Understanding the light environment within a planar cordon cherry system and its relationship to fruit quality and fruit set.

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Abstract

New planting systems for cherry trees being investigated in New Zealand, are using reduced inter-row spacing to increase overall light interception, and two-dimensional planar architecture for increasing light distribution through the canopy. As fruit quality is thought to be dependent on the proportional irradiance (light transmission) experienced by the tree's reproductive structures, these new planting systems are expected to increase fruiting sites and in turn the yield, producing high-quality fruit throughout the canopy. However, in the case of cherries, the level of understanding around both the light environment, and fruit quality distribution using these systems is largely unknown. Therefore, eight-year-old 'Sweetheart' cherry trees trained as a planar cordon and spaced at either 1.5 m or 2 m between rows were used to investigate the effects of the light environment within the canopies over the 2020-2021 season on fruit set and fruit quality was evaluated at harvest.

Light measurements at four vertical positions within these canopies were taken at 5-minute intervals, from flowering (November 2020) through to harvest (January 2021). Photosynthetically active radiation readings recorded were then used to calculate the daily light integral (DLI). The average canopy DLI for all positions and treatments was found to decrease from flowering through to harvest, using a best fit polynomial model, DLI started at 25 mol m^{-2} d^{-1}, and ended the season around 5 mol m^{-2} d^{-1}. Variation due to row spacings became evident later in the season, with average monthly DLI higher in the 2 m rows in November and December than in the 1.5 m rows. Vertical position within the canopy had a high correlation with light penetration, with the lowest vertical position (1 m from the ground) in a 2 m row having an almost equivalent mean light environment to the second highest (2 m from the ground) vertical position in a 1.5 m row spacing.

Yield, soluble solids concentration (SSC), fruit set and leaf area were all shown to be positively influenced by increased DLI, while diameter was slightly negatively influenced. This influence was generally true for vertical position in the canopy also. Early season DLI had the greatest influence on yield, mid-season DLI had the greatest influence on SSC, and late season DLI had little influence on either fruit set/number or on fruit quality.

Introducing reflective mulch into these planar canopy systems was found to improve the light penetration into the lower canopy, however only significantly in the 2 m row spacing. There was little to no influence on fruit quality, fruit set or return bloom.

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In challenging times my father, Desmond recently passed away before he could see the completion of this thesis. So this one’s for you, Dad.

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Chapter 1: Introduction and Background

Prunus avium, or sweet cherry is a flowering plant in the rose family, Rosaceae. It is native to a large area, including the British Isles south to Morocco and north to Norway. As well as Northern Iran, Northern Africa, and Western Asia, and a small isolated population in the western Himalayas. The species is widely cultivated in many countries, including three regions in New Zealand.

As a temperate fruit crop, sweet cherries produce the best crops in areas with cold winters and warm summers. Approximately 700-800 hours of chilling <7°C (Utah Model) are needed for dormancy breaking and optimum flowering, along with 7000-9000 growing degree hours (GDH) (Alburquerque et al., 2008). A measure used to approximate growing heat summation calculated as a cumulative sum of hourly temperature above a threshold, excluding extreme temperatures for each hour of the day. Hence, parts of New Zealand such as Otago and Hawke's Bay are suitable places for growing cherries.

1.1 Industry background

History

Sweet cherry was brought to New Zealand by European settlers in the mid to late 1800s. By 1870 cherries had become naturalised with wild populations growing in New Zealand (New Zealand Plant Conservation Network, 2021). Commercial production of cherry in New Zealand began in the 1920s but did not become viable as an industry until 1985. At this stage it was estimated that there were 236 hectares (ha) of cherries being grown commercially, predominantly in Blenheim. By 1988, the area grown in cherries had increased to 329 ha, producing 1100 tonnes in total. At this time, the common planting density was 670 trees/ha trained in a free-standing centre-leader or vase. The leading varieties were Dawson and Bing (Gillespie, 1988).

Production

Since the 1980s the predominant growing region for cherries has been Central Otago, with lesser amounts in Hawkes Bay, and a small number in Marlborough. Low rainfall and reduced wind in spring/summer made Central Otago a preferable region to Marlborough for cherry production (Paterson, 2003).

Currently New Zealand currently produces around 4,500-5,000 tonnes of cherries each year from approximately 1000 ha, with an estimated 726 ha of this planted in Central Otago (Fresh Facts, 2020). Productivity averages 10-15 tonnes per hectare ($t\text{-}ha^{-1}$) in

New Zealand at mature orchard potential (Paterson, 2003). Cherries have a light first harvest after 3 to 4 years. Volumes increase each year until maturity, at around 6 to 8 years of age (Whenua Māori, 2021). While data is limited for 2-dimentional growing systems in New Zealand, yield estimates for first year fruiting sweet cherries grown as a planar cordon were between 1.1 and 2.1 tonnes per hectare (Stanley et al., 2018).

There are around 90 growers, mostly in Central Otago (85%) due to the district's superior growing conditions. Plantings have been expanding at around 30 to 50 ha per year but is accelerating even more as capital from new sources emerges (Ministry of Business Innovation and Employment, 2018).

