

3.3.6.1 Fruit size distribution – fruit density categories, cultivar and year

Figure 23 shows a relative frequency distribution for fruit size at three different levels of fruit density. This plot uses the data from all tree designs and all row spacing treatments within the experiment.

All four plots show a normally distributed spread of fruit size for each of the three fruit density categories. Centre of distribution is similar for each relative year. The 2018 data had a centre peak of 180-200g, while the 2019 centre peak was slightly less at, 150-175g. This meant that the mean values for each year, irrespective of the cultivar was greater in 2018 than in 2019.

Generally, the population distribution shows that uprights at a fruit density below 8 fruit/cm^2 BCA generally produce slightly larger fruit (from 2-8 g). This is the case for every year and cultivar except 2018 ‘Scifresh’ where fruit densities of 8-12 fruit/cm^2 BCA had a greater MFW compared to fruit densities less than 8 fruit/cm^2 BCA and greater than 12 fruit/cm^2 BCA.



Fruit density	MCL	MFW	SD	n
<8	6.9	188	28.2	2123
8-12;	8.8	186	28.4	2583
>12;	12.7	182	25.3	108

Fruit density	MCL	MFW	SD	n
<8	7.9	183	29.4	887
8-12;	10.3	175	28.1	3312
>12;	15.4	166	28	4839

Fruit density	MCL	MFW	SD	n
<8	6.6	202	35.2	1672
8-12;	9.2	205	34	2362
>12;	12.7	201	36.1	181

Fruit density	MCL	MFW	SD	n
<8	6.3	185	34.6	1272
8-12;	9.7	180	34.3	3373
>12;	14.6	179	33.5	1377

Figure 23. Relative frequency distributions for fruit size (g) in response to branch fruit density ranges for 'Royal Gala' and 'Scifresh' apple on M9 rootstock at harvests 2018 and 2019. Data for each cultivar and year include all uprights from row spacing and tree design treatments. Fruit densities of uprights are divided into three groups, less than 8 fruit/cm² BCA, 8-12 fruit/cm² BCA and greater than 12 fruit/cm² BCA. Fruit density is measured by the amount of fruit/cm² BCA. MCL = mean crop load. MFW = mean fruit weight (g). SD = standard deviation. n = number of occurrences.

3.3.6.2 Row spacing treatments by cultivar – 2019

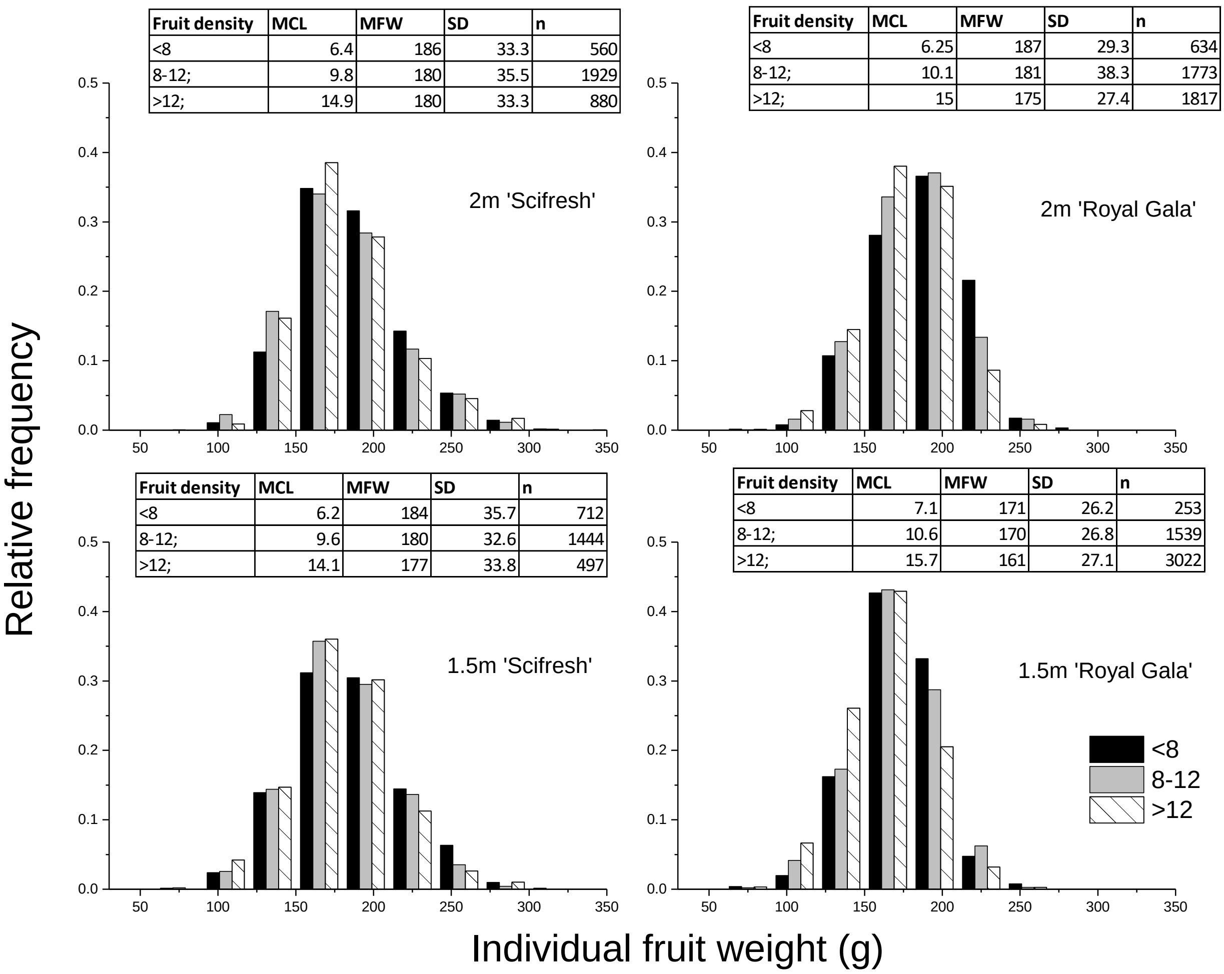
Figure 24 shows a frequency distribution of different levelled categories of fruit density in 2019. This plot illustrates the potential change in fruit size for the two row spacing treatments seen in the yield data (Table 5) for 'Royal Gala'.

3.3.6.2.1 'Scifresh'

The data suggests that for 'Scifresh' alone, the two row spacing treatments have very similar fruit size distributions at each of the different levels of upright fruit density. Both of the plots within the row spacing treatment peaked between 150-175g, with the majority of fruit being at or above this range (slight right skew). The number of fruit in each level of fruit density (n values) are relatively similar for the two row spacing treatments (Figure 24).

3.3.6.2.2 'Royal Gala'

The 2019 'Royal Gala' data shows that the 2.0 m row spacing produced larger fruit than the 1.5 m spacing (Table 5). The mean fruit weight for all three upright fruit density categories are greater in the 2 m row spacing in comparison to the 1.5 m. However, these means are made up of different n values, particularly at the high fruit density category (greater than 12 fruit/cm^2 BCA). There were 3022 fruit harvested from highly cropped uprights (12 fruit/cm^2 BCA or higher) at the 1.5 m row spacing, whereas the 2 m row spacing only contained 1817 fruit at that density (Figure 25). Alternatively, more uprights at the 1.5 m spacing were above 12 fruit/cm^2 BCA compared to the 2.0 m row spacing. This suggests that the mean fruit weight reduced due to the higher number of uprights set at >12 fruit/cm^2 BCA. However, Figure 25 shows the difference in MFW between row spacing treatments for upright fruiting densities **≥ 12 fruit / cm^2 BCA** in 'Royal Gala'. The 2.0 m spacing has a 10-15 g larger mean fruit weight compared with the 1.5 m inter-row spacing at fruit density ranges **≥ 12 fruit / cm^2 BCA**. In addition, as fruit density of uprights increased, mean fruit weight did not change. This finding suggests that although the n value for high fruit density uprights was greater in the 1.5 m row spacing compared to the 2 m, it is not the contributing factor to the overall decline in MFW between row spacing treatments.



Fruit density	MCL	MFW	SD	n
<8	6.4	186	33.3	560
8-12;	9.8	180	35.5	1929
>12;	14.9	180	33.3	880

Fruit density	MCL	MFW	SD	n
<8	6.25	187	29.3	634
8-12;	10.1	181	38.3	1773
>12;	15	175	27.4	1817

Fruit density	MCL	MFW	SD	n
<8	6.2	184	35.7	712
8-12;	9.6	180	32.6	1444
>12;	14.1	177	33.8	497

Fruit density	MCL	MFW	SD	n
<8	7.1	171	26.2	253
8-12;	10.6	170	26.8	1539
>12;	15.7	161	27.1	3022

Figure 24. Relative frequency distributions for fruit size (g) in response to branch fruit density ranges and two row spacings (1.5 m and 2 m) for 'Royal Gala' and 'Scifresh' apple on M9 rootstock at harvests in 2019. Data for each cultivar include all uprights from the tree design treatments (i.e. Vee and Vertical canopies). The fruit densities of uprights are divided into three groups, less than 8 fruit/cm² BCA, 8-12 fruit/cm² BCA and greater than 12 fruit/cm² BCA. Fruit density is measured by the amount of fruit/cm² BCA. MCL = mean crop load. MFW = mean fruit weight (g). SD = standard deviation. n = number of occurrences.

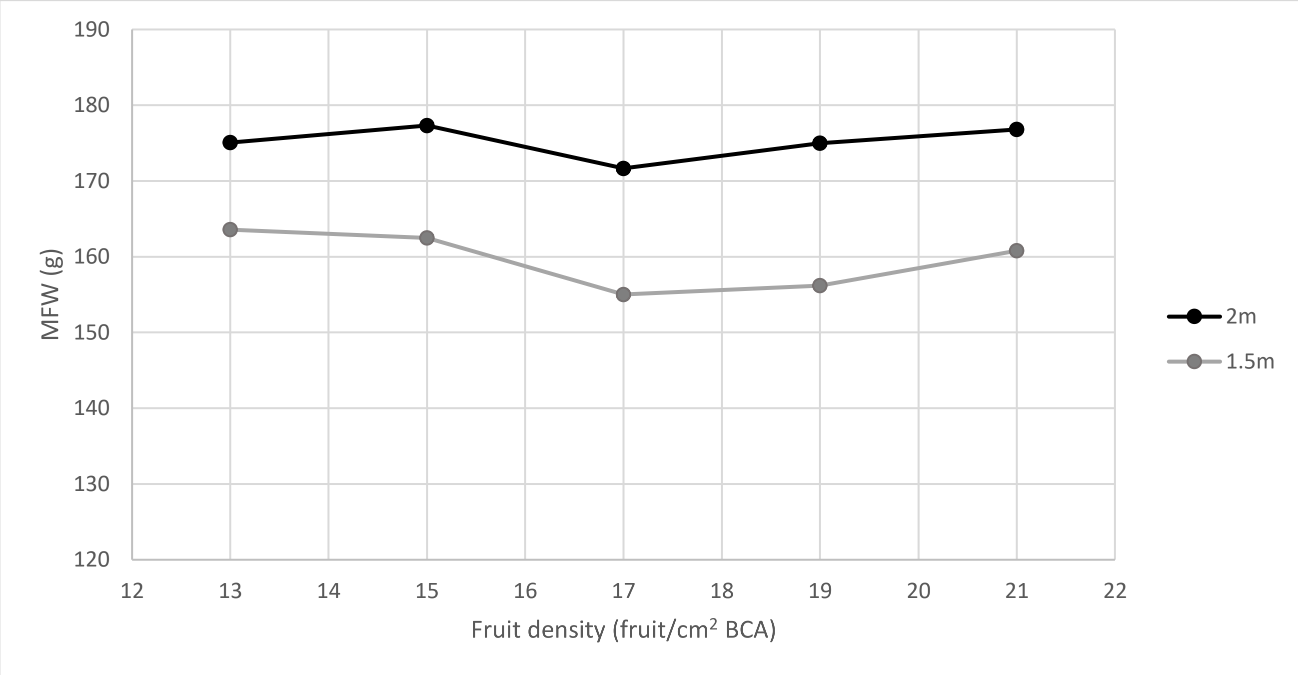


Figure 25. Fruit size (MFW) response to high crop densities ≥ 12 fruit / cm² BCA on the Vert and Vee planar cordon training systems for the 1.5 m and 2 m inter-row spacing treatments in 'Royal Gala' grown on M9, harvest 2019.

3.3.7 Red colour distribution – fruit density categories

Figure 26 outlines the red colour distribution for fruit in different fruit density categories. (Figure 23 and 24).

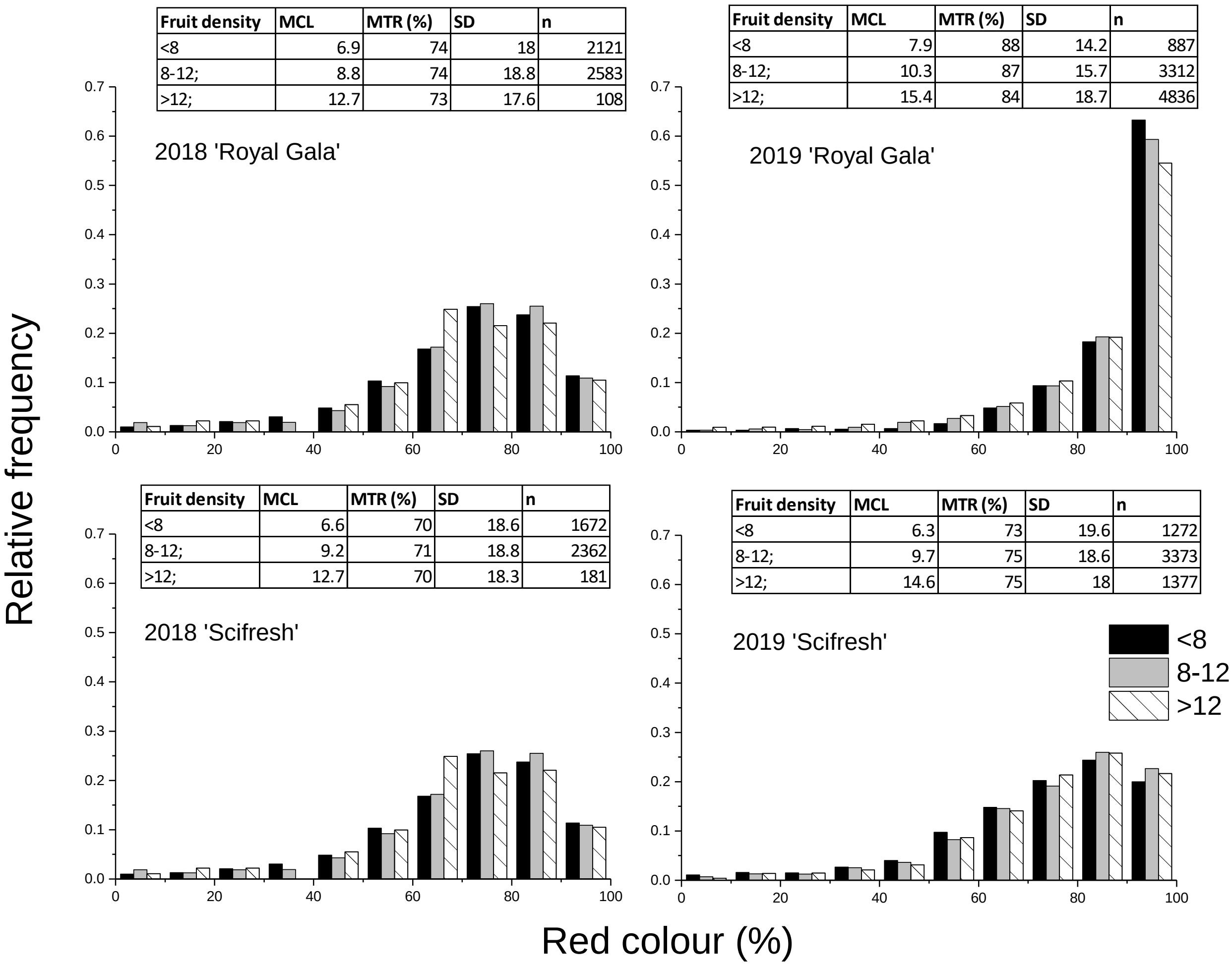
3.3.7.1 2018

The 2018 colour distributions were similar for both 'Royal Gala' and 'Scifresh'. The two lower fruit density categories (<8 and 8-12 fruit/cm^2 BCA) peaked between 70-80% red colour whereas fruit at a higher density (>12 fruit/cm^2 BCA) peaked at a slightly lower red colour of 60-70%. Both plots in 2018 have marked left skew, however the majority (approx. 75%) of the fruit had a red colour coverage of 60-90%. 'Royal Gala' showed no differences in red colour at different fruit densities with the average for fruit density groups <8, 8-12, and >12 fruit/cm^2 BCA being 74%, 74%, and 73%, respectively. Similarly, 'Scifresh' showed no differences in red colour at different fruit densities with the average for <8, 8-12, and >12 fruit/cm^2 BCA being 70%, 71%, and 70%, respectively (Figure 26). Of all fruit grown in 2018, 37% and 12% failed to reach a minimum colour standard for export quality fruit for 'Royal Gala' and 'Scifresh', respectively.

3.3.7.2 2019

Figure 26 shows for 'Royal Gala' a strong right skew indicating the large majority of fruit harvested were of a high red percentage. Approximately 50% of the 'Royal Gala' crop had 90-100% red colour, with the majority of the remaining fruit having more than 60% red colour. In these planar cordon canopies, upright fruit density did not affect fruit colour across the range of fruit density present in this study in 'Royal Gala'.

'Scifresh' shows a relatively similar distribution plot to the 2018 data set. The plot shows that approximately 70% of fruit harvest were coloured to 70-100% red colour. 'Scifresh' showed no differences in red colour percentage at different fruit densities with the average for <8, 8-12, and >12 fruit/cm^2 BCA being 73%, 75%, and 75%, respectively. Of all fruit grown in 2019, 13% and 7% failed to reach a minimum colour standard for export quality fruit for 'Royal Gala' and 'Scifresh', respectively.



2018 'Royal Gala'

Fruit density	MCL	MTR (%)	SD	n
<8	6.9	74	18	2121
8-12;	8.8	74	18.8	2583
>12;	12.7	73	17.6	108

2019 'Royal Gala'

Fruit density	MCL	MTR (%)	SD	n
<8	7.9	88	14.2	887
8-12;	10.3	87	15.7	3312
>12;	15.4	84	18.7	4836

2018 'Scifresh'

Fruit density	MCL	MTR (%)	SD	n
<8	6.6	70	18.6	1672
8-12;	9.2	71	18.8	2362
>12;	12.7	70	18.3	181

2019 'Scifresh'

Fruit density	MCL	MTR (%)	SD	n
<8	6.3	73	19.6	1272
8-12;	9.7	75	18.6	3373
>12;	14.6	75	18	1377

Figure 26. Relative frequency distributions for red colour (%) in response to upright fruit density ranges for 'Royal Gala' and 'Scifresh' apple on planar cordon with M9 rootstock at harvests 2018 and 2019. Data for each cultivar and year include all uprights from row spacing and tree design treatments. Fruit density of uprights are divided into three groups, less than 8 fruit/cm² BCA, 8-12 fruit/cm² BCA and greater than 12 fruit/cm² BCA. Fruit density is measured by the amount of fruit/cm² BCA. MCL = mean crop load. MTR = mean red colour (%). SD = standard deviation. n = number of occurrences.

3.3.8 Yield Data

3.3.8.1 2017 – 2018 season

For 'Royal Gala' in the 2018 season, the 1.5 m row spacing showed no differences in fruit number per tree compared to the 2.0 m row spacing, which resulted in similar yields per tree (Table 2). Consequently the 1.5 m row spacing treatment producing greater yield per hectare, 104.9 t/ha compared to 81.3 t/ha at 2.0 m (p =0.024). The Vee canopy consistently produced more fruit per tree, possibly by having an extra 2 fruiting uprights compared to the vertical tree design, however, this difference was not significant (p=0.283). Therefore, few differences occurred between tree designs for yield per tree (p=0.370) and yield per hectare (p=0.413) in 'Royal Gala' during the 2018 season (Table 2).

For 'Scifresh', the 1.5 m row spacing showed no differences in fruit number per tree compared to the 2.0 m row spacing which resulted in similar yield per tree (Table 3). The 1.5 m row spacing producing greater yields at 122.6 t/ha compared to 92.3 t/ha at 2.0 m (p=0.004). The Vee canopy consistently produced more fruit per tree by having an extra 2 fruiting uprights, however, this difference was not significant (p=0.855). Therefore, few differences between tree designs occurred for yield per tree (p=0.674) and yield per hectare (p=0.855) in 'Scifresh' during the 2018 season (Table 3).

Table 2. Yield and its components in the fourth leaf (2018) for 'Royal Gala' apple trees grown in Hawke's Bay with 1.5-m or 2.0-m between-row spacing, trained to either a Vee or Vertical planar cordon.

Treatment	Fruit density (BCA)	Fruit density (TCA)	Fruit per tree	Mean fruit weight (g)	Red colour (%)	Yield per tree (kg)	Yield per ha (t)
Row spacing (RS)							
2.0 m (1667)	5.69	10.99	261	188	69	48.8	81.3
1.5 m (2222)	5.94	11.84	256	185	70.6	47.2	104.9
p-valve	0.342	0.103	0.749	0.265	0.817	0.639	0.024
Tree design (TD)							
Vert	5.56	10.78	249	187	71.5	46.4	90.5
Vee	6.07	12.05	267	187	68.1	49.6	95.7
p-value	0.098	0.04	0.283	0.919	0.642	0.370	0.413
RS x TD interaction	0.329	0.271	0.294	0.584	0.999	0.337	0.368

Table 3. Yield and its components in the fourth leaf 2018) for 'Scifresh' apple trees grown in Hawke's Bay with 1.5-m or 2.0-m between-row spacing, trained to either a Vee or Vertical planar cordon.

Treatment	Fruit density (BCA)	Fruit density (TCA)	Fruit per tree	Mean fruit weight (g)	Red colour (%)	Yield per tree (kg)	Yield per ha (t)
Row spacing (RS)							
2.0 m (1667)	5.79	10.89	277	200	68.6	55.4	92.3
1.5 m (2222)	6.53	13.17	279	198	67.3	55.2	122.6
p-valve	0.052	0.021	0.814	0.360	0.473	0.898	0.004
Tree design (TD)							
Vert	6.11	11.78	277	198	69.4	54.9	107.8
Vee	6.21	12.28	279	200	66.5	55.7	107.2
p-value	0.724	0.394	0.855	0.595	0.146	0.674	0.885
RS x TD interaction	0.257	0.175	0.143	0.791	0.385	0.148	0.213

3.3.8.2 2018-2019 season

In the 2018-19 season, yields from all four treatments within 'Scifresh' and 'Royal Gala' ranged from 100 to 152 t/ha (Tables 4&5). 'Royal Gala' yields increased by 33% at 2 m and 34% at the 1.5 m row spacing from 2018 to the 2019 season. Alternatively, 'Scifresh' yields increased 20% at 2.0 m and only 8% at the 1.5 m row spacing.

For 'Royal Gala' during the 2019 season, there were no differences in fruit number per tree and subsequently, yield per tree between the two row spacing treatments at 1.5 m and 2.0 m (p=0.467 and 0.895, respectively). However, MFW was much higher at the 2.0 m spacing compared to the 1.5 m at 178 g and 163 g, respectively (p=0.006). However, overall yield per hectare at the 1.5 m row spacing was significantly larger than the 2.0 m spacing at 159.3 t/ha compared to 121.1 t/ha (p=0.05). The tree designs did not differ in terms of fruit per tree (p-value- 0.755), MFW (p=0.395), yield per tree (p=0.852) and yield per hectare (p=0.870) in 'Royal Gala' during the 2019 season (Table 4).

In 'Scifresh', the 2.0 m row spacing produced on average, 51 more fruit per tree than the 1.5 m row spacing, however, this difference was not statistically significant (p=0.137). Yield per tree and yield per hectare did not differ between the two row spacing treatments (p-value 0.100 and 0.102, respectively). There were no significant differences between tree designs for fruit number per tree (p-value – 0.216), MFW (p-value – 0.069), yield per tree (p-value – 0.249) and yield per hectare (p-value – 0.289) (Table 5).

For 'Scifresh' only, there was a row spacing x tree design interaction for mean fruit weight. At the 2.0 m row only, the Vertical canopy produced significantly larger fruit at 185.3 g compared with the Vee canopy at 175.5 g (p-value – 0.032, LSD – 6.75) (Table 5).