Cherries in New Zealand are grown solely for the fresh market. There is no real processing market apart from small-scale juicing (New Zealand Horticulture Export Authority, 2014). New Zealand's fresh cherry exports were $68.9 million in 2019 (Fresh Facts, 2019), with Taiwan as the major export market accounting for 35% of the value sold, and China as the next largest market. New Zealand's cherry sector is very small in the scheme of global production (0.1%) and international trade (0.5%). Its niche competitive advantage is the ability to supply high-quality and super fresh cherries for the main festive season in Asia – Chinese New Year. For this seasonal window, there are only four Southern Hemisphere producers that can service this market, with larger producers Chile and Australia offering any real competition. In New Zealand's case, 80-85% of total production is exported fresh and the majority of that (90%) is destined for Asian countries that celebrate Chinese New Year (Williams, 2019).

Industry representatives

Summerfruit NZ is the industry body that represents the interests of approximately 230 apricot, cherry, nectarine, peach and plum growers. They apply a commodity levy for cherries of 1% at the first point of sale. Their activities are guided by a business plan and governed by their board. Key areas are industry profile and administration, research and development, export and compliance, New Zealand market and communication and education. They have set a goal to increase industry value to $250 million by 2035, of which cherry will be the dominant crop.

Growing Conditions

Cherries require deep, well-drained soils. They can be grown on soils that would not normally be considered suitable for arable cropping provided there is suitable irrigation and nutrient management. Trees need to be protected from wind, which can damage the fruit (Micke et al., 1977).

Bees, usually from hired hives, pollinate cherry orchards. Some varieties need to be cross-pollinated by a different variety of cherries, so it is necessary to plant more than one variety in the orchard (MSU Extension, 2022).

The risk of disease in cherries is high, particularly with a bacterial blast, *Pseudomonas syringae*, which can kill large numbers of young trees when the orchard is being established. Infection tends to follow environmental stress, like frost injury. Silver leaf, caused by *Chondrostereum purpureum,* which starts in pruning wounds or broken branches can also cause tree deaths and spreads rapidly if not addressed (Texas A&M University, 2022).

Rain covers are needed in areas where there is a possibility of heavy rain during summer, especially close to harvest when it can cause fruit to split (Warner, 2012). Consequently, growers are now tending towards installing rain covers or closed protection systems.

Labour

Labour has been identified as one of the major constraints in the cherry industry, particularly post Covid-19. The industry has survived by employing backpackers and Recognised Seasonal Employer (RSE) workers, but with borders currently closed to non-residents, this cohort is in limited supply. Strategies to attract young people into the industry and retain them have been a major focus of Summerfruit NZ, and this is evidenced by the “Handpicked” campaign launched in 2020.

Variety choice and training systems

Almost all of the main cherry cultivars grown commercially in New Zealand have been imported from the breeding programme in Summerland, Canada (McGrath Nurseries, 2022). Some of the main commercial cultivars grown in New Zealand are: Sonnet®, ‘Stella’, Romance®, Kordia®, ‘Lapins’, Skeena®, ‘Sweetheart’, Regina® and Staccato®, and these are almost all grafted on ‘Colt’ rootstock and grown as centre-leader trees.

While the predominant training system is still a conventional centre-leader tree, new developments of planar canopy systems are being planted throughout the main growing regions in New Zealand. In particular, the two-dimensional upright fruiting offshoots (UFO) system developed by Matthew Whiting at Washington State University has been taken up by early adopters (Hansen, 2011).

Returns

Estimated returns for the local market from mid-November to Christmas are around $10-$15/kg retail before packing, packaging and freight are added. Buyer demand for cherries drops after Christmas. At the same time, big volumes come online from the Otago orchards. This sees prices fall to around $4.50-$5.50/kg to the grower. Returns to the exporter in 2017 were estimated at $20/kg and have now fallen to around $17/kg. These figures are approximate because prices vary based on fruit size, fruit firmness and appearance (Whenua Māori, 2021).

Health Benefits

Sweet cherry (*Prunus avium L.*) is one of the most popular and appreciated temperate fruit, not only for its sensory and nutritional properties, but also for its content in bioactive compounds. Consumption of sweet cherries brings beneficial effects on health, which include prevention and modulatory effects in several chronic diseases such as diabetes mellitus, cancer, cardiovascular and other inflammatory diseases. The presence of natural polyphenolic compounds with high antioxidant potential might drive and partly explain such beneficial effects (Faienza et al., 2020). However, much of the research suggests that large volumes of fruit would need to be consumed to make a big difference in overall health.

Chapter 2: General literature review and research objectives

The purpose of this general literature review is to cover the main aspects relevant to this thesis. A more detailed literature review will be included in the introduction of each chapter.

Planar canopy systems

Untouched in its natural environment, sweet cherry will grow as a central leader tree with one main, upright trunk a spiral of branches, usually beginning 60-90 cm above ground, and repeated every 45-60 cm up the trunk (Marshall, 2018). Apical dominance is strong, and the tree is vigorous in its vegetative growth, and non-precocious allowing trees to be able to establish a large "footprint". In a managed orchard, growers provide intervention to limit vegetative growth, improve precocity and increase fruiting spur density. Despite these interventions, cherry production is labour-intensive, traditionally requiring tall ladders and significant effort to reduce vigour in the tops of trees to improve light to the lower parts of the canopy (Lang, 2019).

Many training systems are used around the world, but generally will fit into one of two types of canopies; a central leader or a multi-leader which are three-dimensional systems, or a planar canopy system which is a two-dimensional system where the depth of canopy is significantly narrower than the other two systems.