Table 4. Yield and its components in the fifth leaf (2019) for 'Royal Gala' apple trees grown in Hawke's Bay with 1.5-m or 2.0-m between-row spacing, trained to either a Vee or Vertical planar cordon.

Treatment	Fruit density (BCA)	Fruit density (TCA)	Fruit per tree	Mean fruit weight (g)	Red colour (%)	Yield per tree (kg)	Yield per ha (t)
Row spacing (RS)							
2.0 m (1667)	8.11	13.09	410	178	86.4	72.6	121.1
1.5 m (2222)	8.57	15.39	440	163	82.1	71.7	159.3
p-valve	0.106	0.032	0.467	0.006	0.391	0.895	0.051
Tree design (TD)							
Vert	8.03	13.09	418	172	86.6	71.5	139.1
Vee	8.65	15.39	431	169	81.9	72.8	141.3
p-value	0.054	0.040	0.755	0.395	0.355	0.852	0.870
RS x TD interaction	0.169	0.242	0.966	0.331	0.830	0.858	0.877

Table 5. Yield and its components in the fifth leaf (2018–2019) for 'Scifresh' apple trees grown in Hawke's Bay with 1.5-m or 2.0-m between-row spacing, trained to either a Vee or Vertical planar cordon.

Row spacing	Fruit density (BCA)	Fruit density (TCA)	Fruit per tree	Mean fruit weight (g)	Red colour (%)	Yield per tree (kg)	Yield per ha (t)
Row spacing (RS)							
2.0 m (1667)	6.96	11.22	385	180	80	69.1	115.2
1.5 m (2222)	6.42	12.48	334	179	66.6	59.7	132.8
p-valve	0.208	0.181	0.137	0.521	<0.001	0.100	0.102
Tree design (TD)							
Vert	6.14	10.77	339	182	75.3	61.6	128.8
Vee	7.24	12.92	379	178	71.3	67.3	119.1
p-value	0.047	0.060	0.216	0.069	0.018	0.249	0.289
RS x TD interaction	0.227	0.642	0.225	0.032	0.057	0.315	0.381

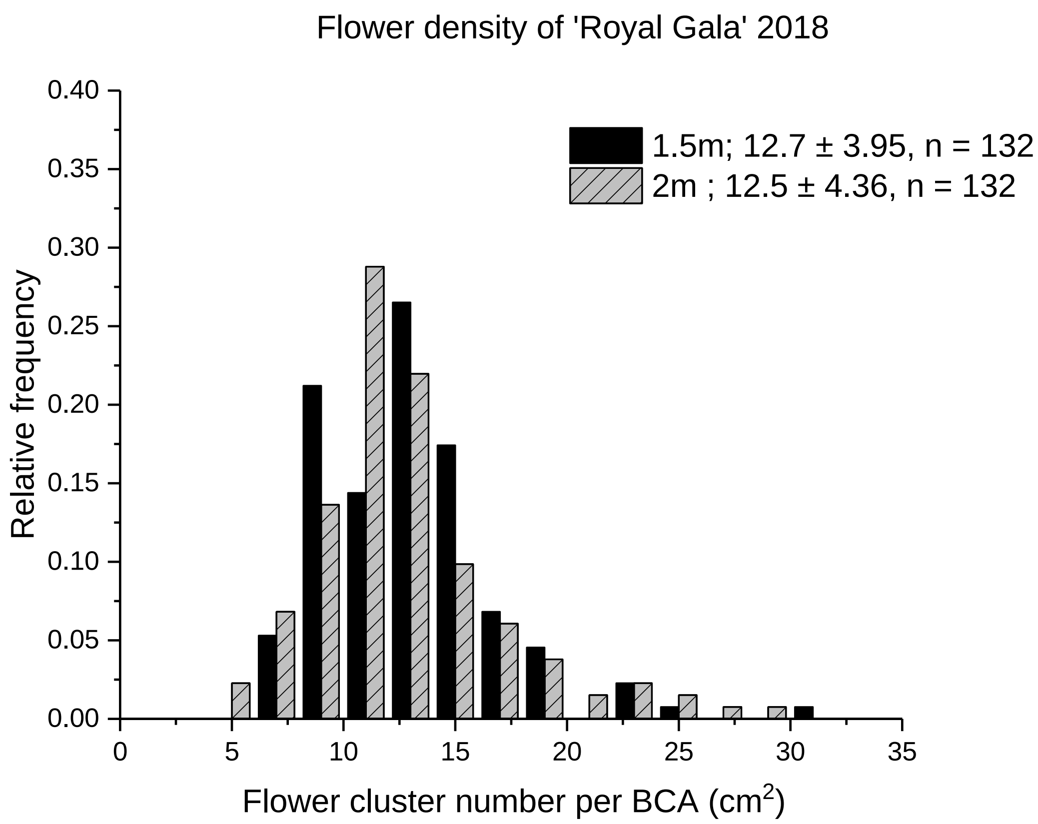
3.3.9 Effect of fruit density on return bloom

3.3.9.1 2018 Flower density

The effect of fruit density on return bloom was assessed using analysis of frequency distributions of individual upright floral bud densities. Flower density was compared between row spacing treatments. This was done as there was no effect between the Vertical and Vee tree designs (data not shown).

For 'Royal Gala', fruit densities carried in 2017-2018 were similar for each row spacing (Figure 27) and these were associated with similar patterns of flowering (mean number of flower clusters (FL) per BCA; 1.5 m = 12.7, 2 m = 12.5). The majority of the uprights had flower bud densities ranging from 12 to 14/cm^2 BCA in the 2 m and 1.5 m row spacings.

For 'Scifresh', the 1.5 m row spacing had a lower mean flower cluster number per cm^2 BCA compared to the wider, 2 m row spacing (mean number of flower clusters per BCA; 1.5 m = 7.7, 2 m = 11.1). The distribution for the 1.5 m peaked at approximately 6 FL/ cm^2 BCA, whereas the 2.0 m peaked at 10 FL/cm^2 BCA (Figure 27). At the 2 m row spacing, close to 100% of uprights have a return bloom value greater than 5 FL/ cm^2 BCA, meaning they have the ability to carry target or greater than target fruit densities in the following season. Alternatively, the 1.5m row spacing consists of approximately 30% of uprights that will not reach a target fruit density of 10 fruit/ cm^2 BCA in the following season.


Flower density of 'Royal Gala' 2018
1.5m; 12.7 ± 3.95, n = 132
2m ; 12.5 ± 4.36, n = 132
Relative frequency
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
5
10
15
20
25
30
35
Flower cluster number per BCA (cm2)

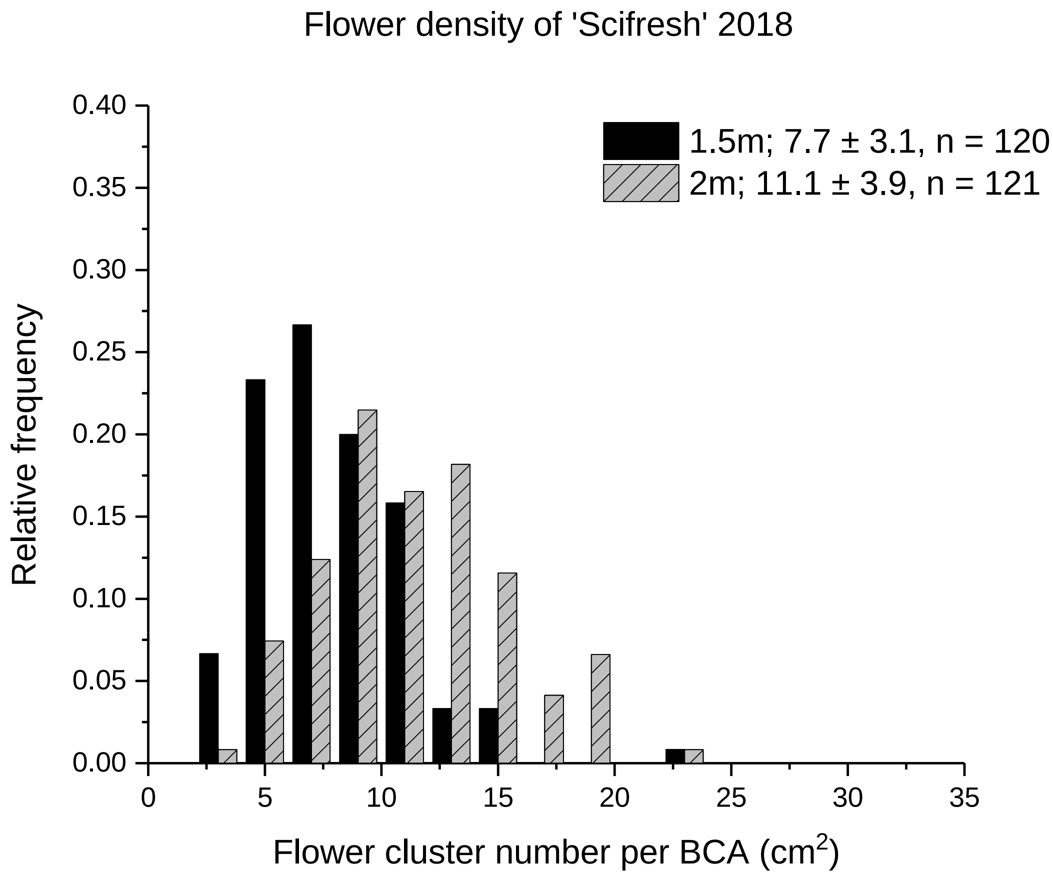


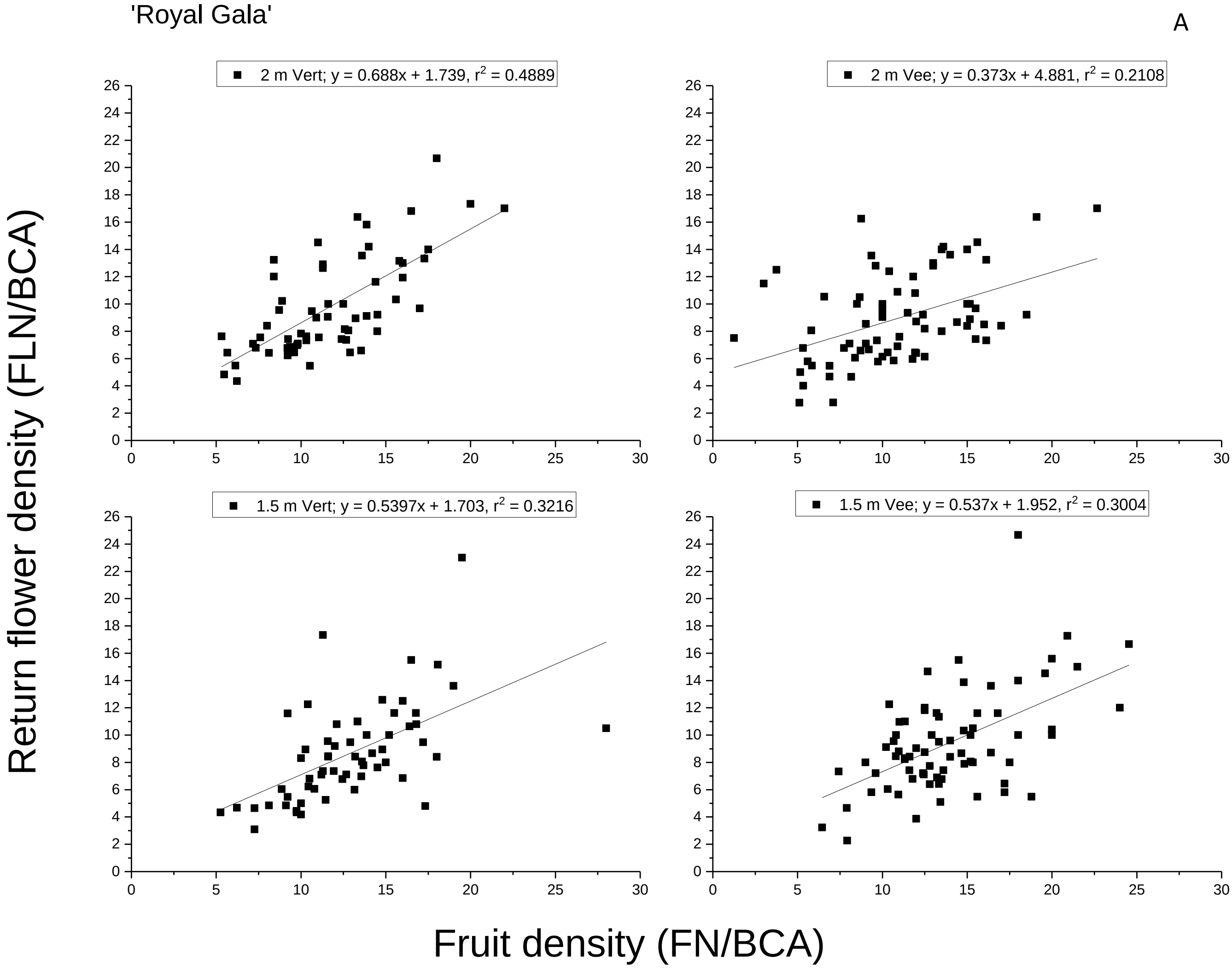
Figure 27. Relative frequency distributions of flower densities on individually measured uprights for 'Royal Gala' and 'Scifresh' in spring 2018, from 2m and 1.5m row spacing treatments trained as Vertical and Vee planar cordon tree structures. Trees, grown off M9 rootstocks of the prototype II study of bi-axis planar cordon planting system trial in their fourth year from planting. Annotated data are the mean flower density (flower cluster number / cm² BCA), standard deviation and n-value (number of observations). The data includes flower densities from the two row spacing treatments ignoring tree design effect.

3.3.9.2 2019 Return bloom response

Return bloom was measured in October 2019 during full bloom for both ‘Royal Gala’ and ‘Scifresh’. The data is displayed to show the effect fruit density has on return bloom at an upright level.

In ‘Royal Gala’ we see a general trend that when fruit density increased, return bloom (flower cluster count) also increased in the following season (Figure 28). This relationship was stronger in the 2.0 m Vert planar cordon (r^2 = 0.4889) than the other treatments (r^2 = 0.2108, 0.3216 and 0.3004). After fruit set on 2019, the average fruit density between the four treatments was 12.4 fruit/cm^2 BCA. As a response to that, the average return bloom (measured as a total of terminal and spur flower clusters) was 9.2 flower clusters/ cm^2 BCA. The fruit densities ranged from 2-28 fruit/cm^2 BCA and the following seasons return bloom densities ranged from 2-25 flower clusters/ cm^2 BCA.

In ‘Scifresh’ there is no relationship between fruit density and return bloom at an upright level (Figure 28). This relationship was negligible in all four treatments (r^2 = 0.032, 0.0216, 0.055 and 0.0405). After fruit set, the average fruit density between the four treatments was 9.4 fruit/cm^2 BCA. As a response to that, the average return bloom was 11.7 flower clusters/ cm^2 BCA. The fruit densities ranged from 2 to 23 fruit/cm^2 BCA and the following seasons return bloom densities ranged from 3-26 flower clusters/ cm^2 BCA.


'Royal Gala'
A
2 m Vert; y = 0.688x + 1.739, r2 = 0.4889
2 m Vee; y = 0.373x + 4.881, r2 = 0.2108
1.5 m Vert; y = 0.5397x + 1.703, r2 = 0.3216
1.5 m Vee; y = 0.537x + 1.952, r2 = 0.3004
Return flower density (FLN/BCA)
Fruit density (FN/BCA)

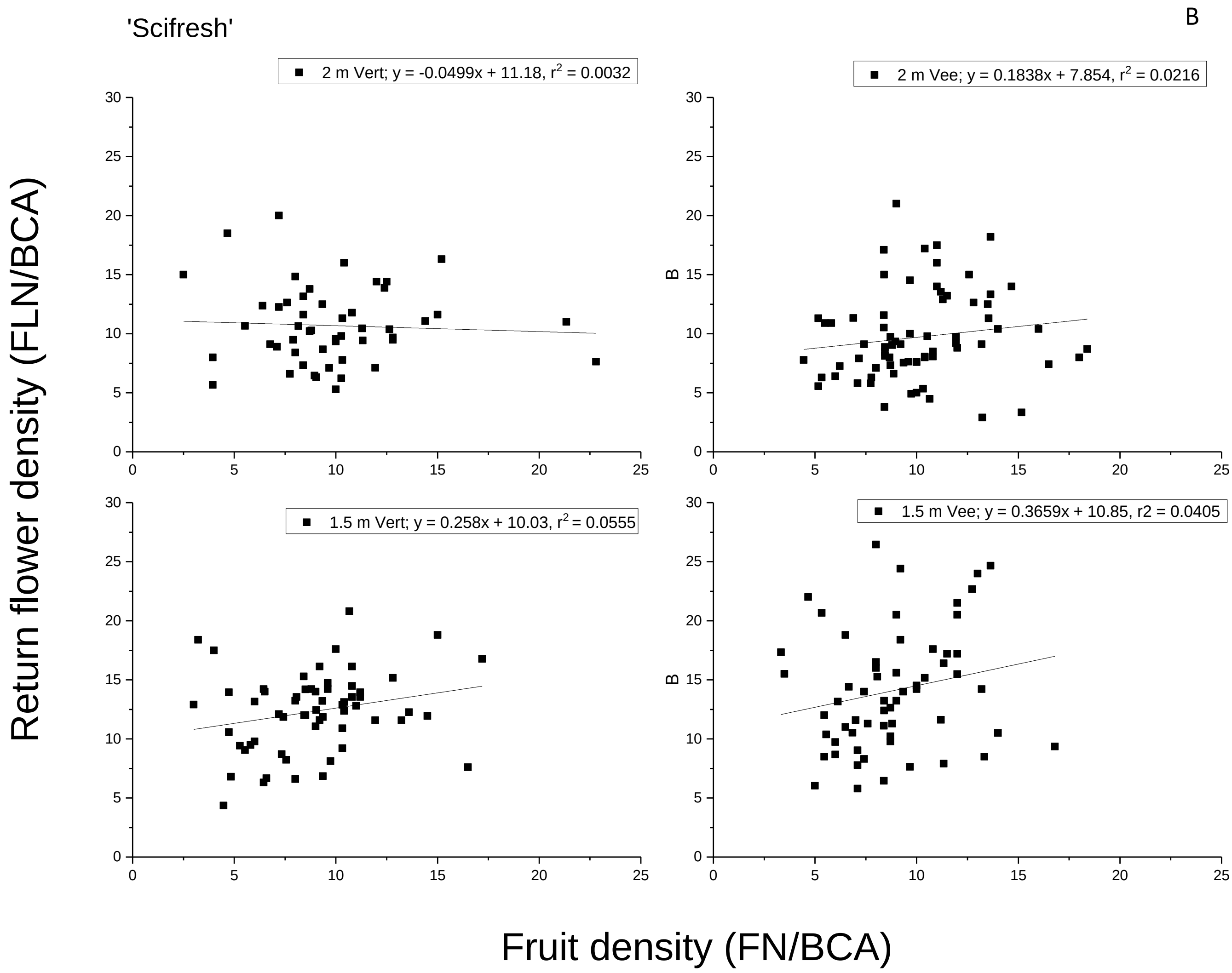


Figure 28. Relationships between fruit density of individual branch units (fruit number (FN) per basal cross-sectional area (BCA)) at harvest 2019 and return flower density (flower number (FLN) per basal cross-sectional area) at flower set in spring 2019 for 5-year-old planar cordon 'Royal Gala' (A) and 'Scifresh' (B) trees on M9 rootstock grown at 1.5 m or 2 m inter-row spacings and trained as Vertical or Vee canopies. Each plot is annotated with a relative treatment description, relationship equation and the r^2 value.

3.4 Discussion

3.4.1 Effect of fruit density on fruit size on an upright level

An important objective was to determine how changes in fruit density of upright branch units influenced fruit size. There is a physiological rationale to use certain units of measurement than others to represent growth responses. As stated earlier, the TCA is not a branching unit and therefore it makes physiological sense to base crop loading decisions on an individual branch basis. However, it is also important to look at the overall tree fruit density to ensure it is not too high. Thus the utilisation of crop loading on a branch BCA and tree total BCA combined becomes useful.

3.4.1.1 2017-2018

The fruit size did not vary across a wide range of upright fruit density between cultivars in 2018. The upright branches were thinned in early summer (November) to create fruiting densities ranging from 4-14 fruit/cm^2 BCA in 'Scifresh' and 1-14 fruit/cm^2 BCA in 'Royal Gala' (Figure 17). Between all four treatments in 'Royal Gala' and 'Scifresh', when fruiting density increased, MFW did not change (Fig 19; r^2 = 0.004 – 0.039). There are apparent differences in fruit size responses from a planar cordon system to a conventional orchard (i.e. tall spindle) when comparing our results to the literature. The optimal fruit density for tall spindle trees on dwarfing rootstocks ranges from 4-6 fruit/cm^2 BCA before fruit size is adversely reduced to below an optimum range that is required for markets and value (Breen et al., 2016). The vertical nature of these planar cordons are allowing branches to reach upwards of 3 m in length to fill the allotted space. Each fruit is spaced within a good light environment, surrounded by supportive leaf area throughout the entire upright branching unit, allowing the fruit to size and colour accordingly. Branches within the planar cordon training system are longer relative to their BCA compared to tall spindle branches, which are short and fat.

In 2018, fruit densities were set not knowing how the trees would respond in terms of fruit quality and return bloom. However, the results obtained allowed us to justify increasing the fruit densities in the following season.

3.4.1.2 2018-2019

Based on the 2018 season's data, fruit densities in 2019 were set with the aim of increasing the average fruit density. This resulted in a large spread of crop densities ranging from 1-28 fruit/cm^2 BCA (Figure 18). Similarly to the 2018 data, MFW is not affected by the increases in fruit density among ‘Royal Gala’ and ‘Scifresh’ at an upright level. Regression calculations shown in Figure 20 illustrate the lack in relationship among all four treatments in ‘Royal Gala’ and ‘Scifresh’.

It was expected, that at fruiting densities, above 20 fruit/cm^2 BCA, (four times that of a conventional tall spindle) that the fruit size would start to decline. However, these data suggest that the vertical nature of this structure is allowing fruiting branches to behave differently in their ability to size fruit.

3.4.2 Effect of fruit density on fruit size on a whole tree level

The association between the trunk cross-sectional area and the total basal cross-sectional area (sum of upright BCA and droppers on the cordon) of each tree showed a polynomial relationship for both cultivars over each of the two seasons (Figure 16). The relationship for ‘Royal Gala’ is stronger than that of ‘Scifresh’, which is likely to be attributed to smaller variation of BCAs between uprights.

The findings suggest that within ‘Royal Gala’, increase in fruit density at a tree level (fruit number per TCA) has a negative effect on MFW. Each treatment through both years showed a negative correlation, however the r^2 values suggest that particular treatment relationship was not strong enough to be fully conclusive (Figures 21). It is possible that this relationship becomes clearer as the trees become fully developed. ‘Scifresh’ showed a strong season effect in fruit size from the 2018 to the 2019 season whereas ‘Royal Gala’ did not. The average fruiting density (per TCA) did not increase in ‘Scifresh’ from 2018 to 2019 but fruit size decreased (Figure 21). This is likely to be a result of early season conditions being cloudy and cool for an extensive period in 2019. R^2 values suggest there was a weak relationship with high variability between fruit density (fruit/cm^2 TCA) and MFW for the four treatments in ‘Scifresh’. The data suggests that we have not yet found the maximum crop density per upright and per tree that causes a reduction in fruit size or colour to a point that becomes inadequate for the export market.

3.4.3 Fruit density categories and their effect on size and colour

Initially it was hypothesised that with increases in fruit density, fruit size would decline. This has been the result of various crop loading experiments in apple over the years (Castro et al., 2015; Embree et al., 2007; McArtney et al., 1996; Wright et al., 2006).

Average fruit density for each category increased from 2018 to 2019 to understand the response of fruit quality to high fruit densities. Existing crop loading metrics were ignored because they were considered less meaningful to the new planar canopy tree designs having completely different branching units in terms of length and BCA ratio.

MFW was reduced from 2018 to 2019 with the increase in fruit density, however, the reduction in size was predominately attributed to a seasonal weather effect after comparing results to industry fruit size averages (See appendix table 8). It was anticipated to see large differences between fruit size at different fruit densities however, the results show only small differences between most cultivar and season treatment combinations.