Some examples of three-dimensional growing systems are Vogel Central Leader (VCL), Kym Green Bush (KGB) and Spanish Bush (SB). Two-dimensional systems include Super Slender Axe (SSA), Tall Spindle Axe (TSA) and Upright Fruiting Offshoots (UFO) (Long et al., 2015). In this thesis, I specifically focus on a type of training system that is a modified version of the UFO with considerably closer row spacing and with two cordons instead of a single cordon.

This type of planar canopy system is a fully trellised system that optimizes labour efficiency and fruit quality by creating a narrow fruiting wall that is precocious and easy to harvest and prune. It produces vertical fruiting stems, which are grown from a horizontal axis (Lang, 2019). The goal is to achieve a full canopy of uniform spacing and vigour to fill the positions of the fruiting wall as completely as possible (Lang, 2016b). The major focus of this training system is increasing light distribution through the canopy to promote increased yields, and high quality fruit throughout the canopy, and to increase light interception by bringing the row spacing closer together. The principles of the canopy architecture are described in Figure 1 by Tustin and van

Hooijdonk (2014). While these authors explain the system for an apple canopy, the same applies for cherry.

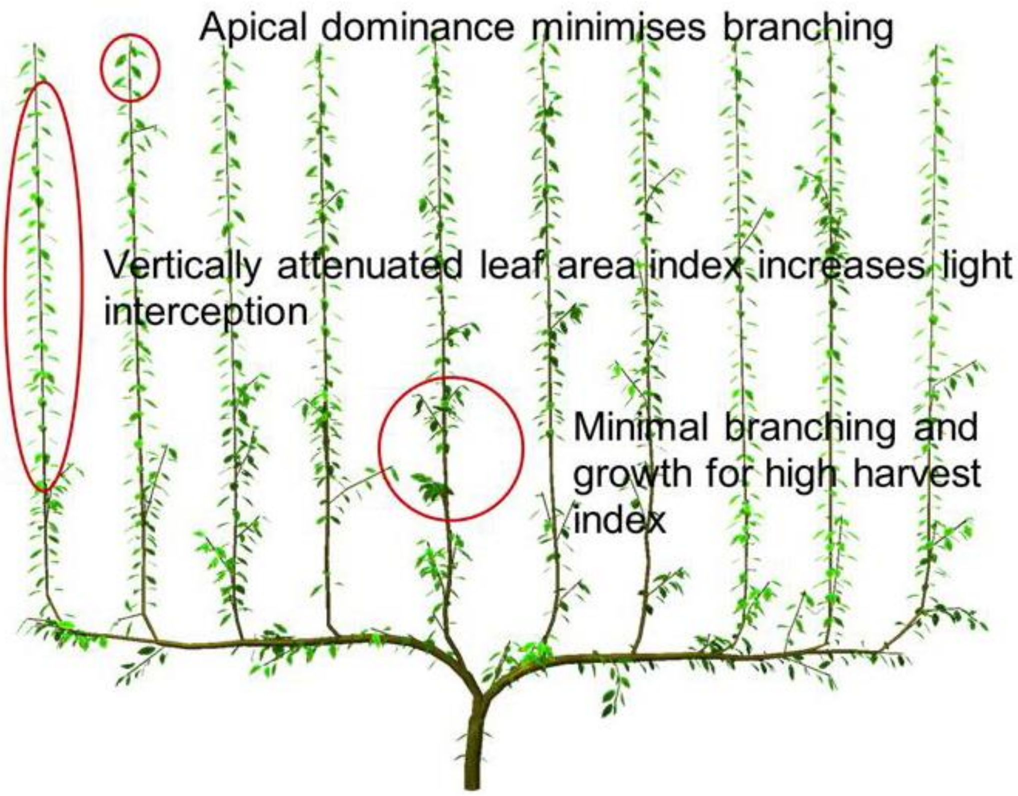

Figure 1: Planar prototype concept apple tree, highlighting the physiological properties considered important for the maintenance of the structure and function of the tree when used in new planting systems layouts. Tree dimensions when grown on M.9 rootstock are envisaged as a 3 m cordon, 0.8 m above ground with 10 upright fruiting stems, spaced 30 cm apart along the cordon. Upright fruiting stems will be 2.7 m in height, so the overall tree canopy height is 3.5 m above the ground (Tustin and van Hooijdonk, 2014). Used with permission.

Light in perennial fruit crops

Total light interception in some fruiting systems is well documented, particularly in apple orchards. Modern conventional and high-density apple orchards have been found to intercept up to 55% (Palmer et al., 2002), and 66% (Robinson, 2007b) of incoming radiation. If light interception can be increased, without compromising light penetration into the centre of the canopy, there is the potential for significant increases in both yields and fruit quality (Palmer et al., 2002; Stanley et al., 2016). This statement provides the basis for the need to understand the light environment within the canopy as well as just the overall light interception.

Jackson (1970) demonstrated that in all apple canopy systems studied, the upper third of the canopy exhibited the highest numbers of flowers and fruit, and the highest amount of sunlight. This study also examined the light environment and the need for high light for optimal colouration of apples, and therefore indicated that light penetration into the tree, is just as significant as overall light interception for fruit quality traits. Palmer (1981) indicated also, that light interception only gives an indication of the yield potential. The actual yield can be influenced heavily by within-tree shading.

Training systems have been an important part of manipulating the architecture of the tree to improve the light penetration within tree canopies (Willaume et al., 2004). High density growing systems are becoming increasingly more important in commercial production. A higher density of trees means smaller trees and earlier orchard productivity. They aim to increase labour efficiency by simplifying picking, thinning and pruning processes. There is also the potential for greater yields and quality, as well as being able to enhance control over uniformity of fruit quality (Lang, 2005). When trying to understand orchard systems and tree architecture, a potential barrier, particularly for stone fruit in New Zealand, is the lack of access to dwarfing, or low vigour rootstocks. Most stone fruit are grown on either peach or plum seedlings, and cherry is most commonly commercially grown on 'Colt' rootstock. Grossman and DeJong (1998) evaluated various training methods in peach, and their photosynthetically active radiation (PAR) interception throughout the day. They concluded that the ideal system would be one that had high light interception, but low growth potential. As New Zealand currently doesn't have access to low vigour scions or rootstocks for commercial use, this is something that may need to be further understood or developed.

Many studies have been able to quantify light environments, but most appear to be focused on total light interception. In a study by De Salvador and DeJong (1989) looking at peach training systems, three systems and/or spacing variations showed various light interception values between 69 and 74% with the traditional "Open Vase" shape as a comparator. One study on peach started to look into tree spacing on modified centre-leader and Y canopies, and the effect on light interception at three vertical positions. They found that row spacing did have an effect, but it was unclear from the study whether this was significant at each level in the canopy (Singh and Kanwar, 2004).

A paper by Zhang et al. (2015) studied the method of measuring canopy light interception as PAR. They determined that as sunlight changes in angle and intensity throughout the day, light interception is variable over time. Therefore, they concluded that 2 hours prior to solar noon was the optimum time to obtain mean PAR under direct light conditions. However, to fully understand the light environment, it may be more practical to use daily light integral (DLI), which encompasses the total available light over one day (Faust and Logan, 2018). DLI is increasingly becoming a tool used by horticultural scientists to understand irradiance in plant systems. DLI may be the best way of understanding the total light environment in planar systems, as the light environment changes a lot during the day depending on the sun angle in these systems. DLI data has been published for a few horticultural crops, but to the best of my knowledge, none for cherry.

Light in cherry production

Sweet cherry productivity is low, averaging 10–15 t ha^{-1} in New Zealand at mature orchard potential for traditional planting systems (Paterson, 2003). To increase productivity, new orchard systems should be designed based on underlying physiological principles. These include the yield x light interception relationship, effects of canopy light transmission on fruit traits (Stanley et al., 2016) increasing early cropping and resource allocation in favour of fruit development, and the efficiency of the light intercepted (Monteith, 1977). The planar canopy concept applies these principles to improve light interception, and therefore increase yields and fruit quality beyond the present production limits of conventionally grown sweet cherry orchards (Stanley et al., 2018).

Within the literature search, there were limited reports of light interception in cherry canopies. An upright fruiting offshoot (UFO) canopy design of seven-year-old sweet cherry orchards with 3-m inter-row spacings intercepted approximately 55 to 66% of incoming radiation, depending on canopy height (Zhang et al., 2015). This was comparable with results we have previously published (Scofield et al., 2018). In this work a similar planar canopy of five-year-old trees showed an average light interception of between 63.6 and 71.9% depending on the row spacings (which were closer together than the UFO study). This was compared with a commercial centre-leader system of the same age which only intercepted 42.6% of incoming light. In addition, the amount of light penetration in these centre-leader systems was also significantly lower overall.

DLI in flower bud initiation is also important, and appears to be limited in centre-leader systems, as flower numbers are frequently low in the inner canopy. In contrast, the planar cordon system has been developed to ensure more even light distribution throughout a canopy in comparison with a centre-leader conventional tree. The minimum DLI needed for cherry floral bud initiation and induction is unknown. However, conventionally grown cherries have shown to have as little as 1% light penetration into the centre of the canopy (Scofield et al., 2018). Therefore, assuming a DLI in Central Otago of 50 mol m^{-2} d^{-1}, the centre of the canopy would have much less than the 1.94 mol m^{-2} d^{-1} for flower initiation and 3.25 mol m^{-2} d^{-1} for flower development that is required in geraniums (Armitage et al., 1981). While not specifically focused on DLI, work on shading in apples has tried to quantify the level of shading responsible for fruitlet retention, as well as flower bud formation. Jackson and Palmer (1977), not only saw a reduction in fruitlet reduction in the current year, but also found increased shading had greater effects on the flowers that set fruit in the following year. The highest level of shading was set at 11%, far above the current estimate of a conventional cherry growing system. Many studies have focused on the importance of percentage of incoming radiation, whereas other factors may also need to be considered. For example, much of the research is focused on the 400-700nm range of light, however other wavelengths of light, particularly in highly shaded areas of the canopy also need to be taken into account, as well as possibly the diffuse/direct proportions of light that is not covered in this thesis.Another aspect to consider at this point, is the other factors at play during the bud initiation stage, namely the multiple demands on the sinks of carbon within each part of the plant i.e., leaf area, dry matter accumulation, shoot branching, bud number, and root growth (Wang et al, 2020). As well as in the case of cherry, as with other tree fruits, fruit and buds concurrently developing within the growing season (Milyaev et al, 2021).