After noticing a significant difference in MFW between row spacing in 'Royal Gala' (Table 5) the next question was to find where this decline in fruit size was coming from. By dividing the two row spacing treatments into separate fruit density categories, we discovered that within the 1.5 m row there were a significantly higher number of uprights cropped at greater than 12 fruit/cm^2 BCA, potentially reducing the MFW. However, looking at each crop density above 12 fruit/cm^2 BCA individually, we were able to see that the response to fruit weight at different spacing treatments appeared to be constant, 10-15g difference between the 2 m and 1.5 m rows (Figure 25). This finding suggests that although the n value for high fruit density uprights was greater in the 1.5 m row spacing compared to the 2 m, it is not the contributing factor to the overall decline in MFW between row spacing treatments. The next obvious reason for the smaller fruit is the influence light has. One possible explanation is that the 2.0 m spacing is receiving more light and therefore has a greater ability to size fruit. This will be investigated in the following chapter.

3.4.3.1 Colour development

In section 3.3.7, the new planar cordon training systems appeared to produce good fruit colour development. However, by looking at the different levels of fruit density and how it influences fruit colour, we were able to identify whether lower coloured fruit was attributed to high fruit density.

It was hypothesised that as long as every upright was thinned to provide good light and spacing for each fruit, that colour would not differ with increases in fruit density. Our findings suggest that fruit density did not have an impact on the red colour percentage of both 'Royal Gala' and 'Scifresh' during the 2018 and 2019 seasons. Figure 26 illustrated this finding through colour distributions and means for each cultivar over the two seasons. Chapter four will examine colour development in more detail however, from this study we can confirm that fruit density in a planar cordon system does not impact colour development. Colour packouts were 87% and 93% of the total crop in 'Royal Gala' and 'Scifresh', respectively. This is likely to be much greater than what is seen commercially as this was very high packout as a result of a strip pick. Commercially, only select-picked fruit are submitted to be packed.

3.4.4 Yield Data

Yields increased each year as trees grew towards their mature size. The trees are at approximately 60% of their full canopy development in 2018 and 80% in 2019. The 2019 season was also a small fruit size year in comparison to 2018 due to a seasonal effect which influences yield significantly. As the trees develop, a story is unfolding around productivity and how a change in tree architecture and row spacing can further optimise light utilisation, ultimately helping to increase the performance of modern orchard systems.

Yield per tree was similar for all row spacing treatments so productivity per ha became a function of tree density per hectare. Thus, the productivity of the 1.5 m row spacing treatment was typically higher than the 2.0 m row spacing which can be attributed to the higher planting density at 2222 tree/ha compared to 1667 trees/ha at 2.0 m row spacing. In 2019, the 1.5 m spacing was producing yields of approximately 133 t/ha in 'Scifresh' and 159 t/ha in 'Royal Gala' compared to the yields at 2.0 m of 115 t/ha in 'Scifresh' and 121 t/ha in 'Royal Gala'.

Inconsistent differences were found between the Vee and Vertical tree designs. However, trends indicated small increases in yield by the Vee canopies which was attributed to slightly higher fruit numbers per tree, caused by two extra upright fruiting units. The results from the last two seasons have proven how quickly an orchard yield can increase annually when effective management strategies are used to develop a canopy (planar cordon) quickly. The lower proportional increase in 'Scifresh' yield was attributed to a high yield in 2018 resulting in slightly lower return bloom in 2019, especially at the 1.5 m row spacing (see next section).

3.4.5 Effect of fruit density on return bloom

It has been found that by significantly increasing fruit densities in apple orchards, return bloom is negatively affected in the following season (Meland, 2009). Fruit density is one of the causes of biennial bearing which is why precision crop load management is becoming more important in modern systems (Racskó, 2006; S. Tustin et al., 2012).

Productivity trials on new orchard systems take time. It becomes difficult to categorise changes and responses when a factor is changed one season and may not exert their effect initially, or even in one to two seasons later. The tree architecture and planting system of the planar cordon is so different from conventional tall spindle systems it was hard to hypothesis the response fruit density would have on return bloom. In a conventional system, high fruit densities can cause dramatic reductions in return bloom for the following season (Embree et al., 2007; Meland, 2009). Therefore, with fruit densities exceeding 20 fruit/cm^2 BCA in the planar cordon training system, it is possible that return bloom will be affected by the previous high fruit densities.

3.4.5.1 Return bloom after the 2018 season

Results showed that although the average fruit density on uprights was the same for the two row spacing treatments, the two cultivars behaved differently. 'Royal Gala' showed a sufficient return bloom distribution with all uprights having flower densities greater than 5 flower clusters/cm^2 BCA, meaning 100% of uprights had the ability to crop at a high fruiting density (10 fruit /cm^2 BCA) in the following season. There were also no differences between tree design (data not shown) and row spacing (Figure 27).

Alternatively, 'Scifresh' showed a significant reduction in return bloom in the 1.5 m row spacing in comparison to the 2.0 m row (Figure 27). The 1.5 m row spacing consists of approximately 30% of uprights that had a flower density below 5 flower clusters/cm^2 BCA, eliminating their ability to reach a target fruit density of 10 fruit/cm^2 BCA in the following season. Further investigation suggested that this was a result of higher fruit densities at the 1.5 m row spacing however, referring back to Figure 6, which illustrates the lack in difference between fruit densities at all four treatments, it is suggested that light could be a causing factor of 'Scifresh' having a significantly lower return bloom capability after a heavy crop compared to 'Royal Gala'. Light is examined in the following chapter which will show differences in the light environment between cultivars.

3.4.5.2 Return bloom after the 2019 season

In 2019, we were able to analyse how fruit density carried in the previous year impacts return bloom in the subsequent spring. Data were analysed on a per upright basis to determine whether uprights at a high fruit density reduced return bloom.

In 'Royal Gala', upright fruit densities ranging from 2-28 fruit/cm^2 BCA did not have a negative impact on return bloom. The regression analysis presented for the four treatments suggest that as fruit density increases, the return bloom density also increases (Figure 28). This goes against what is reported in the literature for existing cropping systems (Embree et al., 2007; Meland, 2009) and suggests that cropping uprights at a high fruiting density do not influence return bloom. In 'Scifresh', again, fruit densities were high ranging from 2-25 fruit/cm^2 BCA, however, there was no relationship between fruit density carried in the previous year and return bloom in the subsequent spring. Overall, similar results have occurred over two consecutive growing seasons which gives confidence to conclude that high fruit densities at an upright level have little influence on the return bloom potential on these planar cordon canopies.

As this result contradicts what has been known in other orchard planting systems, it is logical to look at the obvious reason or difference. There is potential that the planar cordon canopies are creating a superior light environment throughout the tree, thus resulting in better floriferousness the following season.

3.5 Conclusion

The objective of this chapter was to quantify the relationships between tree and branch unit fruit density and fruit size, quality and return bloom, necessary to inform commercial management of planar cordon orchards.

We found that, at a tree level (fruit number per TCA and totBCA), there was a weak negative relationship between fruit density and MFW in ‘Royal Gala’ and ‘Scifresh’. At an upright level, we found that an increase in fruit density (up to 28 fruit /cm^2 BCA) did not have an impact on average fruit size in ‘Royal Gala’ and ‘Scifresh’. The difference in quality (fruit size and colour) between nominally low, medium and high fruit density categories were minimal, supporting the theory that the variability is reduced in the planar cordon system which is examined in detail in the next chapter. The 1.5 m ‘Scifresh’ had significantly lower average flower density compared to the 2.0 m spacing, however, in 2019 after what was considered to be a very heavy crop, return bloom was not affected. The regression analysis suggested that as fruit density increased, so did the flower density in the following year because of the addition of new plant material grown last season and the high level of return bloom.

The results from this chapter have disproved the initial hypothesis, that with increases in fruit density, fruit size is not influenced as seen in other planting systems. The data suggests that we have not yet found the maximum crop density per upright and per tree that causes a reduction in fruit size or colour to a point that becomes inadequate for the export market. It is suggested that crop loading requires the integration of branch fruit density, total tree fruit density together with spatial optimisation of fruit to achieve the best outcomes in terms of increasing fruit size and colour. The next step is to assess internal fruit quality and storage potential (susceptibility to post harvest disease) under the planar cordon planting system.

4 Understanding the light environment of planar cordon canopies.

4.1 Introduction

The yield of apple orchard planting systems at harvest is linearly related to light interception at full canopy development (Palmer et al., 2002). This relationship is a function that relates high light interception (LI) to high yield. Greater light interception can be created by increasing the leaf area of the canopy to a certain point. A relationship shown in Wagenmarkers (1991) outlines that light interception increases to a leaf area index (LAI) of 2-3, beyond this point LI does not increase with increasing leaf area (Patricia S. Wagenmakers, 1991). Too much leaf or excessive canopy development can create shade and limit light to all parts of the canopy, ultimately affecting physiological processes such as photosynthesis or flower evocation/initiation. Palmer (2002) has modelled how light in orchard systems limits productivity to maximum yields of approximately 100 t/ha at 55-60% light interception. He suggests that an upper limit of 169 t/ha can be achieved at 90% light interception. To reach this potential, transformation of current training systems in terms of planting density and tree architecture is essential to intercept more light by having more tree canopy per unit of land area.

LI can influence yield however to be able to produce large portions of high quality fruit, light must be distributed well to all parts of the canopy. Light distribution into apple trees has shown to have a significant effect on fruit quality parameters such as fruit size and colour (J. Jackson et al., 1971; S. S. Miller et al., 2015; I. Warrington et al., 1996). Light intensity in a three-dimensional orchard system decreases within the tree canopy as the outer portion shades the inner canopy, creating variability in fruit quality (J. Jackson et al., 1971; J. E. Jackson et al., 1977; Jakopic et al., 2009).

In three-dimensional systems, the inner portions of the tree may receive high light intensities at times in the day caused by flecks of sun penetrating the canopy or changes in sun position during the day. Thus, sections of the canopy may receive high light for a brief time and predominantly low light for the remainder of the day, but potentially enough to produce high quality fruit. The design of the planar cordon training system aims to improve the light distribution through an open canopy and thus the reducing the variability of fruit quality throughout the crop.

Light influences a number of different traits in apple as light utilisation is the key factor in overall apple crop quality (John E. Jackson, 1989). Fruit size, firmness, soluble solids, anthocyanin and starch concentration (Saure, 1990; Steyn et al., 2002) are all traits affected by light in pome fruit.

To reiterate, light interception and distribution influences yield, quality, and profitability of three-dimensional orchard systems (Bastias et al., 2012; Stephen S Miller, 2001; S. S. Miller et al., 2015). The knowledge around the importance of both light interception and distribution has caused modern commercial orchards to become more efficient at increasing their marketable yield by using intensive planting systems. This can be attributed to the relatively smaller tree size, which increases the light distribution through the tree. However, further advancements in tree architecture in the form of a planar cordon canopy may allow us to continue to heighten the level of marketable yields within orchards.

Studies have shown the requirement for light levels above a critical minimum of approximately 25-30% of incoming radiation for the production of high quality fruit (Heinicke, 1964; J. Jackson et al., 1971; J. E. Jackson et al., 1977; Seeley et al., 1980; S. Tustin et al., 1988). Most of the literature discusses light in terms of a proportion of incoming radiation, which has limitations when comparing different environmental conditions or method of measurement. What has become apparent is the importance of total energy received and the diurnal pattern of light seen within a canopy (Rom, 1991). Particular canopies with well managed leaf area indices (LAI) (2-3) (Patricia S. Wagenmakers, 1991) and also branching density (six branches per metre of tree canopy height) (S. Tustin et al., 2015) distribute light well, creating high quality fruit at all heights of the tree. This is because although light may be below the critical minimum stated in the literature (25-30% of a daily or seasonal average) there are times in the day where low, shaded areas are receiving high light flecks (light at very high levels for short periods of time), thus giving the fruit an adequate environment for high quality development.

A common trend in the literature shows how light levels increase with canopy height and around the outer proportions of the three-dimensional canopies (Terence L. Robinson et al., 1991; S. Tustin et al., 1988; S. Tustin et al., 1989).

Light is a crucial aspect of canopy studies because of its role in photosynthesis. The best way to achieve maximum light interception is to first achieve optimal leaf coverage which is regulated by orchard system design (spacings) and temperature in spring affecting leaf growth. LAI in a three dimensional tree often ranges from 3-5 (Sansavini et al., 1992). The model shown in Wagenmakers (1991) predicts LAI over 3 has no effect on productivity as extra leaf coverage causes shading with no increase in LI (Patricia S. Wagenmakers, 1991). Depending on the tree form and management (pruning to create light wells), light distribution may be limited, restricting growth and production. In terms of the photosynthetic potential of leaves, the maximum Pn occurs at 900 to 1100 $\mu mol/m^2/s$ (45% to 55% of full sun), additionally maximum Pn of leaves that are developed in very low light still occurs at 500 to 600 µmol/m^2/s (25% to 30% of full sun)(the latter expression (% of full sun) gives the ability to compare with other literature, however it is not an accurate description of light quantity or the energy received by the leaves) (Rom, 1991). However, the inadequate distribution of light and shade within the tree will limit fruit size and overall quality of fruit (J. Jackson et al., 1971; J. E. Jackson et al., 1977).

The progression from a three dimensional tree (most commonly the tall spindle system) to a two-dimensional planar cordon tree, based on narrow row spacing as a means to increase LI, is becoming more common as the scientific understanding starts to support the estimated productivity potential hypothesised under the FOPS program (S. Tustin & van Hooijdonk, 2016). It was a part of the design process to create a tree that had the ability to distribute light with numerous light wells created by long thin branching units with small dard-like fruiting sites (Figure 9). The long vertical fruiting branch units are intended to have fruiting structures small and dispersed spatially to create the light wells and keep LAI within the limits understood to be optimum. However, it is currently unknown how light is distributed throughout a planar canopy and how this influences fruit quality.

Differences in tree architecture caused by changes in orchard design; training system, tree size, planting spacing or pruning strategy can have a significant effect on light penetration to all parts of the canopy (Bastias et al., 2012; I. J. Warrington et al., 1996). Fruit quality and fruit size often differ depending on the position within a canopy which is closely correlated with light distribution (S. Tustin et al., 1988; Volz et al., 1995).

The Future Orchard Planting System (FOPS) has redesigned orchards to a planar cordon architecture in order to increase light interception and light distribution. The vertical orientation of the canopy has the ability to allow light to be penetrated throughout the entire tree. Previous work in these planar cordon systems has showed that, seasonal maximum light interception with ‘Royal Gala’ was 84% at the 1.5 m row spacing (2222 trees/ha) and 74% at the 2.0-m row spacing (1667 trees/ha). The range in seasonal maximum light interception with ‘Scifresh’ was 86% for the 1.5-m row spacing, and 76% for the 2.0-m row spacing. The tall spindle comparison at 1.5 m x 3.5 m row spacing reached 44% maximum light interception. All of these canopies were in their fifth year from planting and occupied approximately 80% of their total development (S. Tustin et al., 2019).

As stated above, the common method of communicating units of light in the literature is to use percent of incoming radiation which is not descriptive of the energy level received by the plant. This makes comparisons between experiments within the literature difficult. The total energy requirement from the sun for fruit production in terms of the changes in light pattern within a canopy during the day, the quantity of light and that relationship to fruit quality, has not been well recognised within the literature.

Currently, light distribution in a three-dimensional tree structure is limited due to the branch orientation of the canopy causing very low light and large variations in fruit quality (Volz et al., 1995). The way the new FOPS structure is designed suggests that light distribution may differ to a conventional 3D training system because of the dramatic change in branch architecture (long and thin, vertically orientated branches).

However, the light relations within this planar cordon canopy are still unknown. We are unsure how well light is distributed throughout the tree and how this may affect fruit quality.

Given the scarcity of information, the aim was to quantify and describe the light environment within this planar cordon system in terms of the diurnal light pattern (PPFD), daily light integral (DLI) and percentage of total incoming radiation. From this it was aimed to look at the relationships between light and fruit quality in terms of fresh weight, dry matter content and red colour and additionally leaf properties in terms of specific leaf weight (SLW) and lead area index (LAI).

It was hypothesised that the vertical orientation of the planar cordon canopy will enable light to be transmitted in patterns that will support the production of high quality fruit at each part of the canopy. Specific leaf weight (SLW), daily light integral and the proportion of incoming radiation will increase with canopy height and will overall be an improvement to the literature that describes light transmission in various canopies. We hypothesise that fruit quality in terms of fruit size, red colour and dry matter content will improve with canopy height, coinciding with an increase in PPFD.

4.2 Materials and Methods

4.2.1 Light distribution

Light distribution measurements were completed using LI-COR data loggers (LI-COR 20.02, Lincoln Nebraska, USA, 1990) fitted with the appropriate amount of 'Palmer' sensors for each tree design (5 sensors in the Vertical and 8 in the Vee) (J. W. Palmer, 1987). Sensors were fitted between paired fruiting stems using retort stand clamps fixed onto a vertically oriented rod (Figure 29).

Photosynthetic photon flux density (PPFD) profiles (µmol/m^2/s) were determined to measure the light distribution pattern throughout the canopy. To measure the distribution of light, LI-COR sensors were placed at different heights throughout the tree at 0.5m, 1m, 1.5m, 2m and 2.5m above the ground (Figure 29).

Measurements of light distribution were made when the canopies reached full development ('Scifresh' 10-23 March, 'Royal Gala' 10-17 February), during the fifth leaf (2018-2019 season). Within each treatment (2.0 Vertical, 2.0 m Vee, 1.5 m Vertical and 1.5 m Vee), the centre tree of the measurement rows (Rows 2 and 5; Figure 4) was used for light distribution measurements. Within each tree, four sets of two adjacent uprights were selected for light measurements. This then formed four within-tree replicates in the experiment.

For the Vertical tree design, 5 sensors were used at the 5 heights. For the Vee canopy, a total of 8 sensors were used, two sensors were used at the 1.5m, 2m, and 2.5m heights which were situated on each side of the Vee structure. The reference sensor situated at 4 m in height measured 100% of the incoming radiation. After each set of recordings was made for a treatment set, the sensors were moved to the next within-tree replicates, so that full treatment replication was made over time.

Each replicate was completed over 24 hours, in most cases from midnight to midnight. Only data from daylight hours (between 0600 and 2200 (NZST) each day were used. An instantaneous measurement of PPFD from every sensor was recorded every 5 seconds and then integrated to record a sensor average for each hour. Sensors were calibrated against a reference sensor before and after measurements.

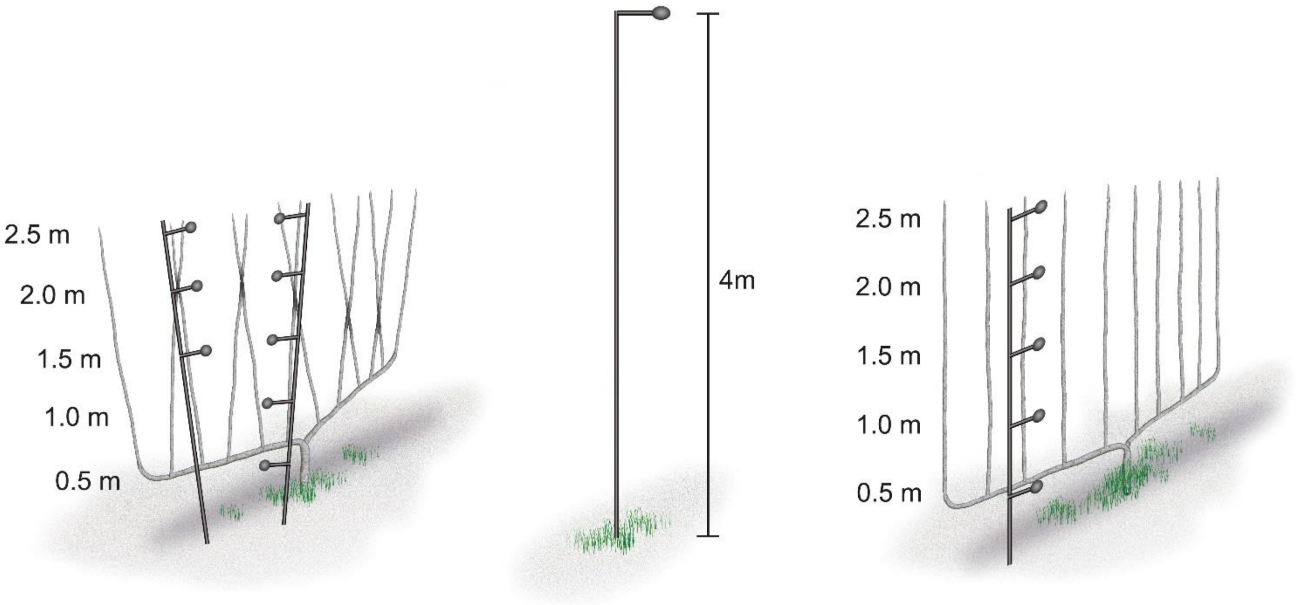


Figure 29. Diagrammatic example of sensor position within the Vertical and Vee canopies. Sensors were placed at 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m from the ground. A reference sensor was placed at 4 m to record the total incoming radiation.

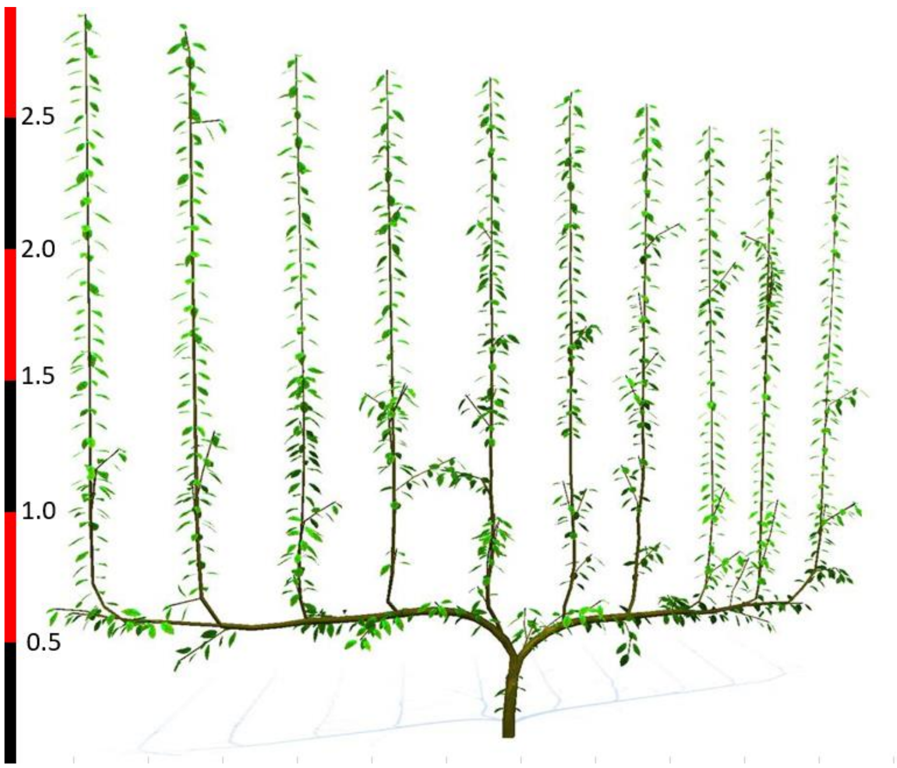


Figure 30. Example of zone separation using red marking tape on the Vertical canopy. Fruit were harvested within these zones and separated with corresponding bags.

4.2.2 Specific leaf weight

Two leaves of similar size were sampled from each of the 5 zones throughout an individual upright. Once the leaves were sampled, they were measured for their leaf area using the leaf area meter (Model LI-3100 Area Meter, Lincoln Nebraska, USA). The leaves were then placed in a dehydration oven (Contherm Digital Series Oven) at 60°C for approximately 56 hours. After the samples were dried to a constant weight each sample was then weighed for its dry mass using a four-decimal point balance. The specific leaf weight (SLW) was then calculated by dividing the dry mass (g) by area (cm^2) of each individual leaf.

4.2.3 Harvest

Fruit were harvested based on height zones (Figure 30). Fruit from each height zone and upright were picked into separate labelled plastic bags and the cordon fruit were harvested into a crate. Dropped fruit were also harvested into a separate crate.

4.2.4 Leaf Area

Leaf area index was calculated during the fourth and fifth seasons (2017-2018 and 2018-2019) by harvesting every 50th leaf, working systematically through every individual upright and cordon of the tree. The leaf number harvested was collected as well as the residual number of leaves left on the tree. Before use, the leaf area meter (Model LICOR LI-3100 Area Meter) was calibrated using a 50cm^2 metal plate. The total leaf sample area of each upright was then measured as well as the leaf number. Additionally, the difference in leaf type was noted. During the leaf harvest, leaves were separated into the three leaf categories, primary spur leaf, spur bourse leaf, and vegetative shoot leaf.