2.1 Research Objectives

The planar cordon system was designed around light capture maximisation, for optimum fruit yields and quality. From experience, and confirmed by the literature outlined above, it is known that light interception and distribution affect fruit quality and development.

However, there is little understanding of these planar cordon systems in cherry and whether they are achieving adequate within-canopy irradiance, particularly in the lower part of the canopy and at narrow row spacing. Therefore, this Master's thesis is aimed at developing an understanding of the following:

- Firstly, the light within these systems needs to be quantified, down to a spur level at various vertical positions in a canopy to understand the within-canopy irradiance.
- Then, the fruit quality at these same spur sites needs to be examined to gauge how the position and the light exposure affect fruit quality. This should then provide insight into whether within-canopy irradiance influences fruit quality.
- Lastly, if the light is compromised, and there is a reduction in fruit quality, is there a way to improve quality by use of reflective mulch technologies?

The first two points lead to the hypothesis posed below

<u>The bud position in the planar cordon canopy does not affect fruit set or fruit quality.</u>

If the hypothesis was to be rejected, the third question will begin to understand whether easy manipulation can then work to modify the environment to such a degree that the bud position in the planar cordon canopy does not affect fruit set or fruit quality.

To test this, three experiments were designed and will correspond with chapters 4, 5 and 6 respectively:

Experiment 1 - Light environment from flowering through to harvest in planar cordon canopies

In the 2020 season, the daily light integral within an experimental orchard of 'Sweetheart' cherry trees growing in planar cordon canopies was measured at harvest time. In the 1.5-m row spacing, the light capture in the lower canopy was very low, and close to the supposed limit of light needed for bud initiation. However, it is not known how the light environment changes over the season, and in particular late in the season when floral bud initiation occurs. To measure this, in 2021, PAR sensors were set up in different positions within 'Sweetheart' cherry planar cordon canopies with 1.5-m and 2-m row spacings to measure DLI for the duration of one season (September to March). Replications of 6 trees of each row spacing were tracked over the season, with 16 sensors within each tree.

Experiment 2 - Fruit set, leaf area and fruit quality

Within all blocks, 32 sites were identified as regions within a canopy. These corresponded to positions on neighbouring fruiting shoots (Figure 5), either side of 16 sensors. Within these 32 sites, individual spurs were tagged at flowering. Flower number and fruit set per spur was determined, and at harvest, measurements of fruit soluble solids concentration, flesh firmness and size were obtained. At seasonal canopy maturity, a leaf area per spur was calculated based on a model of leaf length to leaf area and spur leaf number. These individual spurs were then followed through a second year to gain return bloom statistics.

Experiment 3 - Reflective mulch use in planar cordon canopy systems

Extenday™ reflective mulch was installed from the fruit development stage of straw colour through to leaf fall on three of the trees used for experiment 1. These data were used to assess if light could be improved in the lower canopy. In the 2020 season, it was found that soluble solids concentration (SSC) was influenced by canopy position, but fruit size was not. It was hypothesised that during the early season the light environment in the lower canopy is sufficient during cell division, but that later in the season in a full canopy, SSC is affected by excess shading.

Chapter 3: General Materials and Methods

These general materials and methods explain the initial trial design and fruit quality measurements. More detailed methods are given methods section of 4, 5 and 6.

Trial Design: Block layout

An experimental planting of ‘Sweetheart’, ‘Lapins’ and ‘Staccato’ trees was established at the New Zealand Institute for Plant and Food Research Ltd (Plant & Food Research), Clyde Research Orchard, Central Otago, New Zealand site (-45.202339, 169.313040) in Spring 2013. These trees were planted at a spacing of 3 m between trees and either 1.5 or 2 m between rows (2222 and 1667 trees per ha, respectively) (Figure 3: Visual representation of the overall trial block, a planar cordon cherry block of three varieties: ‘Sweetheart’, ‘Lapins’ and Staccato®, planted in 2013 at the Clyde Research Centre, Plant & Food Research. With 3 m between trees, and either 1.5 m or 2 m between rows. The replicated trial consists of twelve rows, four of which are measurement rows, with guard rows on either side. Tree axes were grown until they reached approximately 1.6 m in height, when they were laid at a ~20° incline from horizontal to form two cordons per tree. At this stage, the distal end of the cordon was pruned to a downward-facing bud. This was done to encourage up to six upright stems per cordon to develop (Figure 5). As they developed, stems were trained either

Figure 2: A single ‘Sweetheart’ cherry planar canopy tree in December 2020, trained in an upright position. Part of the larger trial block, a planar cordon cherry block of three varieties: ‘Sweetheart’, ‘Lapins’ and Staccato®, planted in 2013 at the Clyde Research Centre, Plant & Food Research.

vertically (Figure 2) or as a narrow vee with uprights set alternately at either + or – 10 to 12° from vertical.