4.2.5 Statistical analysis

The experiment was a split plot design with four treatments (2 m Vertical, 2m Vee, 1.5 m Vertical and 1.5m Vee). Diurnal light environment and percentage of incoming radiation data was replicated by four pairs of uprights per tree (4 positions in the canopy). SLW was replicated by 10 and 12 uprights per treatment in the Vertical and Vee canopies, respectively. In this study, only trees in the measurement rows (rows 2 and 5) were used for analysis and all fruit within the trial trees were measured. Cultivars were analysed separately.

Data was analysed by two-way ANOVA using the analysis of variance procedure of GenStat (18th Edition, VSN International, UK). Mean separations were made using the LSD test at *P*=0.05 for fruit quality comparisons.

4.3 Results

4.3.1 Diurnal pattern of the light environment within planar cordon canopies

4.3.1.1 'Royal Gala' light environment

As the sun rose in the east, total incoming radiation increased until 1200 hours reaching 1400 to 1600 µmol/m^2/s. From approximately 15:00 hours, PPFD reduced reaching 0 µmol/m^2/s near dusk to dawn. PPFD at different heights within the Vertical and Vee tree designs followed a similar pattern as the sun moves along the solar track from sunrise to sunset (Figure 31). Generally, PPFD peaked at two separate times during the day. The first peak occurs at 12:00 hours as the sun sits just to the east of the Vertical plane. The PPFD levels then drop significantly at 15:00hr. At most heights in each of the four treatments, PPFD increased approximately 17:00hr to then gradually decline until 22:00hr.

Noon is the time in the day which gives the best representation of how much light is distributed throughout the planar canopy, however, PPFD values are not necessarily maximised at this time. In all treatments, PPFD was lower in lower parts of the planar cordon canopy.

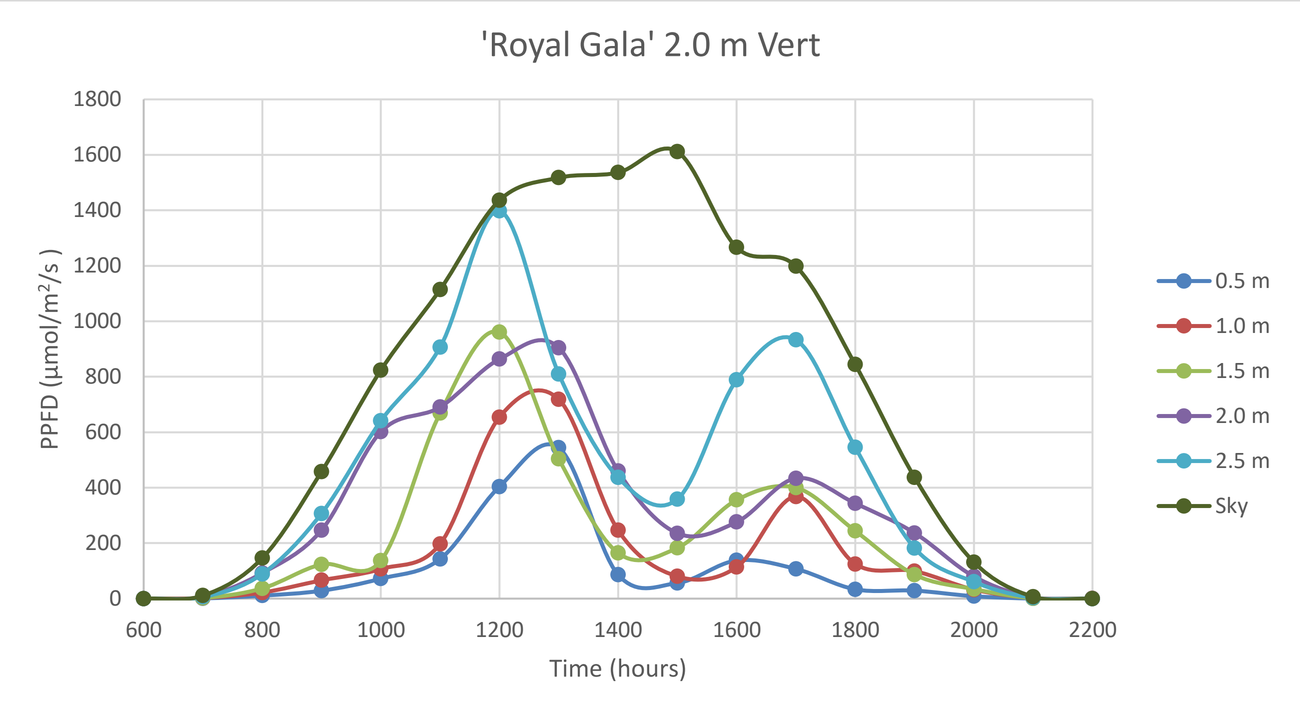
Vertical

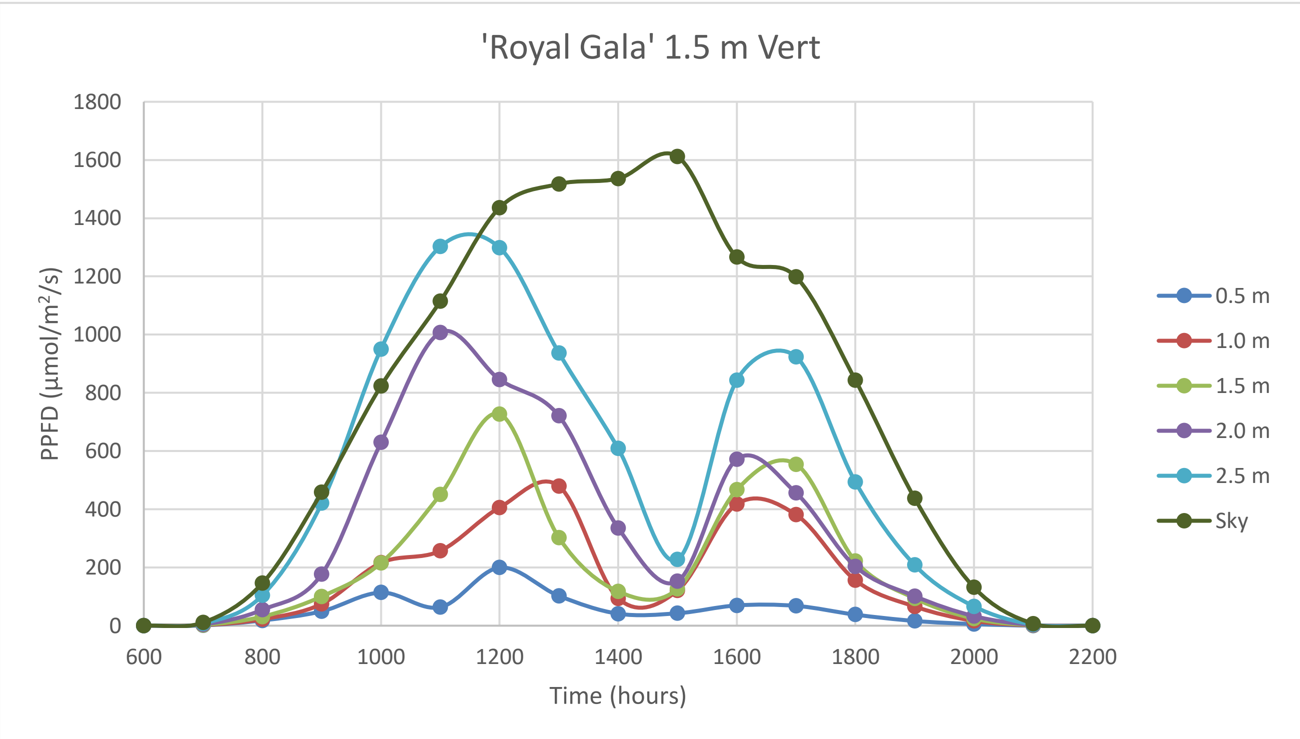
For the Vertical tree design, at 12:00hr for the 2.0 m row spacing, the average PPFD from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 403 (0.5m), 654 (1.0 m), 961 (1.5 m), 863 (2.0 m) and 1398 (2.5 m) (µmol/m^2/s) at their respective heights (Figure 31). At the 1.5 m row spacing, again the Vertical canopy has greater irradiance in the top of the tree compared to the bottom. At 12 noon the average light captured (PPFD) from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 200 (0.5 m), 406 (1.0 m), 727 (1.5 m), 846 (2.0 m) and 1299 (2.5 m) (µmol/m^2/s) at their respective heights.

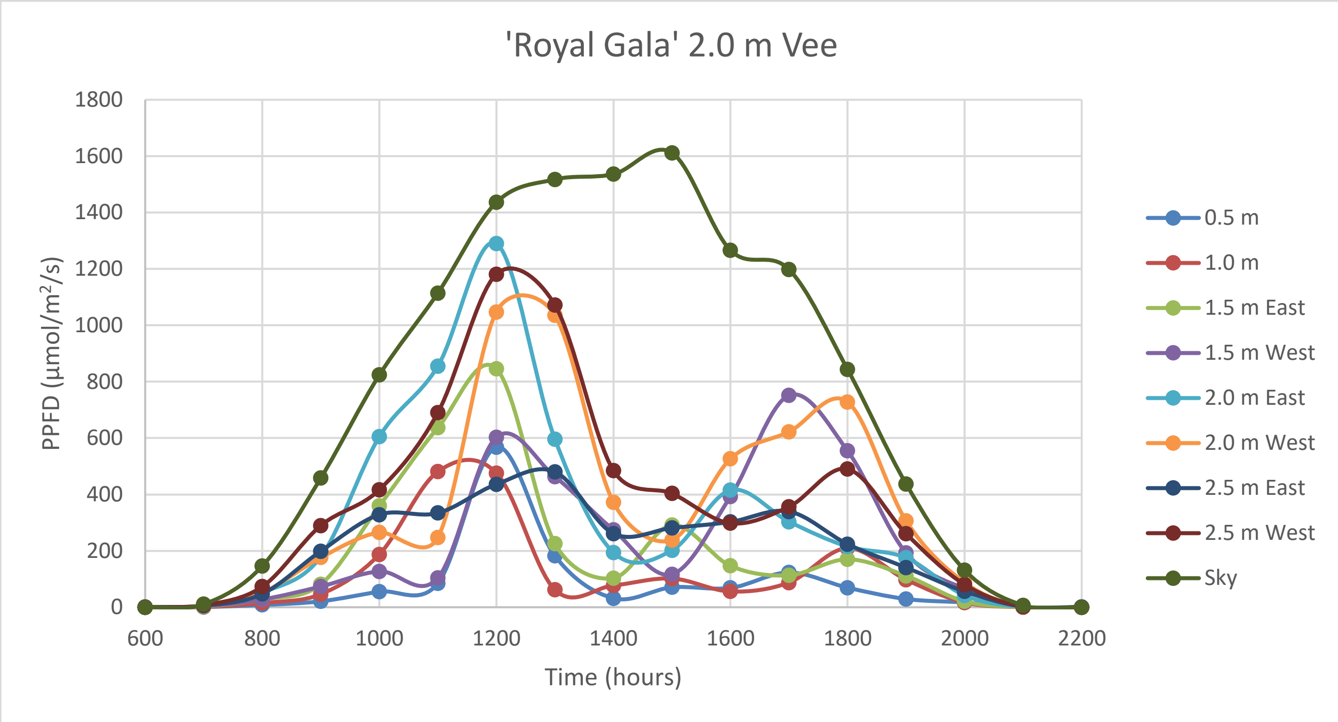
Vee

The Vee tree design showed different responses to light at different heights in the canopy. At 12:00hr for the 2.0 m row spacing, the PPFD from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 568 (0.5 m), 476 (1.0 m), 846 (1.5 m east), 603 (1.5 m west), 1290 (2.0 m east), 1047

(2.0 m west), 436 (2.5 m east) and 1181 (2.5 m west) ($\mu mol/m^2/s$) at their respective heights. The 2.5 m east daily trace was considerably lower in comparison to the other positions at that tree height. This is most likely to be due to shading by surrounding canopy features at that height. At the 1.5 m row spacing, at 12:00hr the average PPFD from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 456 (0.5 m), 242 (1.0 m), 523 (1.5 m east), 261 (1.5 m west), 767 (2.0 m east), 1153 (2.0 m west), 1419 (2.5 m east) and 1259 (2.5 m west) ($\mu mol/m^2/s$) at their respective heights.







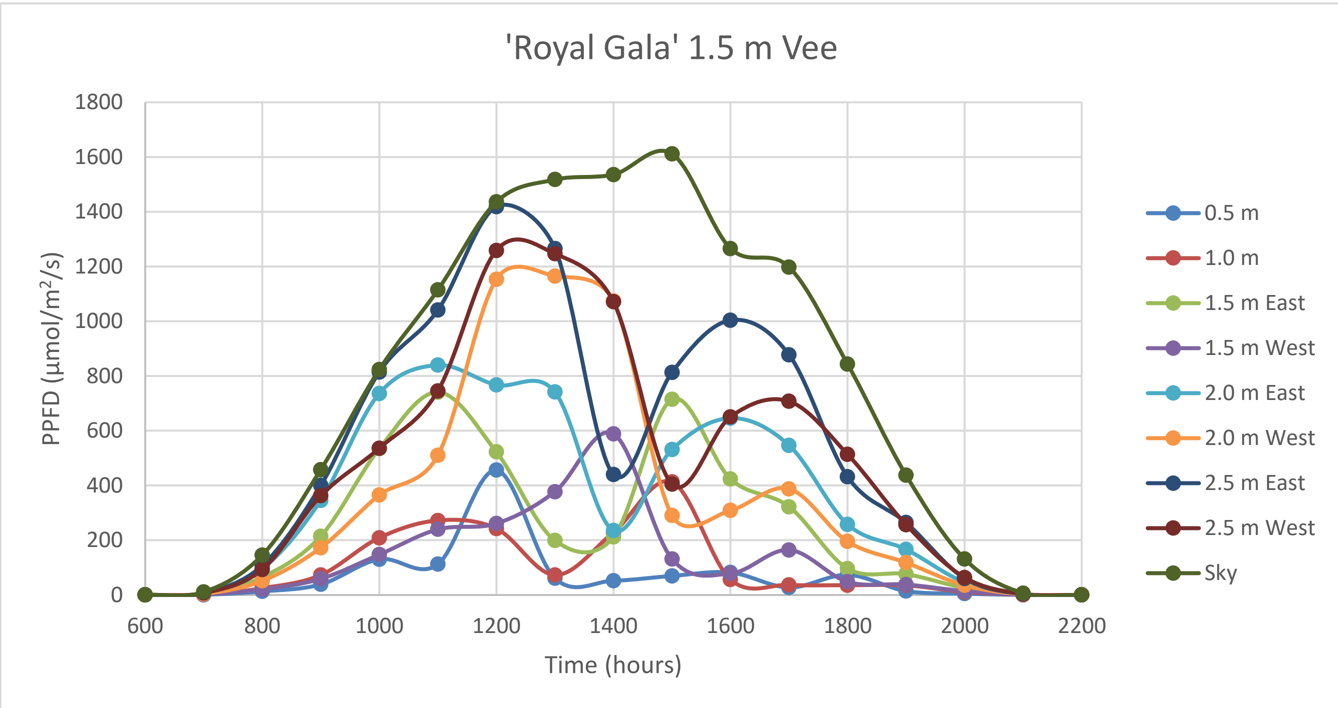


Figure 31. Photosynthetic Photon Flux Density (PPFD) at different heights (0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m) within Vertical and Vee planar cordon 'Royal Gala' trees grown at 1.5 m and 2 m rowing spacings. Light measurements are presented every hour starting from sunrise (06:00hr) to sunset (22:00hr). The Vertical canopy consisted of five sensors placed within two uprights. The Vee canopy contained eight sensors (heights 1.5 m, 2.0 m and 2.5 m were represented by 2 sensors placed along the plane of uprights on the east and west side of the canopy). Each treatment was measured with four reps as well as an open sky sensor which was placed at 4 m in height recording above canopy radiation (open sky).

4.3.1.2 'Scifresh' light environment

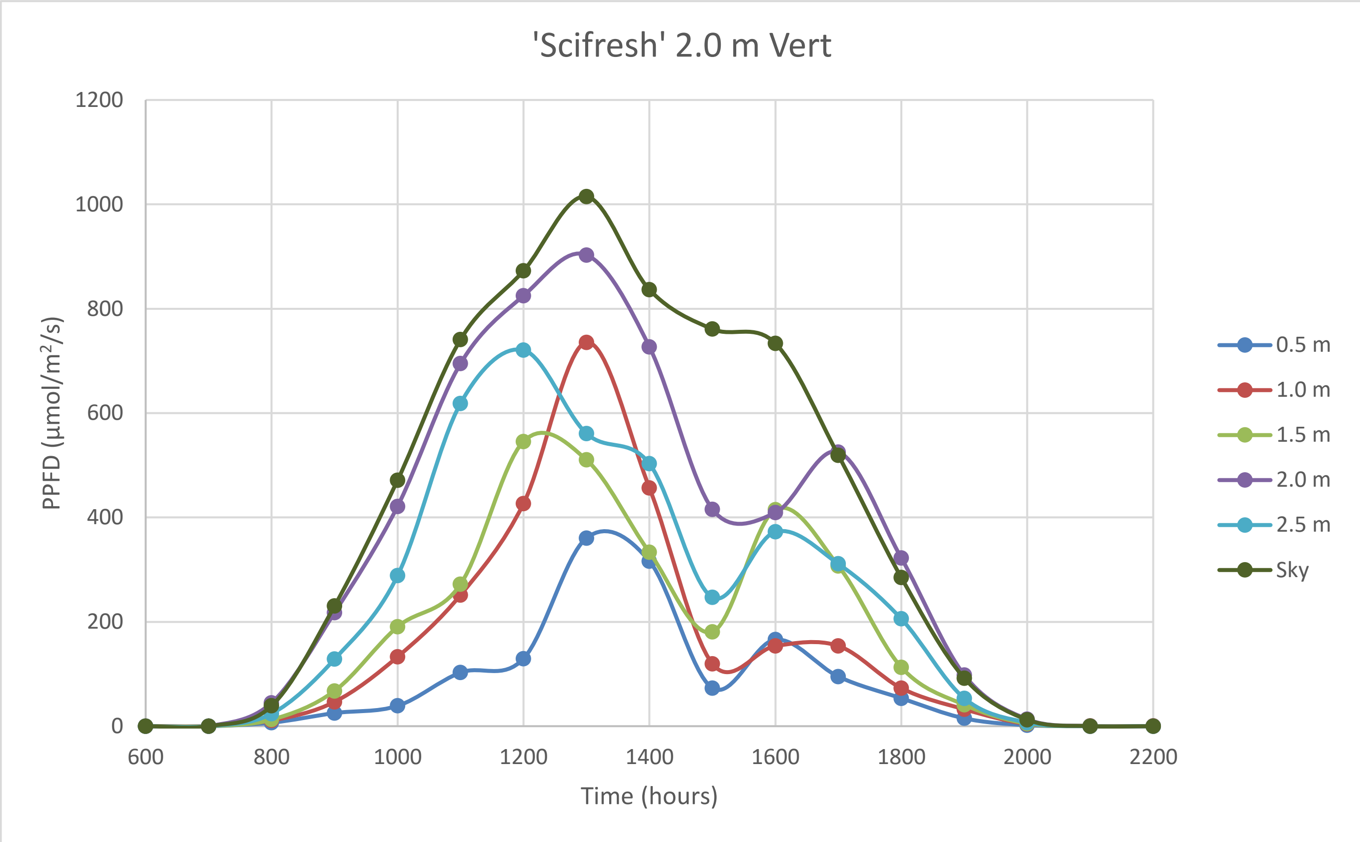
Measurements within the four treatments in 'Scifresh' were taken over the same four replicate days (10^{th} to 23^{rd} March 2019) meaning the average sky plot is identical for all four treatments (seen in Figure 32).

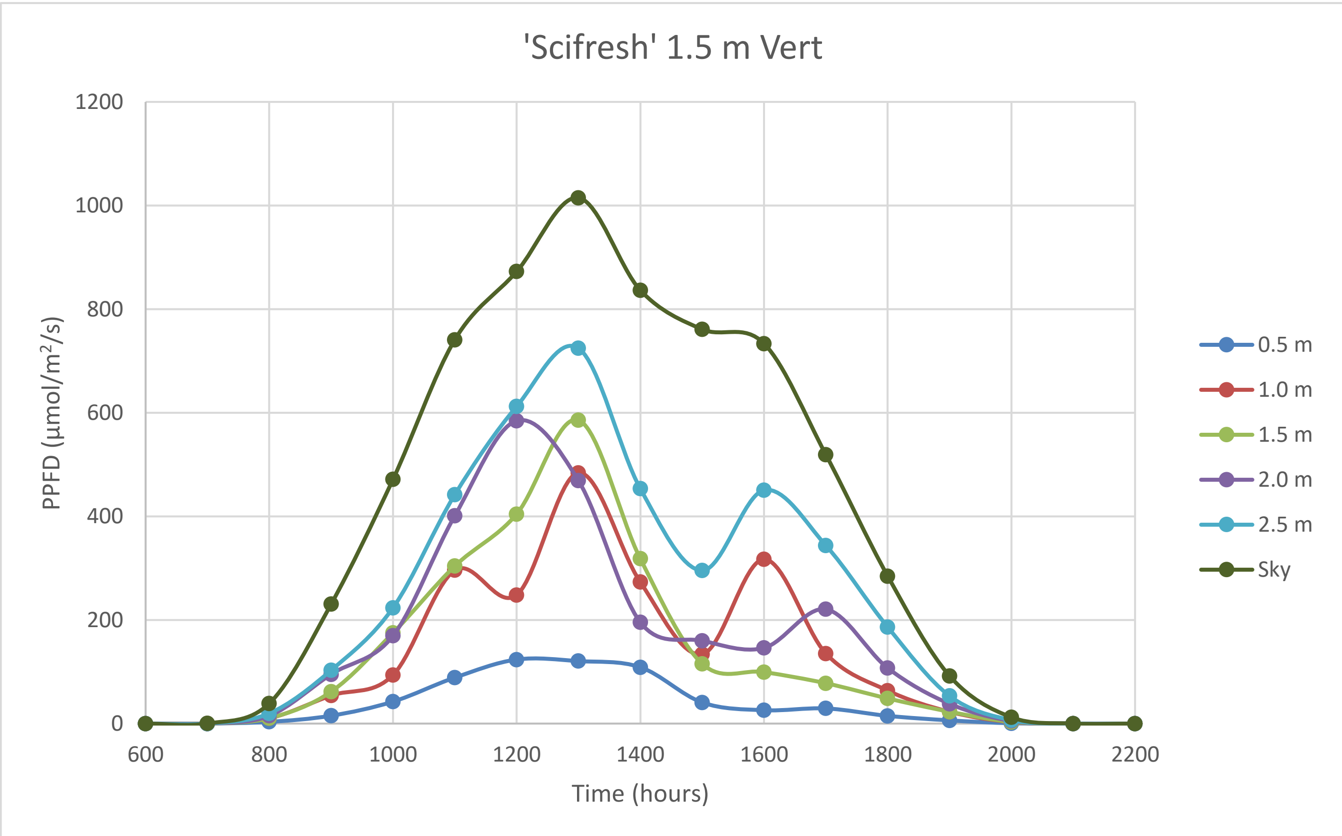
As the sun rose in the east, total incoming radiation quickly rises until 13:00hr when it reaches an average peak PPFD value of 1014 µmol/m^2/s. From approximately 13:00 – 15:00hr until dusk, light levels quickly drop until a PPFD value of 0 µmol/m^2/s.

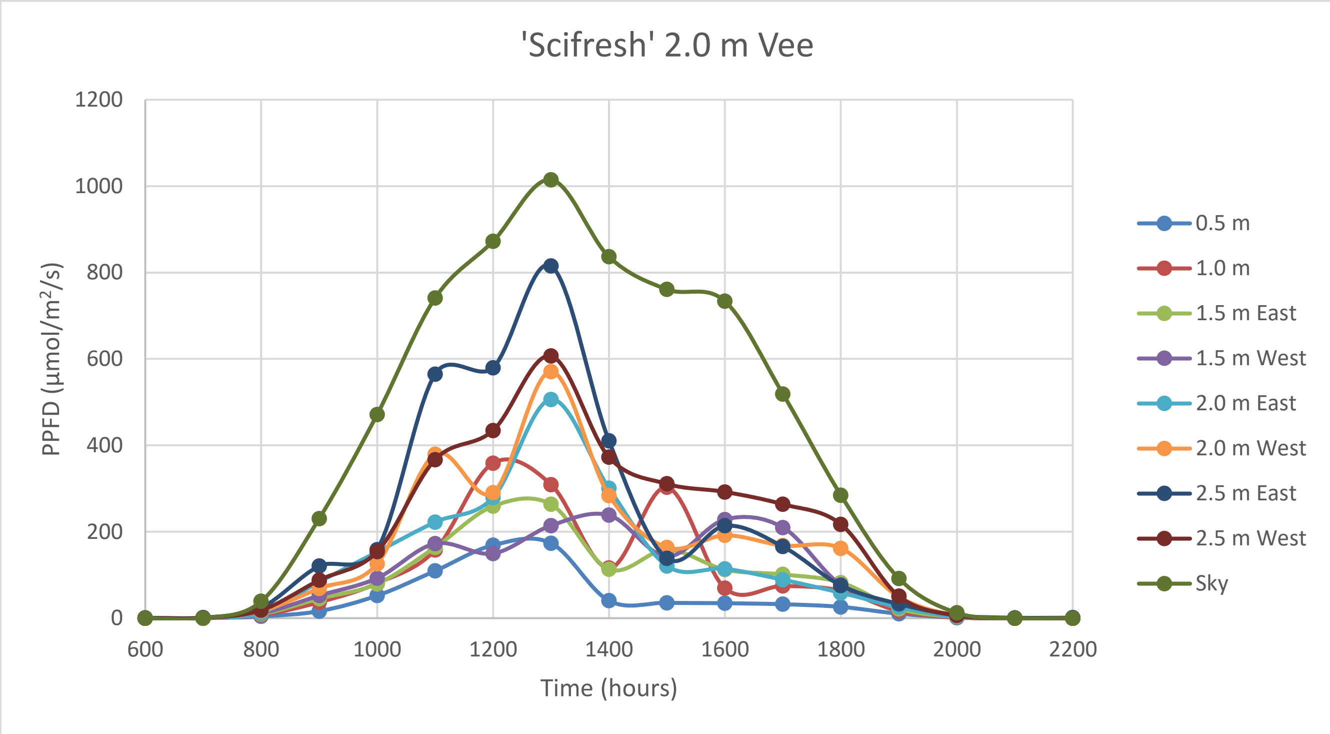
PPFD at different heights within the Vertical and Vee tree designs followed a similar pattern as the sun moves along a plane from sunrise to sunset (06:00hrs to 22:00hrs) (Figure 32). PPFD peaked at two separate times during the day. The first peak occurred at approximately 13:00hr as the sun sits just to the east of the Vertical plane. PPFD levels then drop significantly at approximately 15:00hrs. In the Vertical tree design, PPFD levels then rise again at approximately 16:00-17:00hr to then gradually decline as the sun starts to set (22:00hrs). The Vee tree design did not peak again, instead gradually decreasing from 13:00hrs to dusk at 22:00hrs.

At the 2 m row spacing, the Vertical canopy had greater irradiance in the top of the tree compared to the bottom. At 12:00 noon the average PPFD from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 129 (0.5 m), 426 (1.0 m), 545 (1.5 m), 824 (2.0 m) and 721 (2.5 m) (µmol/m^2/s) at their respective heights. At the 1.5 m row spacing, the average PPFD from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 124 (0.5 m), 248 (1.0 m), 404 (1.5 m), 585 (2.0 m) and 612 (2.5 m) (µmol/m^2/s) at their respective heights.

At the 2 m row spacing, the Vee tree design showed altered responses to light at different heights in the canopy. At 12 noon the average light irradiance from the bottom zone (0.5 m) to the top zone (2.5 m) of the tree was 169 (0.5 m), 359 (1.0 m), 259 (1.5 east), 150 (1.5 west), 279 (2.0 east), 290 (2.0 west), 580 (2.5 east) and 435 (2.5 m west) (µmol/m^2/s) at their respective heights. At the 1.5 m row spacing in 'Scifresh', the light environment was more consistent in comparison to the 2.0 m row spacing. At 12 noon the average light flux (PPFD) from the bottom (0.5 m) to the top (2.5 m) of the tree was 66 (0.5 m), 236 (1.0 m), 442 (1.5 east), 176 (1.5 west), 613 (2.0 east), 679 (2.0 west), 684 (2.5 east) and 768 (2.5 m west) (µmol/m^2/s) at their respective heights.


'Scifresh' 2.0 m Vert
PPFD (µmol/m²/s)
1200
1000
800
600
400
200
0
600
800
1000
1200
1400
1600
1800
2000
2200
Time (hours)
0.5 m
1.0 m
1.5 m
2.0 m
2.5 m
Sky


'Scifresh' 1.5 m Vert
PPFD (µmol/m²/s)
1200
1000
800
600
400
200
0
600
800
1000
1200
1400
1600
1800
2000
2200
Time (hours)
0.5 m
1.0 m
1.5 m
2.0 m
2.5 m
Sky



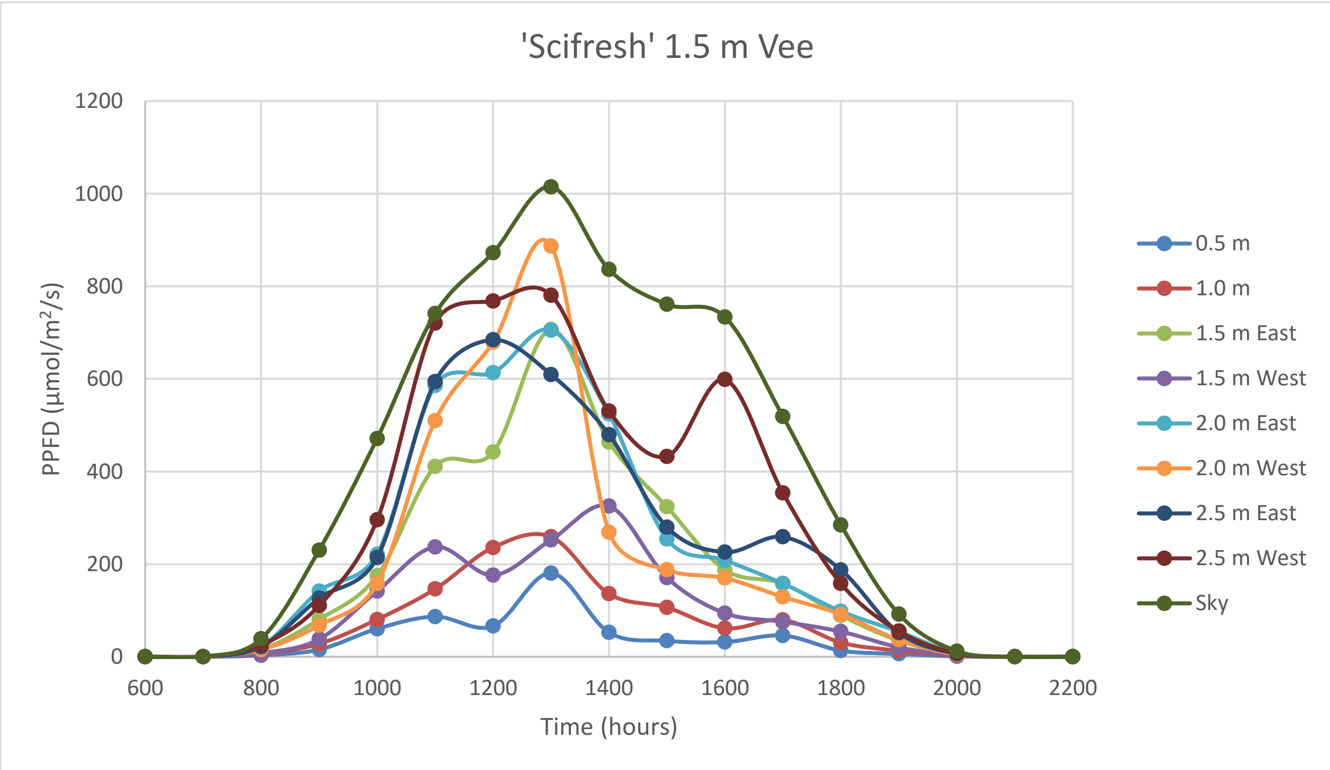


Figure 32. Photosynthetic Photon Flux Density (PPFD) at different heights (0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m) within Vertical and Vee planar cordon 'Scifresh' trees grown at 1.5 m and 2 m rowing spacings. Light measurements are presented every hour starting from sunrise (06:00hr) to sunset (22:00hr). The Vertical canopy consisted of five sensors placed within two uprights. The Vee canopy contained eight sensors (heights 1.5 m, 2.0 m and 2.5 m were represented by 2 sensors placed along the plane of uprights on the east and west side of the canopy). Each treatment was measured with four reps as well as an open sky sensor which was placed at 4 m in height recording above canopy radiation (open sky).

4.3.2 Percentage of total incoming light radiation and accumulative energy received

The daily light integral (DLI) was lower in the lower parts of the canopy and higher at the top for both 'Royal Gala' and 'Scifresh'. In 'Royal Gala', the DLI increased from the bottom to the top of the canopy at 4.48, 8.25, 11.91, 20.23 and 25.77 mol/m^2 at 0.5, 1.0, 1.5, 2.0 and 2.5 m, respectively. The average sky reading was 45.13 mol/m^2. In 'Scifresh', the DLI increased from the bottom to the top of the canopy at 3.0, 6.83, 7.39, 11.58 and 14.3 mol/m^2 at 0.5, 1.0, 1.5, 2.0 and 2.5 m, respectively. The average sky reading was 23.79 mol/m^2. The regression relationship between DLI and canopy height in 'Royal Gala' and 'Scifresh' is shown in figure 33 with r^2 values of 0.98 and 0.97, respectively.

The percentage of incoming radiation increasing with height in the canopy. In 'Royal Gala', percentage of incoming radiation increases through the canopy, from 8%, 18%, 27%, 45% and 60% at 0.5, 1.0, 1.5, 2.0 and 2.5 m, respectively. Equally, in 'Scifresh', percentage of incoming radiation increases from 12%, 26%, 33%, 56% and 58% at 0.5, 1.0, 1.5, 2.0 and 2.5 m, respectively.

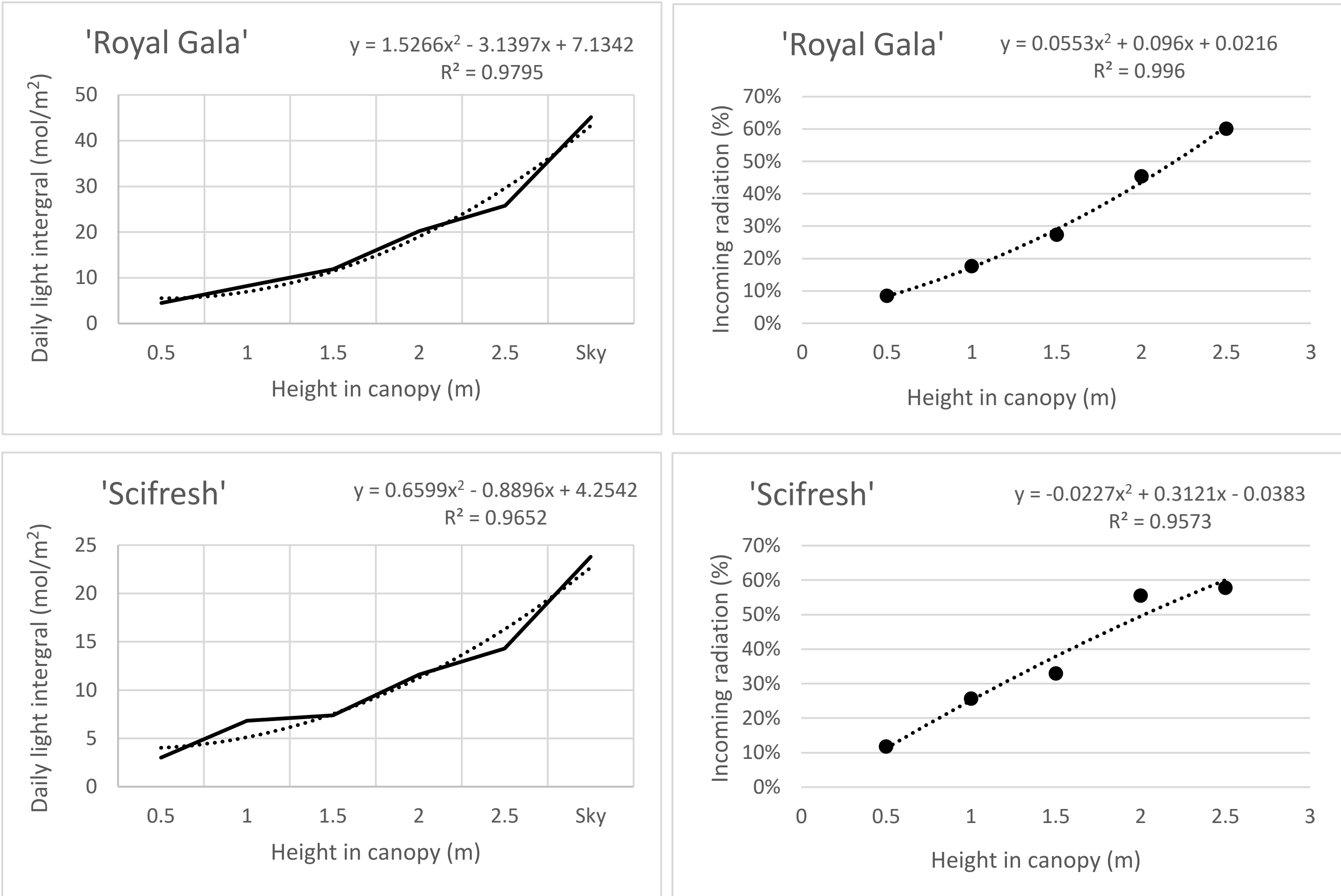


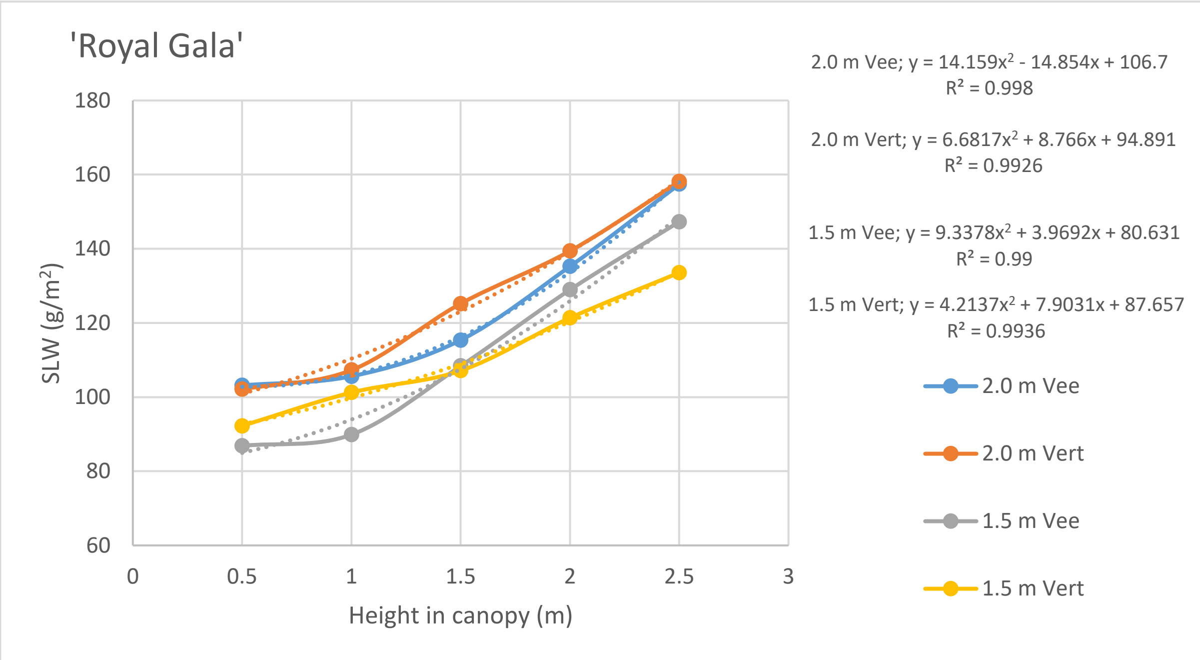
Figure 33. Daily light integral (mol/m²) and incoming radiation (%) at different heights within the 'Royal Gala' and 'Scifresh' canopies averaged across row spacing treatments (1.5 m and 2.0 m) and the Vertical and Vee tree designs during four replicate days.

4.3.3 Specific leaf weight by position in the canopy.

The specific leaf weight (SLW) in 'Royal Gala' decreased as the light regime declined down into the canopy for all treatments (r^2 value > 0.91). Each treatment showed no difference in SLW between the 0.5 m and 1.0 m zones (p-values > 0.05). However SLW increased from 1.0 m to the maximum height of 2.5 m. SLW went from 87 – 102 g/m^2 at the 0.5 m zone to 134 – 158 g/m^2 at the 2.5 m zone showing a difference of approximately 51 g/m^2 from the bottom to the top of the canopy among all four treatments. At all positions in the tree, SLW was greater at both of the 2.0 m row spacing treatments compared to the 1.5 m spacing.

For 'Scifresh', SLW also increased with increasing height in the canopy (r^2 value > 0.89). Most of the treatments showed a significant increase in SLW between the 0.5 m and 2.5 m zones (p-values <

0.05), however, a few adjacent positions did not differ (Table 6). SLW increased from 88 – 118 g/m^2 at the 0.5 m zone to 144 – 174 g/m^2 at the 2.5 m zone showing a difference of approximately 56 g/m^2 from the bottom to the top of the canopy among all four treatments. At all positions in the tree, SLW was greater at the 2.0 m Vertical treatment.



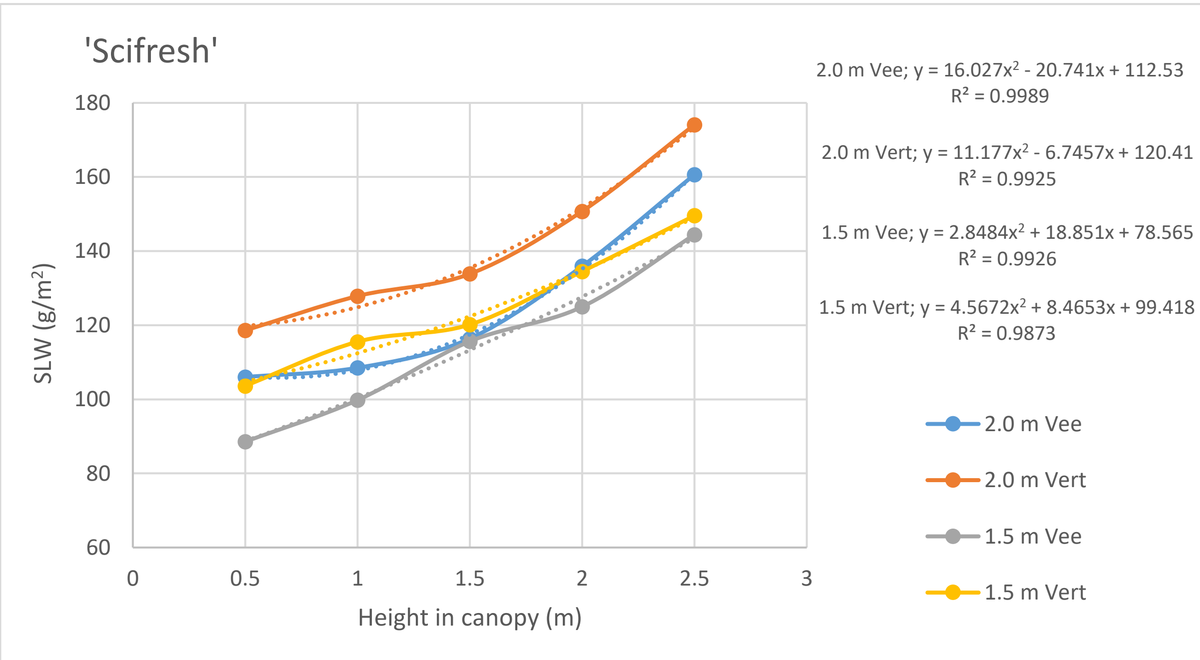


Figure 34. Mean specific leaf weight (SLW; g/m^2) for 'Royal Gala' and 'Scifresh' in response to different canopy heights (0.5, 1, 1.5, 2 and 2.5 m) within Vee and Vertical (Vert) planar cordon apple trees planted at 1.5 m and 2.0 m inter-row spacings. Dotted line represents the polynomial trend curve for each treatment.

Table 6. Specific leaf weight (g/cm^2) comparison between different heights within the canopy of 'Royal Gala' and 'Scifresh' in the four treatments made up of two row spacings (1.5 m and 2.0 m) and two tree designs (Vertical and Vee).

		SLW (g/m^2)			
Treatment	**Height (m)**	**2.0 m Vee**	**2.0 m Vertical**	**1.5 m Vee**	**1.5 m Vertical**
'Royal Gala'	**2.5 m**	157 d	158 d	147 d	134 d
	2.0 m	135 c	139 c	129 c	121 c
	1.5 m	115 b	125 b	108 b	107 b
	1.0 m	106 a	107 a	89 a	101 ab
	0.5 m	103 a	102 a	87 a	92 a
'Scifresh'	**2.5 m**	161 d	175 d	144 e	149 d
	2.0 m	136 c	151 c	125 d	135 c
	1.5 m	116 b	134 b	116 c	120 b
	1.0 m	108 ab	128 b	99 b	116 b
	0.5 m	106 a	118a	89 a	104 a

Within a single cultivar and main treatments (between heights) only, means sharing the same letter are not significantly different using the LSD test. ANOVA at P >0.05.

4.3.4 Leaf area index comparisons

Leaf area index was consistently greater at the 1.5 m row spacing in comparison to the 2.0 m spacing. Within 'Royal Gala', trees at the 1.5 m spacing had a LAI of 4.0 whereas trees at the 2.0 m row spacing had a LAI of 3.0. Within 'Scifresh', trees at the 1.5 m spacing had a LAI of 3.1 whereas trees at the 2.0 m row spacing had a LAI of 2.6.

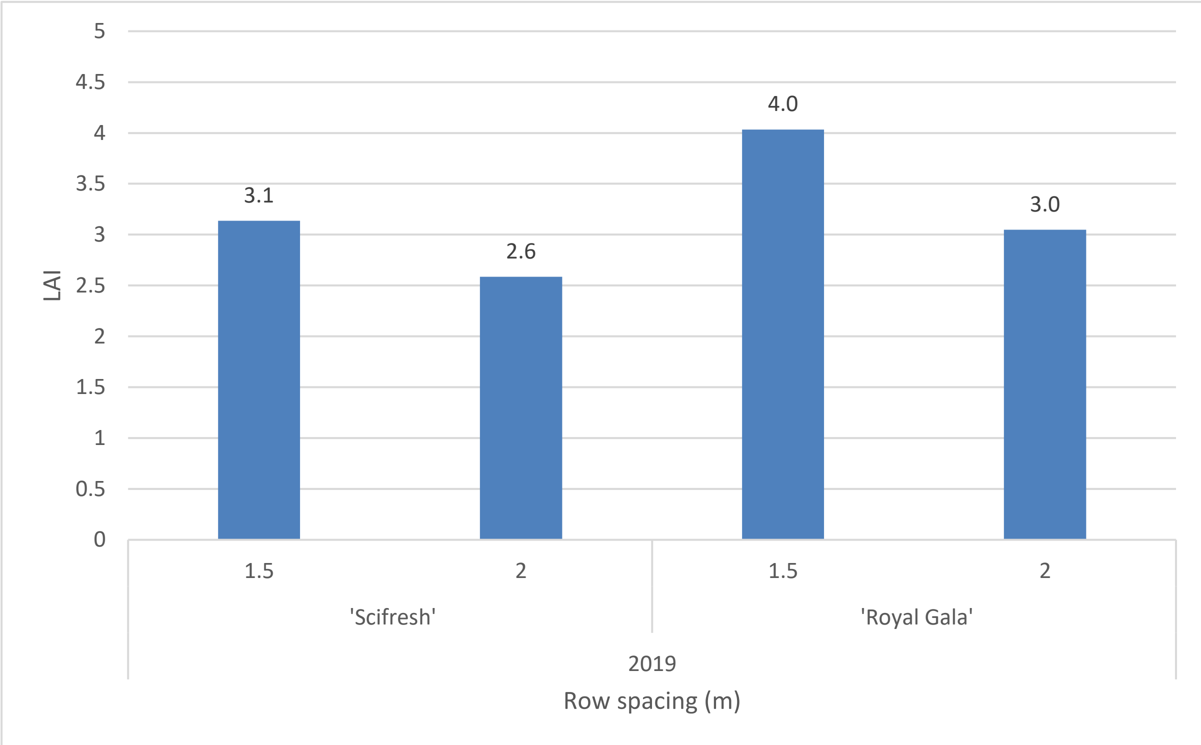


Figure 35. Leaf area index (LAI) of 'Royal Gala' and 'Scifresh' during the 2019 season within the Vertical (Vert) planar cordon apple trees planted at 1.5 m and 2.0 m inter-row spacings.