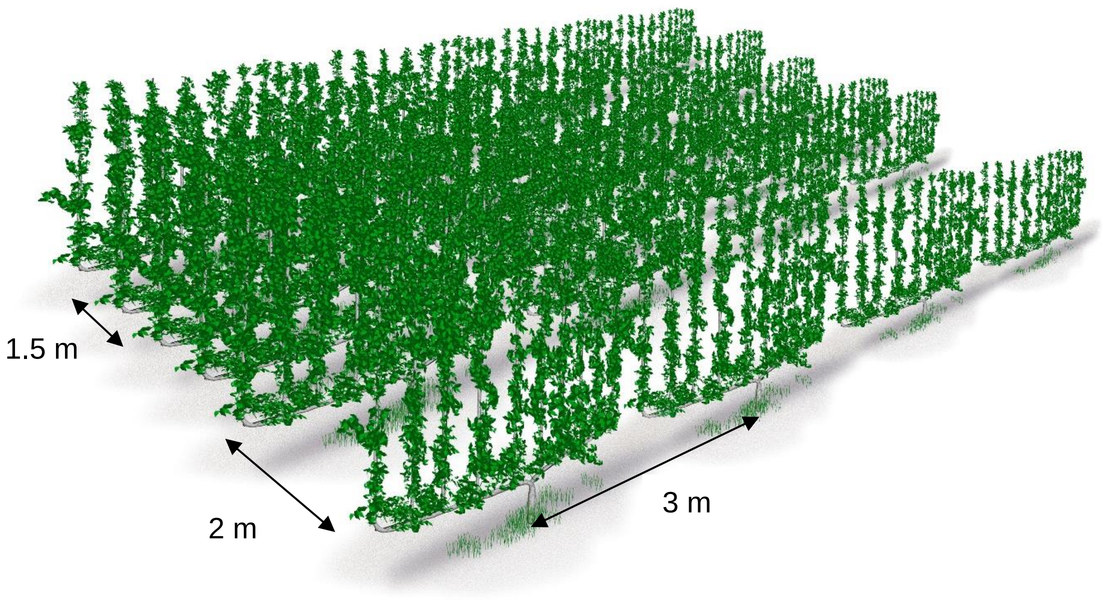

Figure 3: Visual representation of the overall trial block, a planar cordon cherry block of three varieties: ‘Sweetheart’, ‘Lapins’ and Staccato®, planted in 2013 at the Clyde Research Centre, Plant & Food Research. With 3 m between trees, and either 1.5 m or 2 m between rows. Credit Tony Corbett, PFR.

This trial was split into four replicated randomised blocks. Within these blocks, six plots of three trees of ‘Sweetheart’ trained vertically were selected, three in a 1.5 m row, and three in a 2 m row based on a similar number and size of upright shoots (Figure 4). Of these six plots, two were selected for a reflective mulch treatment, and the other four were left with no treatment as shown in Figure 4 depicted in yellow or orange.

H	H	H	L	L	L	H	H	H	S	S	S
H	H	H	L	L	L	H	H	H	S	S	S
H	30	H	L	36	L	H	42	H	S	48	S
H	H	H	L	L	L	H	H	H	S	S	S
S	S	S	H	H	H	L	L	L	L	L	L
S	29	S	H	35	H	L	41	L	L	47	L
S	S	S	H	H	H	L	L	L	L	L	L
L	L	L	S	S	S	S	S	S	H	H	H
L	28	L	S	34	S	S	40	S	H	46	H
L	L	L	S	S	S	S	S	S	H	H	H
H	H	H	L	L	L	L	L	L	S	S	S
H	27	H	L	33	L	L	39	L	S	45	S
H	H	H	L	L	L	L	L	L	S	S	S
L	L	L	H	H	H	H	H	H	L	L	L
L	26	L	H	32	H	H	38	H	L	44	L
L	L	L	H	H	H	H	H	H	L	L	L
S	S	S	S	S	S	S	S	S	H	H	H
S	25	S	S	31	S	S	37	S	H	43	H
S	S	S	S	S	S	S	S	S	H	H	H
L	L	L	H	H	H	H	H	H	L	L	L
L	6	L	H	12	H	H	18	H	L	24	L
L	L	L	H	H	H	H	H	H	L	L	L
S	S	S	L	L	L	S	S	S	H	H	H
S	5	S	L	11	L	S	17	S	H	23	H
S	S	S	L	L	L	S	S	S	H	H	H
H	H	H	S	S	S	L	L	L	S	S	S
H	4	H	S	10	S	L	16	L	S	22	S
H	H	H	S	S	S	L	L	L	S	S	S
S	S	S	S	S	S	H	H	H	H	H	H
S	3	S	S	9	S	H	15	H	H	21	H
S	S	S	S	S	S	H	H	H	H	20	H
H	H	H	L	L	L	S	S	S	L	L	L
H	2	H	L	8	L	S	14	S	L	20	L
H	H	H	L	L	L	S	S	S	L	L	L
L	L	L	H	H	H	L	L	L	S	S	S
L	1	L	H	7	H	L	13	L	S	19	S
L	L	L	H	H	H	L	L	L	S	S	S
L	L	L	H	H	H	L	L	L	S	S	S

Figure 4: Overall trial block, a planar cordon cherry block of three varieties: ‘Sweetheart’ (H), ‘Lapins’ (L) and Staccato® (S), planted in 2013 at the Clyde Research Centre, Plant & Food Research. With plots of three trees used in this experiment highlighted in yellow and orange. Orange colour depicts the plots that had Extenday™ installed, and yellow plots are without Extenday. Three plots were in rows 2 and 8, which are 2 m row spacing, and three plots are in rows 5 and 11, which are 1.5 m rows.