4.3.5 Effect of light on fruit quality

The first main effect (canopy height) shows the influence of canopy height on the light environment and furthermore, how that effects fruit quality in the form of MFW, red colour and DMC. In both 'Royal Gala' and 'Scifresh', average daily PPFD, daily light integral and the percentage of incoming radiation increased from the bottom to the top of the canopy. Average PPFD increased from 77 μmol/m^2/s at the 0.5 m zone to 433 μmol/m^2/s at the 2.5 m zone in 'Royal Gala' and 45 μmol/m^2/s at the 0.5 m zone to 227 μmol/m^2/s at the 2.5 m zone in 'Scifresh'. The percentage of income radiation was similar for both cultivars ranging from 9% to 60% from the bottom to the top of the canopy and was associated with all three forms of fruit quality increasing from the bottom to the top of the canopy.

MFW in 'Royal Gala' increased from 169.4 g to 192 g between the 0.5 m to the 2.0 m zone. The 2.5 m zone had a MFW of only 183.5 which was characteristic of fruit size grown on one year old axillary buds. Alternatively, MFW increased from 172 g to 211 g in 'Scifresh'.

Red colour increased from 75% to 92% in 'Royal Gala' and 67% to 77% in 'Scifresh' from the bottom to the top of the canopy. Dry matter content increased from 14.9% to 15.7% in 'Royal Gala' and from 15.8% to 16.7% in 'Scifresh'.

In 'Royal Gala', there were no differences between the 1.5 m and 2.0 m row spacing treatments in the light environment, however significant differences were seen in fruit quality. The 2.0 m row spacing produced larger fruit (2.0 m=195.8 g, 1.5 m = 168.5 g - p-value = <0.001) with a higher average dry matter content (2.0 m= 15.7%, 1.5 m = 15.0% - p-value = <0.001) whereas the 1.5 m row spacing produced fruit with higher red colour (1.5 m= 82.3%, 2.0 m = 87.9% - p-value = <0.001). The only measurable difference between tree designs was for red colour. The Vee canopy produced redder fruit compared to the Vertical canopy (Vee = 87.3%, Vert = 83%, p-value – 0.006).

In 'Scifresh', no differences were measured between row spacing treatments for light environment and MFW. However, red colour and dry matter content were both higher at the 2.0 m row spacing compared to the 1.5 m spacing (red colour; 2.0 m = 82%, 1.5 m = 69%, DMC; 2.0 m = 16.5%, 1.5 m = 15.9%). The Vertical tree design had significantly higher light in terms of average PPFD and DLI and consequently higher red colour compared to the Vee canopy.

A number of interactions were seen between row spacing (RS) and height, and tree design (TD) and height. In 'Royal Gala', interactions between row spacing and height for the percentage of incoming radiation, MFW and dry matter content occurred. Each of these attributes were higher at 2.0 m compared to the 1.5 m spacing. Interactions between TD and height occurred for red colour and DMC. The Vee canopy had significantly higher red colour and DMC at low levels of the canopy compared to the Vertical tree design.

In 'Scifresh', interactions occurred between RS and height and TD and height in percentage of incoming radiation and red colour. For the RS and height interactions, both percentage of incoming and red colour were greater at the 2.0 m row spacing compared to the 1.5 m spacing. For the TD and height interactions, both percentage of incoming and red colour were greater in the Vertical canopy compared to the Vee canopy.

Table 7. Effect of light (average daily PPFD - $\mu mol/m^2/s$ and daily light integral mol/m^2) on fruit quality (fruit size, colour and dry matter content) in 'Royal Gala' and 'Scifresh' at two spacings, (1.5 m and 2.0 m) and two tree designs (Vertical and Vee) during the 2019 season. Statistical differences were made at a p=0.05 confidence interval (ANOVA). Light readings were made on four different days for each cultivar within the season.

		PPFD ($\mu mol/m^2/s$)	DLI (mol/m^2)	Incoming radiation (%)	Mean fruit weight (g)	Red colour (%)	DMC (%)
'Royal Gala'							
Height	**2.5**	433	26.42	60.1	183.5	92	15.7
	2.0	326	19.88	45.4	192.1	89	15.7
	1.5	205	12.55	27.3	185.0	87	15.3
	1	135	8.25	17.6	180.7	83	15.1
	0.5	77	4.42	9	169.4	75	14.9
p-value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD		60.25	3.698	7.4	4.75	3.26	0.17
Row spacing (RS)	**1.5 m**	244	14.75	32.4	168.5	87.9	15.0
	2.0 m	227	13.86	31.4	195.8	82.3	15.7
p-value		ns	ns	ns	<0.001	<0.001	<0.001
Tree design (TD)	**Vert**	247	15.12	33.7	183.6	83.0	15.3
	Vee	223	13.49	30.1	180.7	87.3	15.4
p-value		ns	ns	ns	ns	0.006	ns
Interactions				RS x H – 0.046	RS x H - <0.001	TD x H - <0.001	RS x H – 0.017 TD x H - <0.001
'Scifresh'							
Height	**2.5**	227	14.02	56.9	211	77	16.7
	2.0	198	12.27	53.6	187	81	16.3
	1.5	131	8.16	32.5	176	78	16.1
	1	107	6.76	25.3	175	73	16.0
	0.5	45	2.98	11.6	172	67	15.8
p-value		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
LSD		44.8	2.767	6.9	8.71	3.49	0.19
Row spacing	**1.5 m**	138	8.31	33.5	184	69	15.9
	2.0 m	145	9.36	38.4	185	82	16.5
p-value		ns	ns	ns	ns	<0.001	0.001
Tree design	**Vert**	166	10.12	41.5	181	77	16.2
	Vee	117	7.55	30.4	187	74	16.1
p-value		0.008	ns	ns	ns	0.027	ns
Interactions				RS x H - 0.002 TD x H - 0.002		RS x H - <0.001 TD x H - <0.001	

Within a single cultivar and main effect only, means sharing the same letter are not significantly different using the LSD test. ns = non-significant ANOVA at P >0.05.

4.3.6 Relationship between daily light integral (DLI) and fruit quality

4.3.6.1 Fruit weight

The data below (Figure 36 and 37) shows the relationship between DLI and MFW at the four different treatments within 'Royal Gala' and 'Scifresh'. Within this, r^2 values ranged from 0.2875-0.4951 in 'Royal Gala' (Figure 36) and 0.054-0.647 in 'Scifresh' (Figure 37). Trends suggest that as DLI increased from 1.1 to 38 mol/m^2, there was an association with greater MFW. This was less apparent at 1.5 m spacing in 'Royal Gala' and the Vertical tree design in 'Scifresh'.

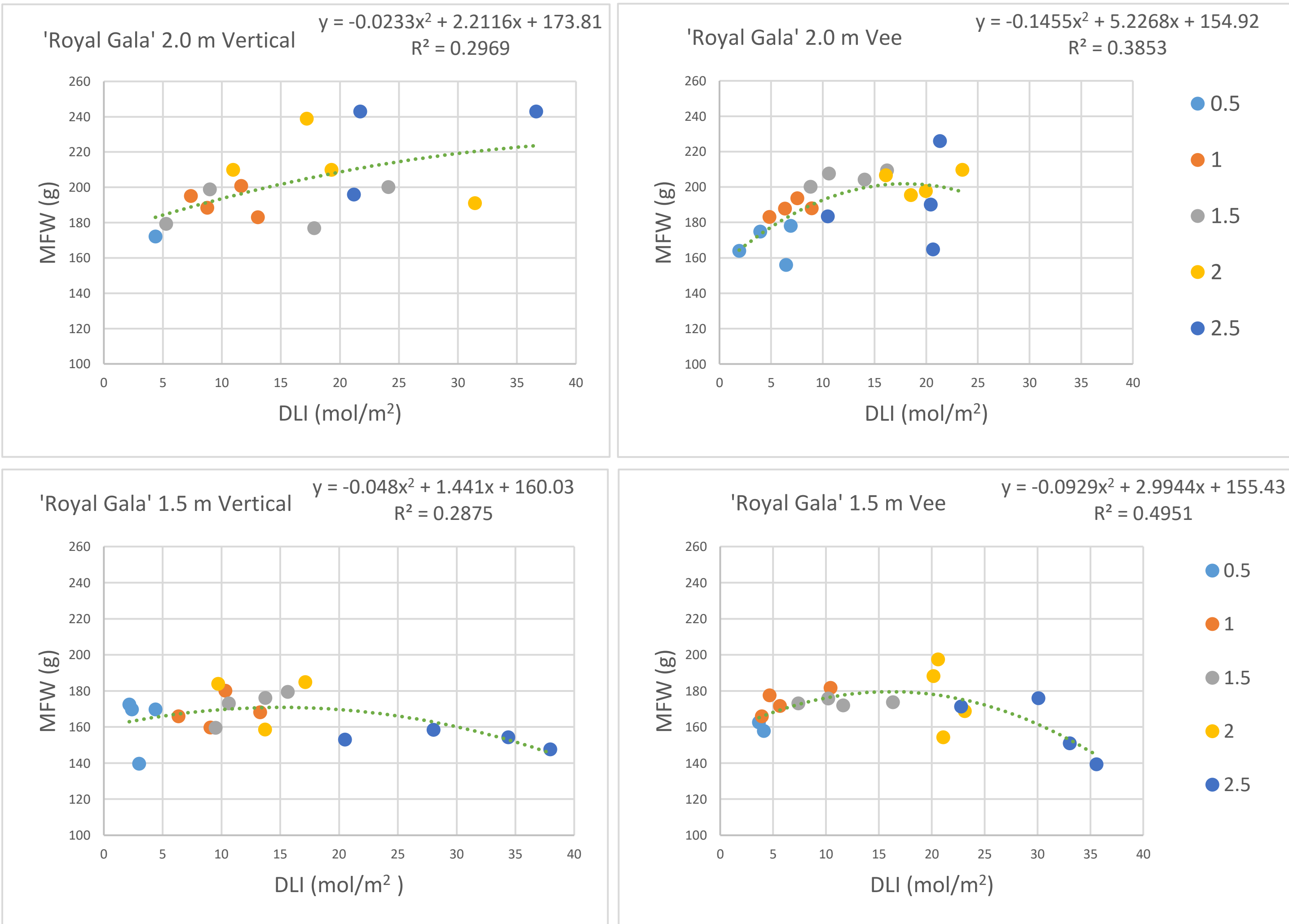


Figure 36. The effect of the daily light integral (DLI) on mean fruit weight (MFW) at different heights in the canopy in 'Royal Gala' at an upright level during the 2019 season. Fruit were grown on a two-dimensional planar cordon training system. The trial consisted two different row spacing treatments at 1.5 m and 2.0 m and two different tree design, Vertical and Vee structures. Each data point represents the MFW from each light measurement replicate (day) consisting fruit from two adjacent uprights.

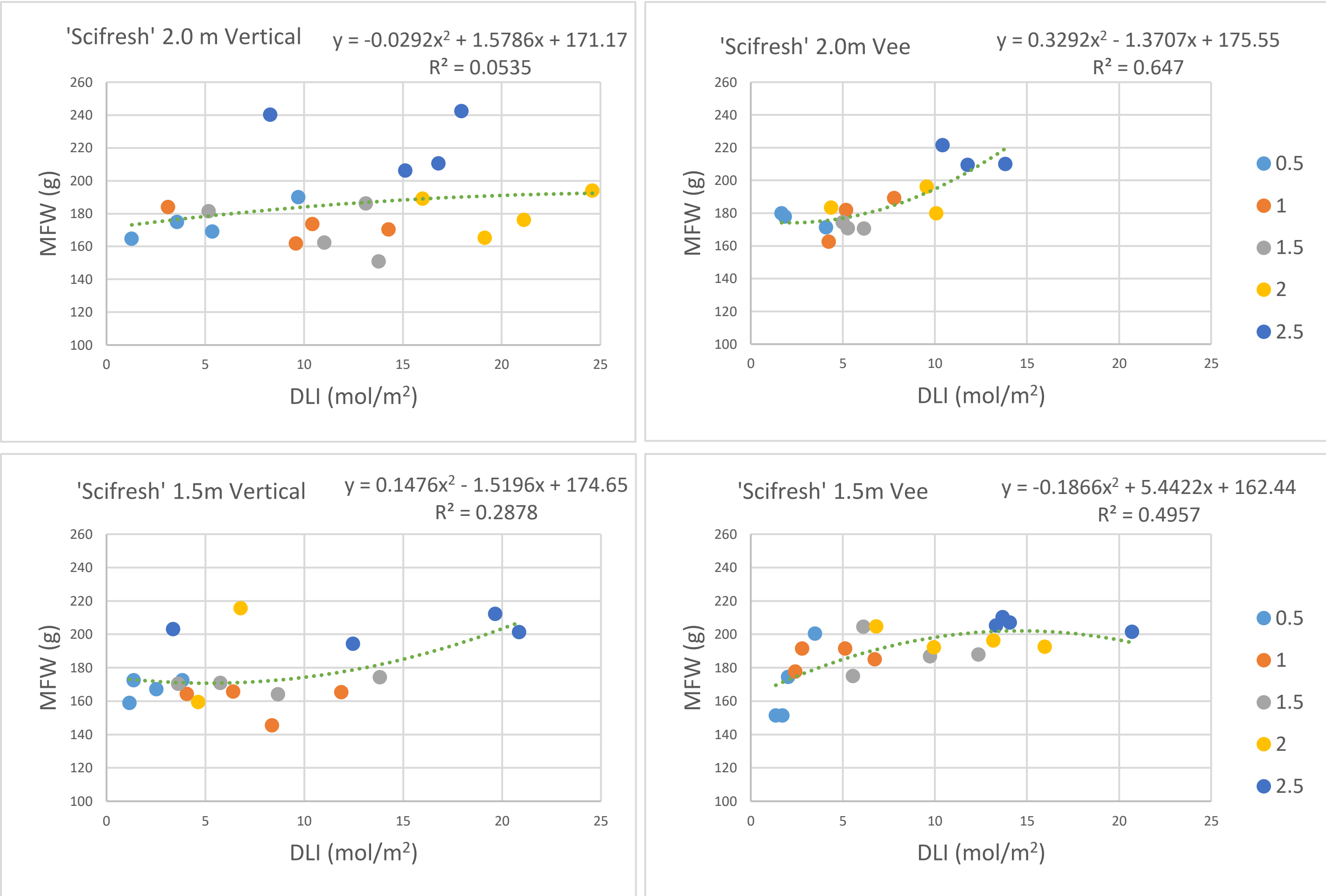


Figure 37. The effect of the daily light integral (DLI) on mean fruit weight (MFW) at different heights in the canopy in 'Scifresh' at an upright level during the 2019 season. Fruit were grown on a two-dimensional planar cordon training system. The trial consisted two different row spacing treatments at 2.0 m and 1.5 m and two different tree design, Vertical and Vee structures. Each data point represents the MFW from each light measurement replicate (day) consisting fruit from two adjacent uprights.

4.3.6.2 Dry matter content

The data below (Figure 38 and 39) shows the relationship between DLI and dry matter content (DMC) at the four different treatments within 'Royal Gala' and 'Scifresh'. The r^2 values ranged from 0.13-0.429 in 'Royal Gala' (Figure 38) and 0.051-0.695 in 'Scifresh' (Figure 39). Trends suggest that as DLI increased from 1.1 to 38 mol/m^2, there was an association with increasing DMC. This was less apparent at 1.5 m spacing in 'Royal Gala' and the Vertical tree design in 'Scifresh'.

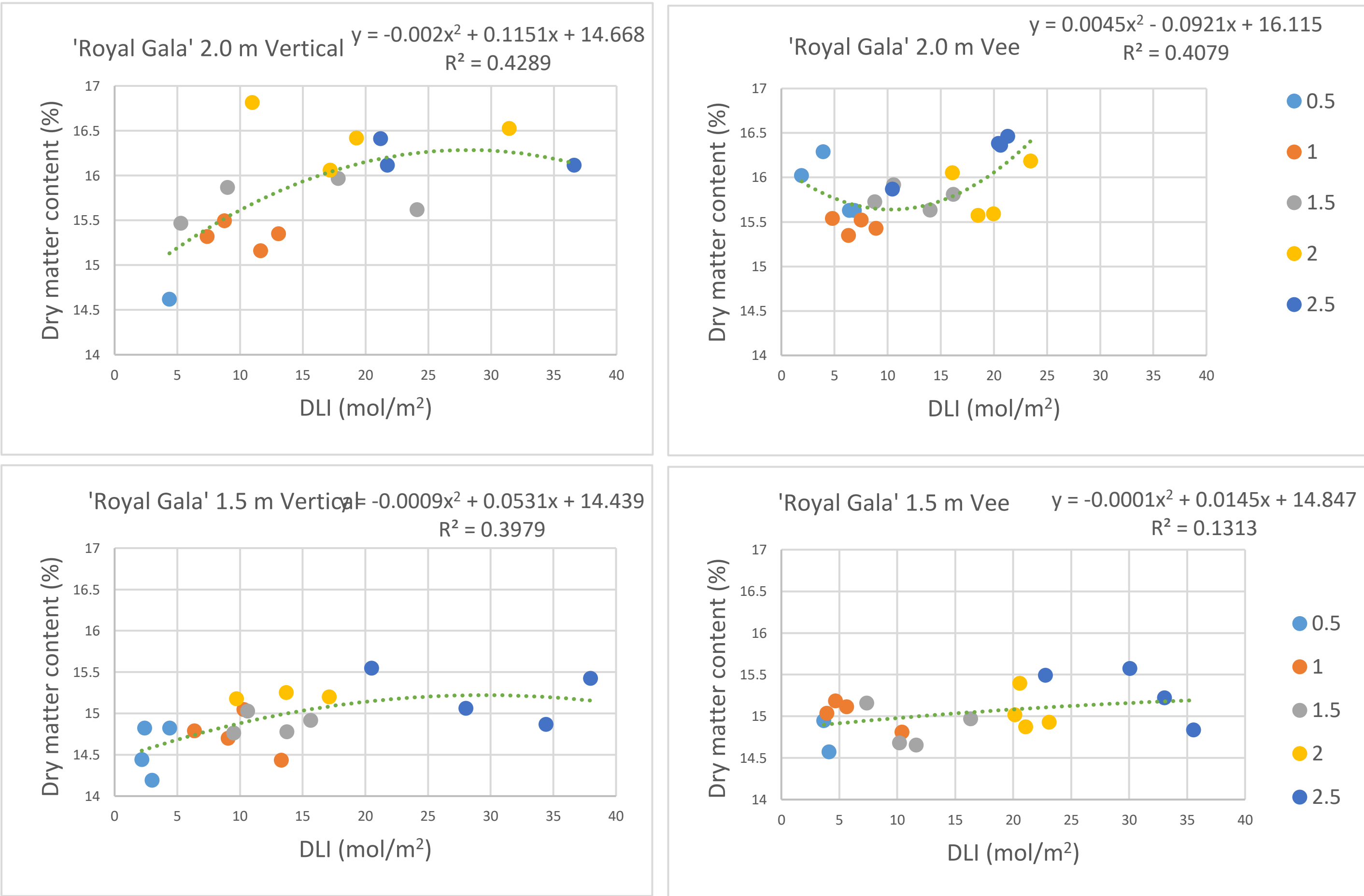


Figure 38. The effect of the daily light integral (DLI) on dry matter content (%) at different heights in the canopy in 'Royal Gala' at an upright level during the 2019 season. Fruit were grown on a two-dimensional planar cordon training system. The trial consisted two different row spacing treatments at 2.0 m and 1.5 m and two different tree design, Vertical and Vee structures. Each data point represents the MFW from each light measurement replicate (day) consisting fruit from two adjacent uprights.

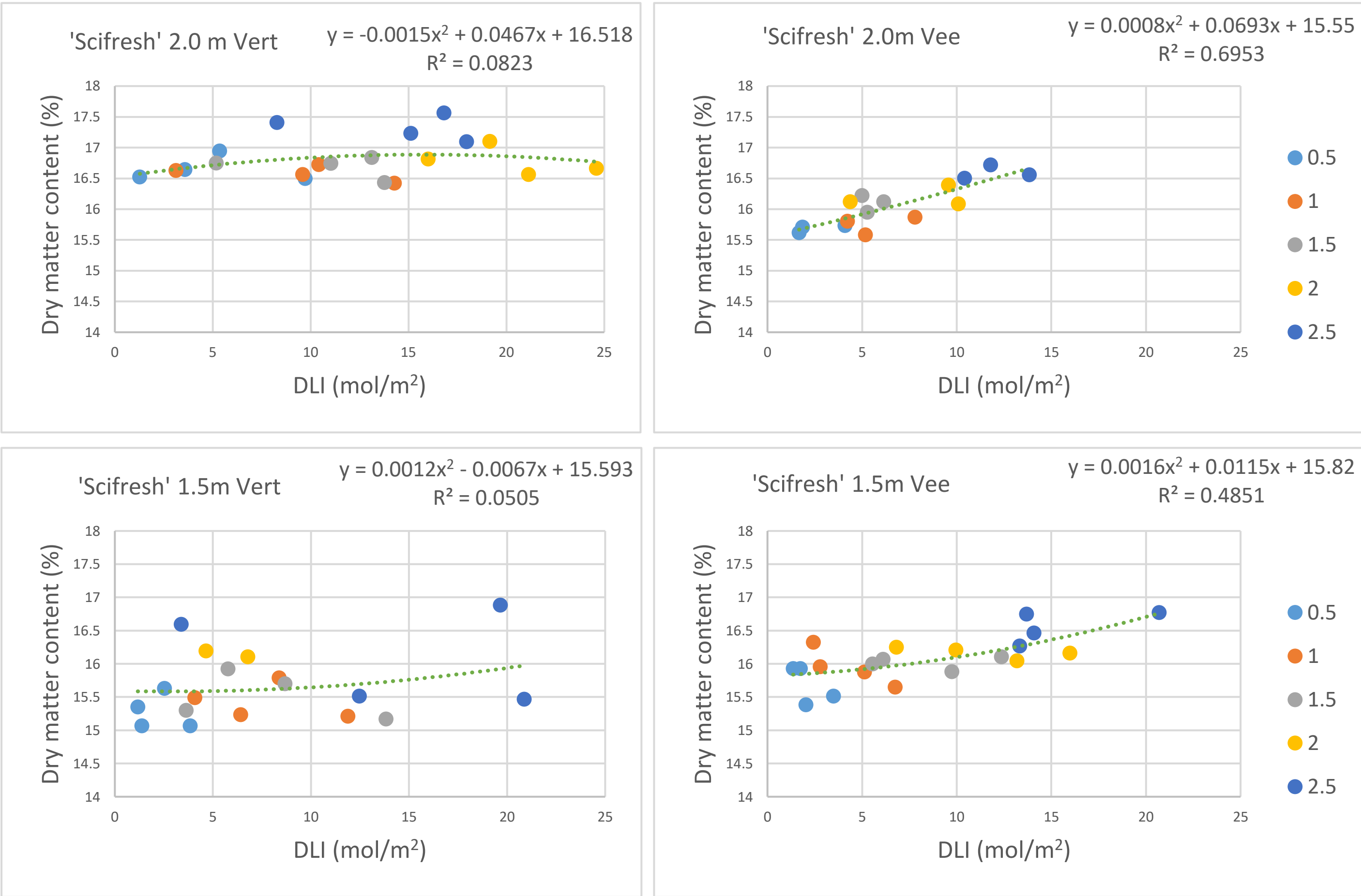


Figure 39. The effect of the daily light integral (DLI) on dry matter content (%) at different heights in the canopy in 'Scifresh' at an upright level during the 2019 season. Fruit were grown on a two-dimensional planar cordon training system. The trial consisted two different row spacing treatments at 2.0 m and 1.5 m and two different tree design, Vertical and Vee structures. Each data point represents the MFW from each light measurement replicate (day) consisting fruit from two adjacent uprights.

4.3.6.3 Red colour (%)

The relationship between DLI and red colour at the four different treatments within 'Royal Gala' and 'Scifresh' is shown below in Figure 40 and 41. The r^2 values ranged from 0.2209-0.7452 in 'Royal Gala' (Figure 40) and 0.1255-0.5689 in 'Scifresh' (Figure 41). There were trends that suggest that as DLI increased from 1.1 to 38 mol/m^2, there was greater red colour. Correlations were stronger at the 1.5 m row spacing compared to the 2.0 m.

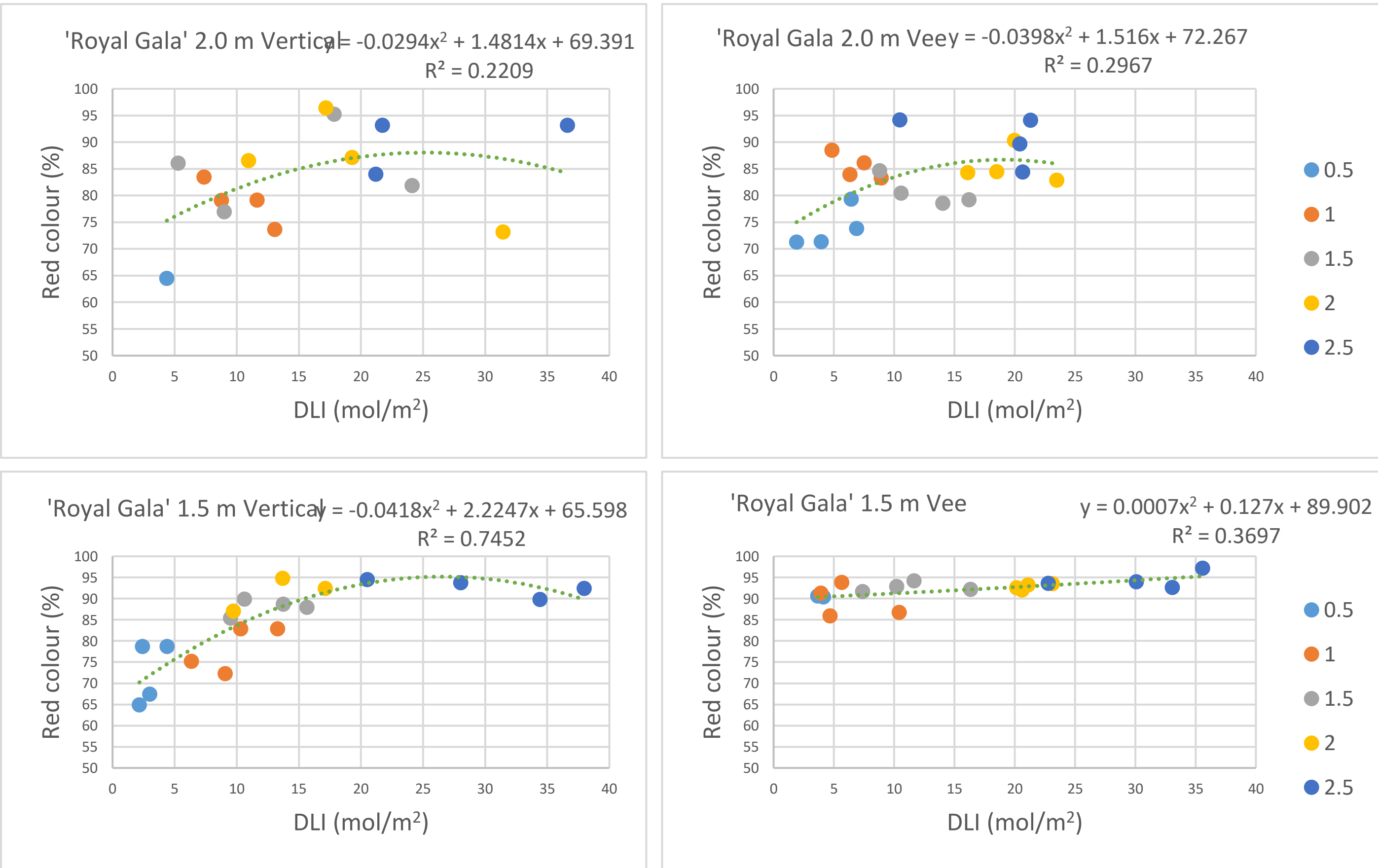


Figure 40. The effect of the daily light integral (DLI) on red colour (%) at different heights in the canopy in 'Royal Gala' at an upright level during the 2019 season. Fruit were grown on a two-dimensional planar cordon training system. The trial consisted two different row spacing treatments at 2.0 m and 1.5 m and two different tree design, Vertical and Vee structures. Each data point represents the MFW from each light measurement replicate (day) consisting fruit from two adjacent uprights.

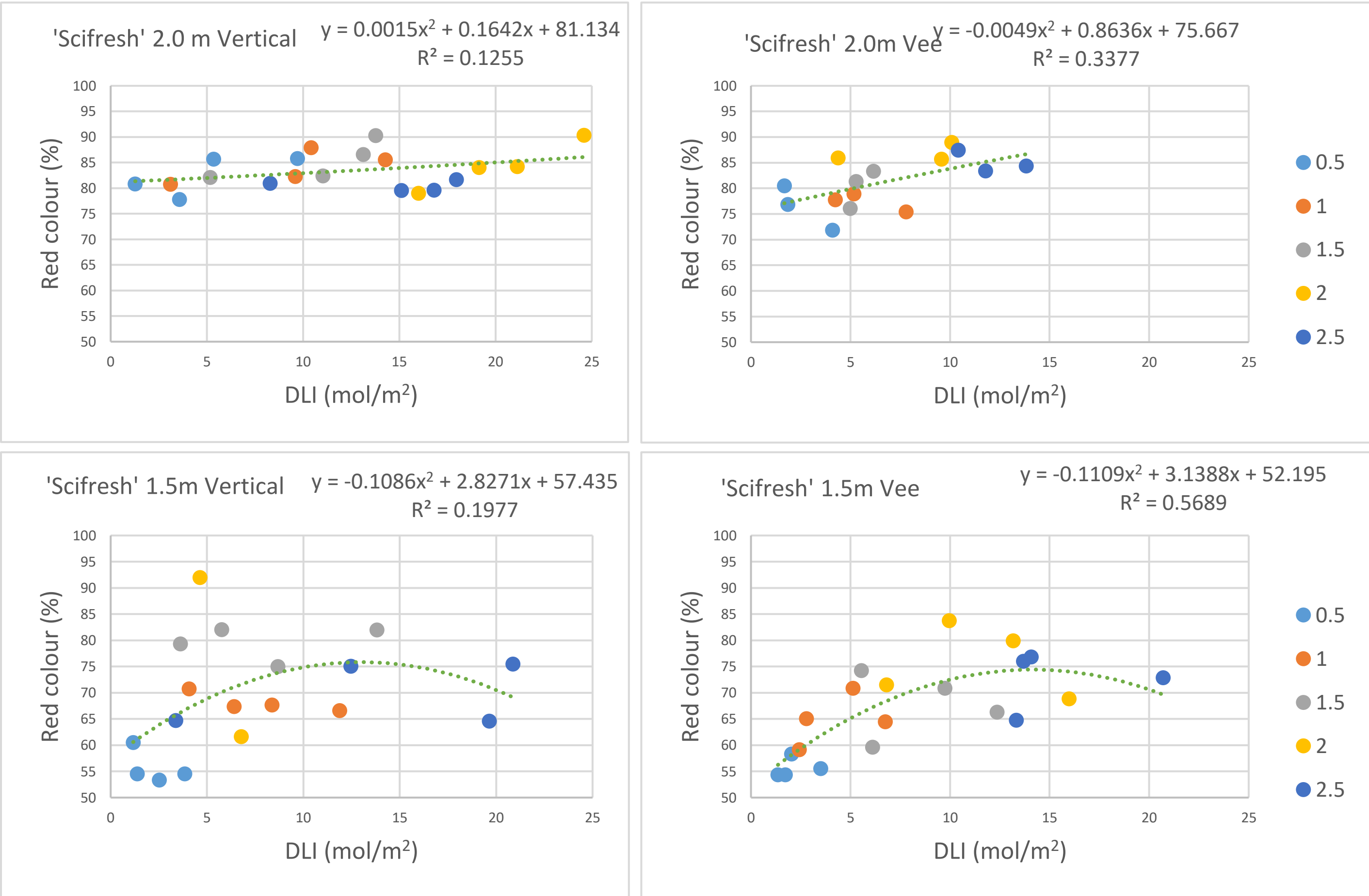


Figure 41. The effect of the daily light integral (DLI) on red colour (%) at different heights in the canopy in 'Scifresh' at an upright level during the 2019 season. Fruit were grown on a two-dimensional planar cordon training system. The trial consisted two different row spacing treatments at 2.0 m and 1.5 m and two different tree design, Vertical and Vee structures. Each data point represents the MFW from each light measurement replicate (day) consisting fruit from two adjacent uprights.

4.3.7 How does position throughout the tree effect fruit quality

4.3.7.1 All treatments

Figure 42 shows the frequency distribution of 'Royal Gala' over all treatments for fresh weight (g), red colour (%) and dry matter content (%) and their corresponding heights within the canopy. For fresh weight, the majority of the fruit was larger than 120g with some reaching 280-300g. The MFW for each distribution slowly increases from the bottom of the tree at 0.5 m to the top of the tree at 2.0 m. Fruit at 2.5 m showed variable fruit size and as a consequence, the MFW dropped in comparison to the 2.0 m height. This was supported by the standard deviations (SD) which increased with canopy height meaning the top of the tree had greater variability that the bottom in terms of fruit size.

Red colour distributions showed that the large majority of fruit were harvested between 80-100% red colour. SD's were smaller at the top of the tree compared to the bottom meaning the variation was reduced in top for colour. The minimum colour was 40-50% red blush which was seen at the 2.0 m height. The overall average colour of each height stayed relatively consistent within the bottom section of the tree (85-88%). However, fruit at the top of the tree had a greater ability to colour to a very high standard with the majority of fruit being 90-100% red, averaging 93.6%. The black line on each distribution graph outlines 66% red colour, the level of market acceptability in terms of colour for 'Royal Gala'.

Dry matter content in 'Royal Gala' ranged from 13 to 18 % at all heights throughout the canopy. Again, similarly to fresh weight, DMC slowly increases with height up the tree. The bottom section of the tree (0.5 m) was relatively scattered in distribution with the majority of fruit achieving a DMC of 14.5-15 %. The distribution curve visually increases with canopy height. However, there doesn't seem to be a major difference in DMC within the top metre of the tree (2.0 m = 15.6% and 2.5 m = 15.6%).

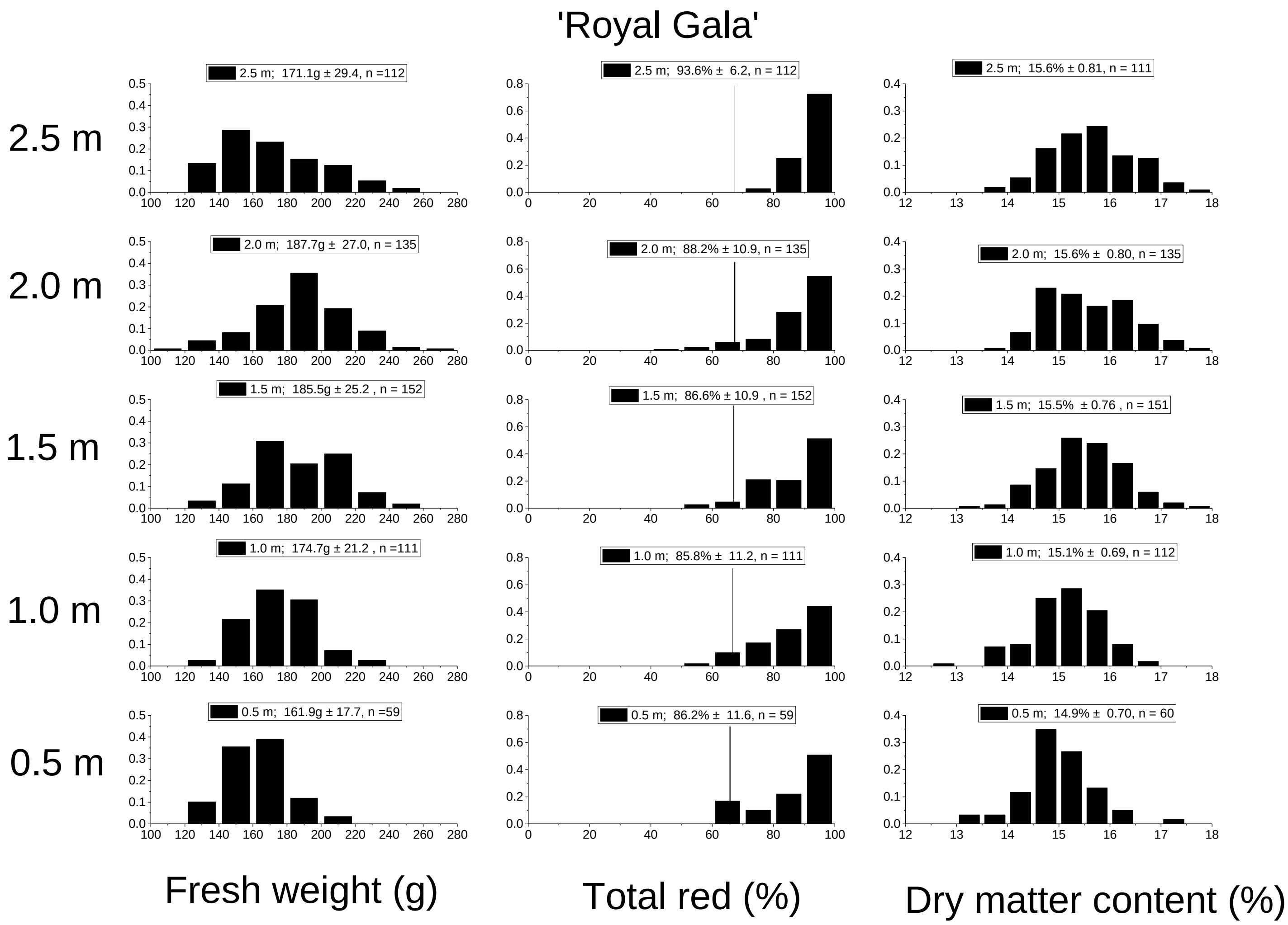


Figure 42. Fruit fresh weight, colour and dry matter content distributions for 'Royal Gala' in 2019. Distributions are for different heights throughout the canopy by quality attribute. Each distribution is made up of fruit from both row spacing and tree design treatments. Distributions are annotated with the average value for each quality parameter, (MFW, TR% and DM%), standard deviation and number of observations (n).

Figure 43 shows the frequency distribution of 'Scifresh' over all treatment variables (fresh weight (g), red colour (%) and dry matter content (%)) and their corresponding heights within the canopy. For fresh weight, the majority of fruit were larger than 120g with some reaching 280-300g at the top of the tree. The MFW for each distribution stayed consistent at the bottom section of the tree from 0.5 m to 1.5 m averaging 172 – 175 g. The top section of the tree produced larger fruit overall with averages of 187g at 2.0 m and 208 g at 2.5 m. The top of the tree had a larger proportion of big fruit ranged from 240-300g. However, the distribution at 2.0 m and 2.5 m was still variable, thought to be contributed to by the presence of axillary fruit. This was supported by the SD's which increased with canopy height meaning the top of the tree had greater variability that the bottom.

Red colour distributions showed that colour was variable at all heights within the tree. However, SD's were smaller at the top of the tree compared to the bottom meaning the variation was reduced in top for colour. The minimum colour was approximately 30-40% red colour, which was measured at the bottom of the canopy (0.5 m). The maximum colour reached 90-100% red and was measured at all parts of the canopy. The overall average colour of each height slowly increased by approximately 4% going up the tree. However, fruit at the top of the tree showed a slight reduction in the average red colour with more fruit coloured between 50-70% compared to the 2.0 m zone. The black line on each distribution graph outlines 40% red colour, the level for market acceptable colour for 'Scifresh'.

Dry matter content in 'Scifresh' ranged from 13 to 18.5 % at all heights throughout the canopy. The average dry matter content slowly increases with height up the tree going from 15.9% at 0.5 m to 16.5% at 2.5 m. The normal distribution pattern stayed consistent between the different heights. SD decreased with canopy height from 0.5 m to 2.0 m showing less variation in DMC with height, however, the top zone of the tree (2.5 m) showed slightly more variation (higher SD) caused by slightly more fruit containing high dry matter (17-18%).

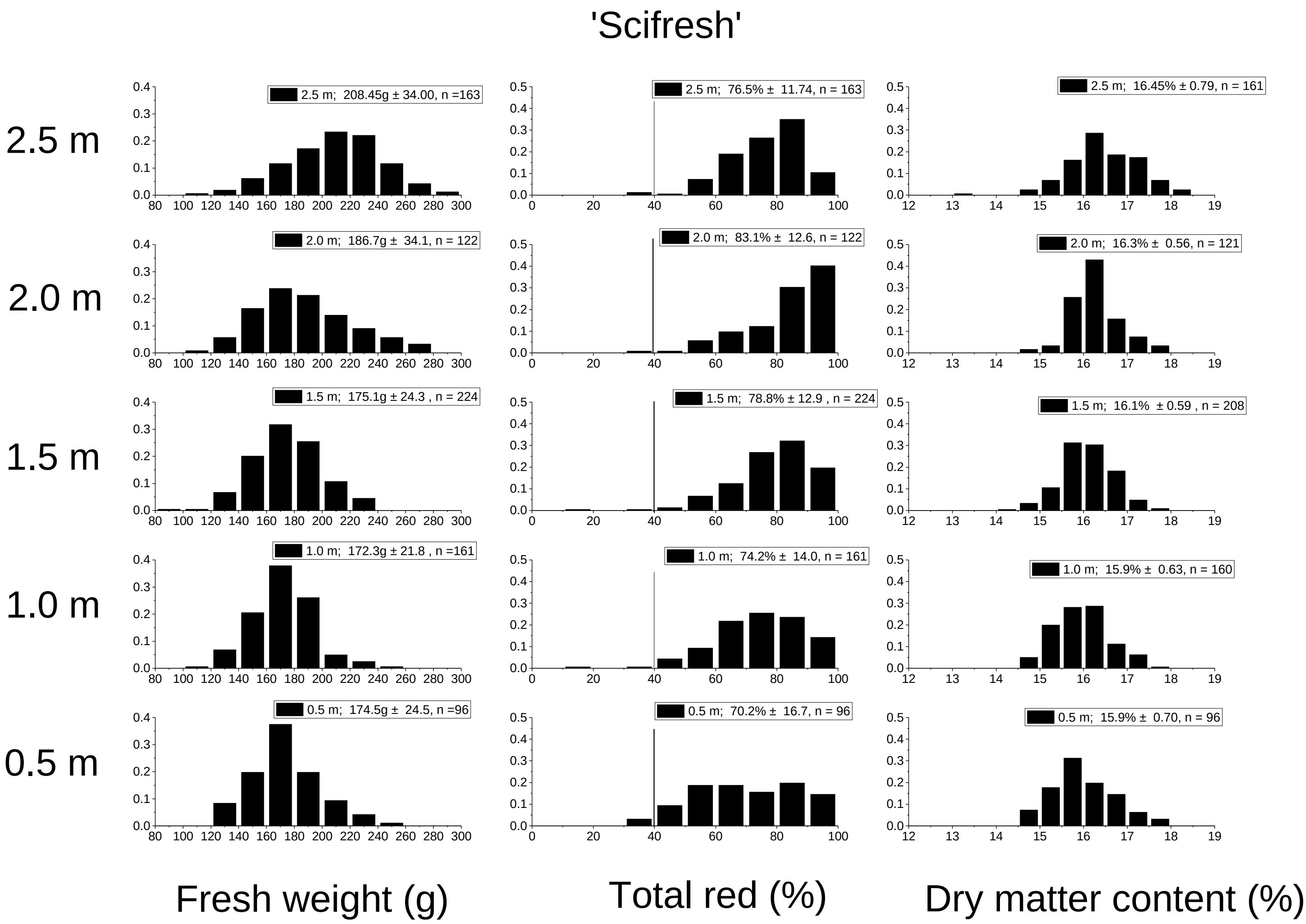


Figure 43. Fruit fresh weight, colour and dry matter content distributions for 'Scifresh' in 2019. Distributions are for different heights throughout the canopy by quality attribute. Each distribution is made up of fruit from both row spacing and tree design treatments. Distributions are annotated with the average value for each quality parameter, (MFW, TR% and DM%), standard deviation and number of observations (n).

4.4 Discussion

4.4.1 Light environment

The light transmission within trees grown in a two-dimensional planar cordon system has not previously been quantified. Given the scarcity of information, this research aimed to measure how light is distributed throughout the tree to then compare how this may differ to other current conventional systems.

Total light interception is directly related to yield (Palmer et al., 2002). However, the sufficient penetration of light throughout an apple canopy improved fruit size, colour, soluble solid content, dry matter content, photosynthetic capacity and floral bud formation (Heinicke, 1964; J. Jackson et al., 1971; J. E. Jackson, 1970; J. E. Jackson et al., 1977; I. Warrington et al., 1996).

After reviewing the literature in apple, information regarding the amount of light energy received at various layers within the canopy is limited. Alternatively, results are presented as percentage of total incoming radiation. This is not a quantitative determination of specific molar light energy received by the plant whether it be in any point in time or over an extended period. This limits the potential comparisons made between different tree designs and growing regions across the global industry.

The literature in a global context reports that light transmission changes with position in the canopy and suggests that a minimum of 25-30% of full sunlight is required for adequate photosynthesis and productivity (Heinicke, 1964; S. Tustin et al., 1989; I. Warrington et al., 1996). However, in a New Zealand context, Tustin et al. (1988) found that fruit weight declined below optimal size (> 160g) at 12% - 15% of incident PPFD (S. Tustin et al., 1988). The architecture of traditional large apple canopies causes an excessive amount of shading, leaving a large proportion of the tree exposed to less than 30% of the incident light (TL Robinson, 1983). Planting densities have increased and the trees have become smaller with the use of dwarfing rootstocks, however, because of the three-dimensional nature, the same problem of excessive shading continues creating variability of fruit quality. Attempts at reducing this problem have included summer pruning and the use of reflective mulch, however, to permanently address light distribution limitations, a shift to a two-dimensional planar canopy must be considered. This would enable a higher light irradiance to all parts of the apple tree and therefore greater proportions of high quality fruit in terms of fruit size, colour and dry matter content.

For relevance to the industry and to other literature in different growing conditions in the world, the data in this thesis is presented as the amount of energy received in terms of photosynthetic photon flux density (PPFD) (Section 7.3.1). We discovered that light within a two-dimensional canopy is distributed with significantly higher PPFD values at the top of the tree in comparison to the bottom of the tree. PPFD peaked at two parts of the day at approximately 12:00hr and 16:00-17:00hr, approximately 1.5hrs and 2.5hrs before and after solar noon. This biphasic pattern is caused by a significant drop in PPFD during the afternoon when the sun sits directly above the canopy. The very top of the tree is well illuminated at this time of the day and inflicts shading upon the rest of the canopy causing a dramatic dip in PPFD.

The average amount of energy received by the plants (PPFD) did not differ between the 2.0 m (227 µmol/m^2/s = RG, 145 µmol/m^2/s = 'Scifresh') and the 1.5 m row spacing (244 µmol/m^2/s = RG, 138 µmol/m^2/s = 'Scifresh') (refer table 7). However, light transmission to the bottom zone of the canopy was greater at the 2.0 m row spacing at 76.9 µmol/m^2/s (12.6% of incoming radiation) compared to the closer 1.5 m spacing at 46.2 µmol/m^2/s (7.6% of incoming radiation) at the 0.5 m zone.

The light irradiance was greater in the Vertical tree design compared to the Vee tree design, however, the difference was significant in 'Scifresh' only (166 µmol/m^2/s = Vert, 117 µmol/m^2/s = Vee). This difference is likely to be caused by the different orientation of branching units in the Vee tree design making it harder for light to be transmitted to all parts of the canopy.