Within each plot, four pairs of adjacent upright shoots were selected (8 shoots total) (Figure 5) as generally representative of the remainder in the block. The preference was to select these from the centre tree of each plot. On each upright, four spurs were selected and tagged at each of four vertical positions, approximately 1.0, 1.5, 2.0 and 2.5 m above the ground (16 spurs per upright). Midway between each pair of adjacent uprights and at each vertical position, a horizontally orientated, upward facing PAR sensor was fixed (4 sensors per pair of uprights). In experiment 3, where reflective mulch was used, an additional downward facing sensor was used at each position.

Trial design: Plot layout

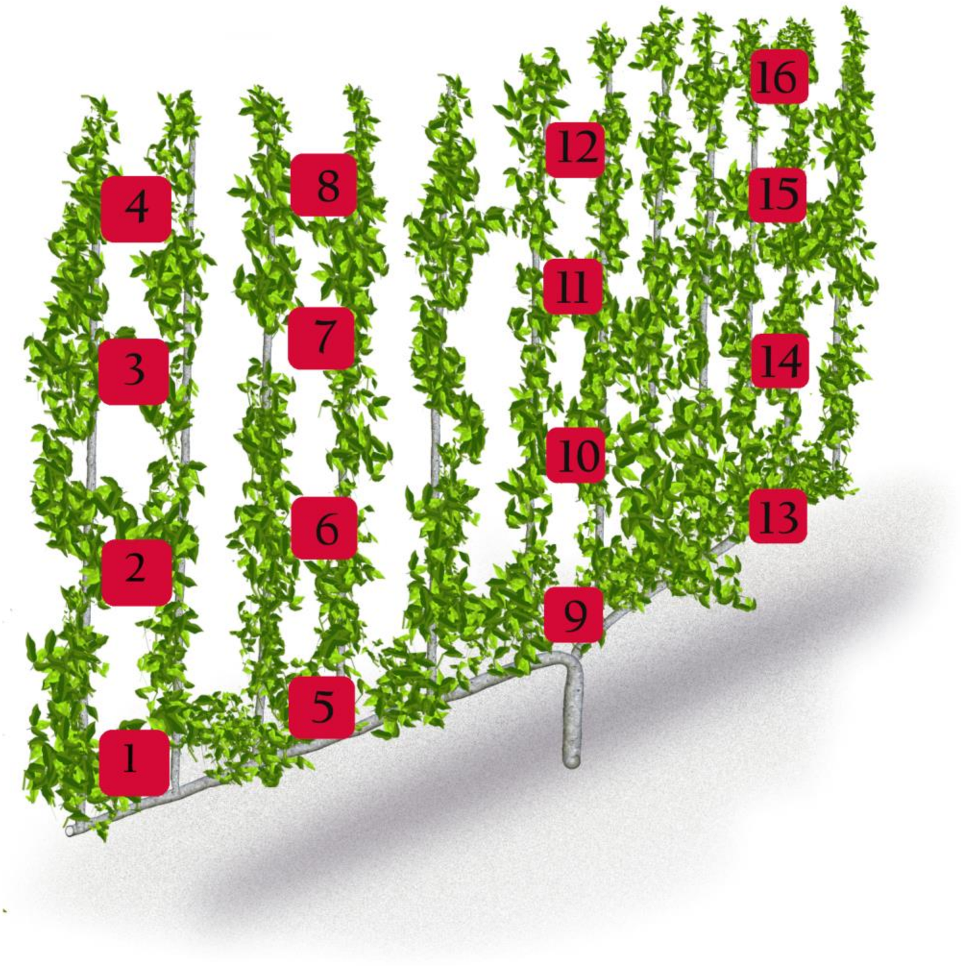

Figure 5: Vertical and horizontal canopy positions, numbered from 1 to 16 where PAR sensors were attached on horizontal wires within a planar cordon cherry block of three trees of 'Sweetheart' variety, planted in 2013 at the Clyde Research Centre, Plant & Food Research.

Shoots were tagged just before flowering, and would be used for all flower, fruit and leaf assessments as well as PAR measurements.

Photosynthetically active radiation (PAR)

At each of the 16 positions identified prior to flowering, a PAR sensor was placed (Tranzflo NZ Ltd, Hokowhitu, Palmerston North) (Figure 6). These sensors are designed similarly to the LI-COR sensors that have a cosine corrected design. Three sensors were placed on tall poles to measure above-canopy PAR. These sensors were connected to a CR850 logger (Campbell Scientific, Logan, Utah USA), with a channel relay multiplexer (Campbell Scientific) to accommodate the 19 sensors and connected to a 12V battery. The logger was programmed to read each PAR sensor every 10 seconds and log average readings of PAR every 5 minutes. Sensors were set to read one replication at a time for four to five days and then the whole array was moved to a new replication up until full leaf cover, and then again after leaf drop was starting to occur. Due to constraints of equipment, with 2 loggers and 19 sensors for each logger, a multiple day series rather than continuous measurement was achieved. However, two sets of sensors were able to capture plots within each row spacing within each time series, allowing these to be compared more accurately without day to day variation influences.