The 2.0 m Vertical canopy showed to have the best light environment in terms of irradiance. Light was distributed well throughout the entire canopy as all parts of the tree received upwards of 540 µmol/m^2/s (35% of total incoming irradiance) in 'Royal Gala' and 360 µmol/m^2/s (35%) in 'Scifresh'. Low PPFD levels (below 200 µmol/m^2/s or 28-30% of incoming radiation) were common within the bottom zones of the canopy however, frequent light flecks observed when in the trial orchard on multiple different occasions suggest the bottom zone of the tree is regularly receiving short bursts of high PPFD levels leading to the production of export market grade fruit.

4.4.2 Specific leaf weight of the planar cordon system

Specific leaf weight has been proposed as a good index of the light environment of current season/canopy position of leaves and net photosynthesis (Barden, 1978; Brown et al., 1997). Kuo-Tan Li (2004) looked at summer pruning in an attempt to improve light exposure. Within this study, they discovered that leaf material off thirteen year old 'Empire'/M.26 central leader apples, SLW ranged from approximately 4-10 mg/cm^2 (equivalent to 40-100 g/m^2) (Li et al., 2004). Previous canopy shade reduced the photosynthetic ability of the interior leaves and after re-exposure to high light levels after summer pruning, the leaf photosynthetic ability did not recover. Correlations suggest SLW increases from 4 – 10 gm/cm^2 with Pn from 6 -18 µmol/m^2/s in this study (Li et al., 2004).

It seems that the upper limit of specific leaf weight in apples is approximately 180 g/m^2 from young 'Royal Gala' primary shoot leaves grown in M9 rootstock (van Hooijdonk, Tustin, et al., 2015). A study from China looked at the pattern of SLW at different heights within an apple canopy using 15-year-old 'Red Fuji' trees in an attempt to regenerate what had become a micro-environmental deterioration of fruit quality because of the development of closed canopies. Although SLW levels were low (35-65 g/m^2) they discovered that SLW decreased from the top to the bottom of the canopies, sharply at 0.4-0.8 of the relative tree height (45-63 g/m^2) (Sun et al., 2016). Warrington et al (1996) presented SLW at inner and outer regions of six different canopy types and found that shaded leaved had a SLW of 70-80 g/m^2 while leaves on the outer tree reached a maximum of 128 g/m^2. This is following the theory that thinner leaves are found in more light limited situations which apple seems to follow regardless of the cultivar.

We found that for 'Royal Gala' and 'Scifresh', SLW increased with canopy height. Similarly to the results in Sun et al (2016), SLW tended to stay relatively consistent from the 0.5 m to the 1.0 m zone and then increased sharply from the 1.0 m zone to the top of the tree. SLW ranged from 87 g/m^2 in the bottom of the tree to 158 g/m^2 in the top of the tree for 'Royal Gala' and 89-175 g/m^2 in 'Scifresh' (Table 7), showing improvements when compared to the literature for a three dimensional tree architecture where SLW in apples often ranges from approximately only 40-130g/m^2 (Li et al., 2004; Sun et al., 2016; I. Warrington et al., 1996). SLW is cultivar dependent having different morphology characteristics in terms of leaf thickness in this case.

From literature reporting the correlation between light environment, photosynthetic potential and SLW (Li et al., 2004; S. Tustin et al., 1989) the photosynthetic potential of leaves in most locations within planar cordon canopy increase with height which is likely to be attributed to an improved light environment (Barden, 1978; Brown et al., 1997). By comparing the SLW values from this study to the literature above, results suggest the leaves at all parts of the canopy have the photosynthetic potential to support high quality fruit development. One indication of this is the narrow range in specific fruit quality traits seen at different positions in the tree when compared to other literature, especially in terms of red colour and DMC in other tree designs.

4.4.3 Leaf area index (LAI)

LAI is m^2 leaf area / m^2 of land occupied by the tree. A common LAI of a tree on a dwarfing rootstock would be approximately 3 (Tustin et al., 2001; Wünsche et al., 2000). J. Palmer (1992) estimated LAI for different planting densities (2000-8333 trees/ha) in 'Golden Delicious' and discovered LAI ranged from 1.4 at the lowest tree density to 3.3 at the highest. Light interception ranged from 49-83% and yields ranged from 35-83 t/ha again from low to high planting densities (J. W. Palmer et al., 1992). Leaf area index at a whole tree level (uprights as well as the cordon) within the planar cordon system (Vertical canopy only) ranged from 3.1 – 4.0 at the 1.5 m spacing and 2.6 – 3.1 at the 2.0 m row spacing. LAI at the 1.5 m spacing tended to be slightly higher due to the reduction in ground area used and consequently produced higher yields. In comparison with the literature, the planar cordon system produced higher LAI and significantly higher yield (J. W. Palmer et al., 1992) at 132-159 t/ha at 1.5 m (planting density of 2222 trees/ha) and 115-121 t/ha at 2.0 m row spacing (planting density of 1667 trees/ha) for 'Royal Gala' and 'Scifresh'.

4.4.4 Canopy heights influence on fruit quality

Variability in fruit quality is an aspect that growers are always looking to reduce. Studies have shown that fruit quality (fruit size and colour) improves with good light environment in terms of percentage of total incoming radiation (J. Jackson et al., 1971). The three-dimensional nature of a conventional orchard limits the access of light throughout the entirety of individual trees. Thus causing more variable light irradiance from the inner part of the tree to the outer.

The effect a fruits position on the tree has on fruit quality and its correlation to light distribution has been discovered a number of times within the literature (J. Jackson et al., 1971; I. Warrington et al., 1996). Tustin et al (1988) showed that fruit fresh weight and soluble solids concentration (SSC) increased with canopy height. MFW and SSC was higher in the outer compared with the inner horizontal canopy position which was strongly correlated to transmission of photosynthetic photon flux density (PPFD), which in this case was maximised at approximately 47% PPFD at fruiting sites (S. Tustin et al., 1988). J.E. Jackson (1977) found that fruit from the inner parts of the tree differed significantly from those from the outer portions of the tree in terms of, fruit size, colour and storage behaviour in 'Cox's Orange Pippen' apple.

What the literature lacks is an assessment of the entire fruit population, quantifying fruit quality traits in fresh weight, red colour and dry matter content and then relating that to the total light energy received by different positions of the plant in terms of the daily light integral. This method has enabled the ability to test for variability in fruit quality within an orchard (population mean and SD) down to each individual fruit produced.

Generally, fruit quality improved from the bottom of the canopy to the top. However, the significant improvements came from the comparison of the 0.5 m zone and the 2.5 m zone. Little differences were seen throughout the middle sections of the canopy in terms of fruit size, dry matter content and colour. The differences observed between the fruit harvested from the upper and lower part of the tree are primarily because of the microclimatic differences experienced. Upper canopy fruit in both cultivars were redder. This is because the higher irradiance in the upper canopy enhances anthocyanin development in apple peel (Awad et al., 2001; Steyn et al., 2004). However, from the literature reviewed, it was unknown how DLI or PPFD correlated to red colour percentage of fruit. By doing this on an entire population of fruit it was discovered that as DLI increased (from 3-40 mol/m^2 DLI), the percentage of red colour on the fruit also increased from 60-95% red colour in places.

In this planar cordon training system, fruit quality at the bottom of the canopy was not affected. Although the general trend suggested fruit quality was greater in the top portions of the tree, it does not suggest fruit quality was poor at the bottom of the tree. Figures 42 and 43 suggest close to all of the fruit harvested at the bottom zone of the canopy met market requirements in terms of colour (89% in 'Royal Gala' and 97% in 'Scifresh'). The average dry matter content was exceptionally high (14.9% in 'Royal Gala' and 15.9% in 'Scifresh') and average fruit size at the bottom of the canopy was consistently greater than the total industry average in both 'Royal Gala' and 'Scifresh' ('Royal Gala': bottom of canopy – 162 g, industry average – 158 g, 'Scifresh': bottom of the canopy – 175 g, industry average – 148 g) (see Appendix, table 8).

4.5 Conclusions

A significant portion of an apple tree’s canopy is exposed to shading during most daylight hours each day, and consequently, such shade influences productivity and variability of fruit quality. Shading often results from competition between trees and between branches on the same tree. Often the more complex a canopy may be, the more intra-canopy competition for light has an effect on its productivity.

This chapter elucidated how light was transmitted throughout a two-dimensional planar cordon canopy and how this influences fruit quality including size, colour and DMC. The vertical orientation of the planar cordon architecture allows trees to grow in their natural direction and by doing this it is allowing high light to be transmitted to all parts of the canopy. Light levels were higher in the upper parts of the canopy however, light levels at the bottom of the canopy were high enough at key parts of the day to support high quality fruit production (large fruit size (average approximately 170g), high percentage of red colour and high dry matter (>15%)). Greater light utilisation in this planar cordon canopy lead to an improvement in fruit quality in terms of fruit size, colour and dry matter. Fruit quality improved from the bottom to the top of the tree (‘Royal Gala’ - MFW: 162 g to 188 g, red colour (%): 86% to 93%, DMC: 14.9% to 15.6%. ‘Scifresh’ - MFW: 174 g to 208 g, red colour (%): 70% to 83%, DMC: 15.9% to 16.5% - ‘Scifresh’) which is likely to be attributed with the corresponding increase in light. Low quality fruit was minimal with the majority of the crop at each height meeting market requirements in terms of colour and consumer preference in terms of fruit size and dry matter (packout of total fruit population: ‘Royal Gala’: 87%, ‘Scifresh’: 93%).

Researchers should be aware of the importance of presenting appropriate units of light in terms of interception and distribution. Some questions regarding critical energy requirements in light for high quality fruit production and canopy development need further research. Additional further studies are required to identify differences in internal fruit quality at different light environments and the potential for a reduction in post-harvest disorders such as soft scald.

5 General discussion and conclusions

In current orchard training systems, light interception is maximised at 55-60% of the total seasonal radiation which is limited by wide inter-row spacings for machinery access, reducing the amount of plant canopy per unit of land area. This level of light interception limits orchards to maximum yields of approximately 100 t/ha by using a linear regression developed by (Palmer et al., 2002). This relationship suggests an upper limit yield of 169 t/ha at 90% light interception, slightly greater that the maximum yield ever recorded of 163 t/ha on a mature 'Granny Smith' orchard (Warrington, 1994). To overcome this limitation, a change in orchard design and tree architecture is required, reducing the amount of light energy lost to the ground. The planar cordon canopy (Figure 3) was designed in a two-dimensional manner to reduce row width (to 1.5 m or 2.0 m) and to provide an easy to manage canopy which ultimately improved the overall light environment in terms of irradiance and the total daily light integral. This planting system was developed at Plant and Food Research Centre, Hawkes Bay. This thesis is made up of two research components, the first is examining the relationship between fruit density and fruit size, quality and return bloom while the second component examines the light environment within the planar cordon canopy and how that influences fruit quality.

- The objective of the first research component was to quantify the relationships between tree and branch unit fruit density and its influence on fruit size, quality and return bloom, necessary to inform commercial management of planar cordon orchards. Using a wide range of fruit densities (1 to 28 fruit /cm^2 BCA) per upright to assess the response to fruit size, colour and return bloom in the following season was assessed.
- The objective of the second research component was to be able to understand and describe the light environment within the planar cordon system and how this influences fruit quality. This research was completed by measuring how light is distributed within the canopy using several different sensors to record the incoming PPFD at different heights within the tree as well as the total energy received by each position within a day. Comparisons were made between different row spacing treatments (1.5 m and 2.0 m) and different tree designs (Vertical and Vee). This study gave us a better understanding how light in terms of average PPFD, DLI and the percentage of incoming radiation influences fruit quality.

Within the literature, it is commonly reported that fruit density influences fruit size, colour and a number of other different quality traits in apple (Castro et al., 2015; Embree et al., 2007; Jakopič et al., 2013; McArtney et al., 1996; Meland, 2009; Racskó, 2006; T. Robinson et al., 2012). The majority of research has been performed in conventional, three-dimensional tree structures on a whole tree basis (measured by fruit number per trunk cross-sectional area (fruit/cm^2 TCA)). The effect of fruit quality has been measured at a range of different fruit densities between 2 and 17 fruit/cm^2 TCA. All of which show that with increasing fruit density, fruit quality declines in terms of fruit size (Castro et al., 2015; Jakopič et al., 2013; Meland, 2009) and colour (Meland, 2009). It is suggested that the optimum fruit density for a tall spindle structure per tree is 8 to 12 fruit/cm^2 TCA depending on the cultivar (Castro et al., 2015; Elfving et al., 1993; Embree et al., 2007; McArtney et al., 1996; Wright et al., 2006). The planar cordon canopy at a whole tree level showed tendencies of fruit weight to decline with increasing fruit density per TCA. However, fruit weight at the maximum fruit density (16-18 fruit/TCA) averaged no lower than 150g in 'Royal Gala' and 170g in 'Scifresh' suggesting the tipping point, or maximum fruit density, before fruit size declines dramatically, has not yet been met in these planar cordon canopies, and further work is required to elucidate this as the trees mature.

Crop loading studies at a branch unit level (base cross-sectional area, BCA) are limited and only originated in 1995 from Lauri along with the development of the 'mafcot' wheel, used as a tool to standardise spur extinction (fruit density management technique) (Lauri et al., 1995). In 2009, Tustin then looked at the concept of regulating floral bud distributions within the tree, in order to manipulate fruit set and early fruit development to more optimally use dry matter resources (S. Tustin et al., 2012). Breen (2016) also looked at the difference between artificial spur extension (ASE) and unmodified trees in terms of differing bud loads between 2, 4, and 6 buds/cm^2 BCA which at harvest equated to fruit densities of 3.3 to 5.2 fruit/cm^2 BCA. The results showed that in both ASE and unmodified trees, fruit at lower densities were significantly larger (ASE =184 g, Unmod = 169 g) than fruit at higher densities (ASE =170 g, Unmod = 156 g) on tall spindle trees (Breen et al., 2016). At an upright level on the planar canopy, it was discovered that as fruit density increased (from 1 to 28 fruit/cm^2 BCA), fruit size, colour and return bloom was not influenced in both 'Royal Gala' and 'Scifresh' during the 2018 and 2019 seasons. The second research component examines fruit size and colour in more detail however, from this study we can confirm that fruit density, up to 28 fruit/cm^2 BCA in a planar cordon system does not reduce fruit size, red colour percentage and return bloom from observing two consecutive growing seasons. Thus suggesting that the crop loading metrics for these planar cordon canopies differs to the conventional tall spindle system. Overall, an important finding highlighted in the difference in effects on fruit quality between tree and branch unit crop loading. The slightly different outcomes discussed above suggests the two approaches should be used together to achieve the best results in terms of fruit size and colour.

The distribution of light can often be limited within a conventional tall spindle tree (J. Jackson et al., 1971; J. E. Jackson et al., 1977). Light distribution throughout the canopy plays an important role when it comes to affecting flowering, fruit size and colour (Hirst et al., 1990; J. E. Jackson, 1970). The three-dimensional tree shape restricts light entering the inner parts of the canopy and consequently, fruit quality declines (J. Jackson et al., 1971). Studies have shown that the light levels need to be above a critical minimum of approximately 25-30% of incoming radiation for the production of high quality fruit (Heinicke, 1964; J. Jackson et al., 1971; J. E. Jackson et al., 1977; Seeley et al., 1980). However, in a New Zealand context, Tustin et al. (1988) found that fruit quality started to decline at 12% - 15% of incident PPFD (S. Tustin et al., 1988).

The common method of describing light in the literature is to express data as percent of full sun or incoming radiation. This is not descriptive of the amount of light energy received by the plant whether it be in any point in time or over an extended period. For apple, it is unknown how DLI received by fruit at different positions in the canopy modifies fruit size, colour and DMC at harvest. Work from Tustin *et al* (1989) found that light increased with height in an Ebro-Espallier trellis in 'Granny Smith'. Light levels reached 50 μmol/m^2/s and rarely exceeded 400 μmol/m^2/s for the three lowest trellis layers throughout the day while open sky readings ranged from 500 and 2200 μmol/m^2/s. Consequently, mean fruit weight and specific leaf weight decreased down the layers of the trellis which coincided with declining PPFD levels (S. Tustin et al., 1989). However, this study did not report DLI and its effects on the distributions of fruit size, colour and DMC. It was not reported how fruit were sampled for quality assessment. In Chapter 4, DLI was found to increase with increasing height in planar tree canopies, and was associated with increases in fruit size, colour and DMC in both 'Royal Gala' and 'Scifresh'. Unlike previous studies, improvement in fruit quality traits was quantitatively determined using a state of the art Compac grader + InVison to measure all fruit within the experiment, thereby providing robust quality assessment.

We discovered that light within a two-dimensional canopy is distributed with significantly higher PPFD values at the top of the tree in comparison to the bottom of the tree.

The average amount of energy received by the plants (PPFD) did not differ between the 2.0 m (227 μmol/m^2/s = RG, 145 μmol/m^2/s = 'Scifresh') and the 1.5 m row spacing (244 μmol/m^2/s = RG, 138 μmol/m^2/s = 'Scifresh'). However, light transmission to the bottom zone of the canopy was greater at the 2.0 m row spacing at 76.9 μmol/m^2/s (12.6% of incoming radiation) compared to the closer

1.5 m spacing at 46.2 μmol/m^2/s (7.6% of incoming radiation) at the 0.5 m zone. The light environment was greater in the Vertical tree design compared to the Vee, however, the difference was significant in 'Scifresh' only (166 μmol/m^2/s = Vert, 117 μmol/m^2/s = Vee). The 2.0 m Vertical canopy showed to have the best light environment. Light was distributed well throughout the entire canopy as all part of the tree received upwards of 540 μmol/m^2/s (35% of total incoming irradiance) in 'Royal Gala' and 360 μmol/m^2/s (35%) in 'Scifresh'.

Low PPFD levels (below 200 μmol/m^2/s or 28-30% of incoming radiation) were common within the bottom zones of the canopy however, frequent light flecks observed when in the trial orchard on multiple different occasions suggest the bottom zone of the tree is regularly receiving short bursts of high PPFD levels.

The DLI, percentage of incoming radiation and the SLW increased with canopy height in both 'Royal Gala' and 'Scifresh' which supported the results found in 15 year-old 'Red Fuji' (Sun et al., 2016). SLW ranged from 86 to 174g/m^2 from the bottom to the top of the canopy which is high considering the highest reported SLW in apples was 180 g/m^2 from young 'Royal Gala' trees (van Hooijdonk, Tustin, et al., 2015). DLI ranged from 5-10 mol/m^2 in the bottom zone of the canopy and 15-25 mol/m^2 in the top of the canopy which provided similar outcomes shown in Tustin (2001).

Fruit quality improved from the bottom of the canopy to the top. The significant improvements came from the comparison between the 0.5 m zone and the 2.5 m zone. Little differences were seen throughout the middle sections of the canopy in terms of fruit size, dry matter content and colour. Upper canopy fruit in both cultivars were redder which is likely to be due to the higher irradiance in the upper canopy which enhances anthocyanin development in apple peel (Awad et al., 2001; Steyn et al., 2004).

Interestingly, fruit quality at the bottom of the canopy was still market acceptable. Although the general trend suggested fruit quality was greater in the top portions of the tree, it does not suggest fruit quality was poor at the bottom of the tree. Fruit harvested in the bottom zone of the canopy met market requirements in terms of colour (87% of the crop in 'Royal Gala' and 93% in 'Scifresh'). The average dry matter was exceptionally high (14.9% in 'Royal Gala' and 15.9% in 'Scifresh') and average fruit size at the bottom of the canopy was significantly greater than the total industry average in both 'Royal Gala' (planar cordon = 169g, industry average =158g) and 'Scifresh' (planar cordon = 178g, industry average =148g) (see appendix table 8).

There were a number of strengths to this study giving us further understanding around the productivity of these planar cordon systems. One of the main advantages was the robustness of the data collected. Within this study we had the ability to measure every piece of fruit that was harvested from the trial orchard using the InVision grading system. This meant we were about to analyse extremely high sample numbers reducing the need to rely on sample averages. This sampling method gave us a wide range of information from fruit weight, colour profiles, diameter, grade and more of each individual apple.

As well as strengths, there were limitations to this study. Firstly, because 'Royal Gala' is a sport of 'Gala' it often suffers from reversion causing the fruit to be under coloured. This limitation would have skewed the results causing distribution and sample averages to be less than what they might have been without reversion. This was noted and explained in detail earlier on in the thesis to make this limitation clear. Secondly, due to resource limitation the leaf area index measurements were only completed on the Vertical tree design. It is hard to judge what the LAI of the Vee canopy would be, however, knowing that the Vee canopy contained two extra uprights than the Vertical tree design it is suggested that the LAI would be slightly higher in comparison. Another limitation to this study was the sampling method of the light readings. The light environment of each treatment was completed over 4 different days. Four days is not representative of the entire season and is only seen as a snapshot in time. With unlimited resources, light would be recorded over the entire season from bud break to leaf fall. The final limitation would be the timing of this trial. The trees had filled approximately 80% of their allotted space meaning the results are not representative of a training system under full production. This condition would give a better understanding of the peak performance of the planar cordon canopy.

5.1 Conclusions

In summary, the objectives set out at the start of this project have been met. Through the analysis of instantaneous PPFD, DLI and the percentage of incoming radiation at different heights within the canopy, it is now understood that although the light energy received declines from the top to the bottom of the canopy, it does not get to a level that is detrimental to fruit quality (fruit weight, red colour and dry matter content). This study shows that a planar cordon canopy in its 5th leaf was intercepting a higher proportion of incoming radiation than a mature slender spindle at conventional row spacing (86% vs 44% of total incoming radiation in the fifth leaf). This led to exceptionally high yield for this age of canopy (159 t/ha - maximum yield recorded in this study). Even at these high levels of light interception, the light distribution within the entire canopy was acceptable, leading to high fruit quality (fruit weight, colour and dry matter content) even in the lower parts of the canopy. This is probably down to superior canopy design with obvious light wells creating sufficient light in low regions of the tree. The data from these 5th leaf canopies tends to support the initial hypothesis that 85-90% light interception is possible without threatening light distribution causing a decline in fruit quality. As these canopies mature to reach full development, the target yield of 170 t/ha of high-quality fruit according to this data would appear achievable. This would create a paradigm shift in canopy design for modern fruit growing. This new understanding of the light environment in a 2D planar cordon canopy gives an opportunity to further expand the physiological limits of the modern apple tree with more advanced canopy development.

This canopy design with narrow row spacing, dwarfing rootstock, a cordon with multiple upright fruiting branches and light wells within is unique in the world of fruit growing. The metrics of fruit density at both an upright branch- and tree-level basis require readjustment in a 2D planar cordon system. Therefore, further investigation into a new crop loading metric is required to identify an optimal fruit density for this planar tree design. This study showed that fruit number per TCA can be higher than current recommendations on a slender spindle tree (18 fruit/cm^2 TCA compared to 10-12 fruit/cm^2 TCA). It was discovered that the maximum fruit density before fruit size, colour and return bloom declines has not yet been met. The study of fruit number per BCA showed that even branches with fruit numbers of up to 28 fruit/cm^2 BCA were still able to produce fruit of export quality and size. We need to be mindful that although each individual upright branch has certain cropping metrics, we also need to take heed of the total fruit load of each tree as measured by either fruit per TCA or fruit per total BCA. This study has clearly demonstrated that the metrics of a planar canopy are different to a slender spindle, require further analysis under a mature cropping scenario, but give promise that higher level of branch efficiency is possible with this new canopy system. These findings are only the beginning of what will potentially become industry-changing research. Further work in this area will help a shift in mind set, leading to what could be a new design for highly productive orchards.

5.2 Further directions and recommendations:

- The performance of a new training system can only be truly understood after several years at full production. Continued research on these planar cordon trees would give the industry conclusive evidence as to how well this system performs on a long-term basis.
- Further investigation is needed into the effects the planar cordon planting system has on the internal fruit quality of apples. As seen in this thesis, the variation of external quality has been improved and thus it is suggested that internal quality will improve along with the potential reduction of postharvest disorder susceptibility.

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7 Appendix

Average fruit size comparison (g) between the Future Orchard Planting System and the commercial industry.

Table 8. Average fruit size comparison (g) between the Future Orchard Planting System (grown on M9 rootstock from bi-axis planar cordon planting system) and the commercial industry (grown on a range of rootstocks and training systems throughout the industry) average for 'Royal Gala' and 'Scifresh' in 2018 and 2019 seasons (AgFirst, 2019).

Mean fruit weight (g)	'Royal Gala'	Industry Average	'Scifresh'	Industry Average
2018	186	164	199	171
2019	169	158	178	148