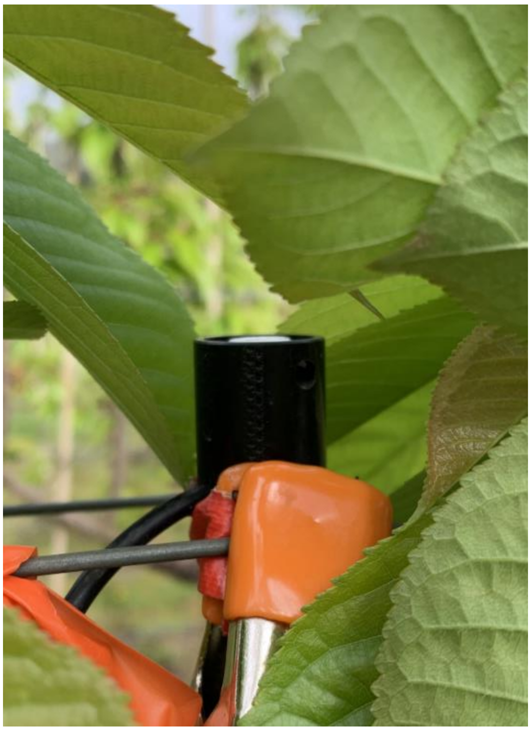

Figure 6: Photosynthetically active radiation (PAR) sensors developed in New Zealand by Tranzflo (Tranzflo, Palmerston North).

On reflective mulch treatments, both PAR from above and reflected PAR (sensors facing down) were measured.

Flowering and fruit set assessments

Figure 7: individually labelled spur sights within vertical positions in the canopy of a ‘Sweetheart’ planar system planted in 2013 at the Clyde Research Centre, Plant & Food Research.

Individual spurs were tagged prior to flowering (Figure 7), at each of the 16 sensor positions where available on all eight upright shoots. These spurs were selected based on a maximum distance of 200 mm from each sensor. Flower numbers per spur were counted and recorded, and then an initial fruit set prior to secondary fruit drop was obtained. A final fruit set was counted at harvest, and then fruit quality assessments were made. In terms of orchard level inputs, no crop manipulation was used, such as fruitlet thinning or leaf removal. However, a summer prune pre-harvest was done to make harvesting more efficient.

Fruit quality assessments

Fruit from each tagged spur on all plots were harvested once they were considered at commercial maturity. These were harvested into Plix® trays with barcoded identifiers (Figure 8). For each fruit, the maximum equatorial diameter (digital callipers), fresh weight in grams (Mettler Toledo, Columbus Ohio, USA), fruit firmness using a flat plate on the fruit texture analyser (GÜSS, Strand, South Africa) to gain a compression firmness with skin on, and total soluble solids (TSS) (ATAGO Pocket refractometer PAL-1 Tokyo, Japan) were measured. After the spur fruit samples were harvested, the total weight and fruit numbers were recorded for fruit remaining at each position that had been harvested into individually labelled punnets.

Figure 8: ‘Sweetheart’ fruit harvested in the field into labelled Plix® trays (above), and the equatorial diameter measurement with callipers (bottom).

Leaf area assessments

The leaf area to both leaf length and width relationships were determined at harvest by sampling 100 spur leaves from 'Sweetheart' plots on either side of the experimental plot. All leaves were measured for length and width and then put through ImageJ (Rasband, 2022) analysis to determine leaf area. After determining a close relationship (R^2=0.96), all leaves on tagged spurs were then measured for length.

Chapter 4: Seasonal and daily light variability within planar cherry canopies

4.1 Introduction

In both perennial and annual fruiting crops, there have been many studies investigating the association between total light interception and dry matter accumulation, yield and fruit quality (Jackson, 1970; Lakso, 1980; Flore and Layne, 1990; Tustin et al., 1992; Wünsche et al., 1996; Wertheim et al., 2001; Haverkort, 2007; Bastías and Corelli-Grappadelli, 2012; Breen et al., 2020). In addition, light is involved in the flower-initiation process. This is defined as all the necessary developments required for commitment by the meristem to create an inflorescence (Erez et al., 1966; Jackson, 1969; Okie and Blackburn, 2011; Peavey et al., 2020; Singh et al., 2020). In these studies, low light penetration into the canopy corresponded with poorer bud break rate, as well as reduced total percentage of bud break in peach, nectarine and apricot. In these situations it is possible that allocation favours vegetative components that increase light capture. It has also been suggested that the light availability may also affect plant-pollinator interactions. For instance, Cao et al. (2017) found that plants in an open canopy had an 8-11 times higher visitation rate by pollinators than those in a shaded canopy.

In many of the publications above, the focus has been on apple production systems, where it has been suggested that light penetration into the centre of the canopy has considerable economic importance, as shading of more than 55% of visible light reduces fruit quality, particularly fruit size and red blush percentage (Jackson, 1970; Musacchi and Serra, 2018). Conventional apple systems such as a centre-leader or multi-leader system have been estimated to receive around 55% of incoming light in the upper canopy, and as little as only 2-12% of the available light in the centre of the canopy (Tustin et al., 1998; Fouché et al., 2010; Kviklys et al., 2022). As annual fruit dry matter production and fruit yield are related to the total amount of sunlight intercepted by the orchard, higher density planting systems that achieve higher light interception generally produce higher dry matter and fresh weight yields of fruit (Wünsche et al., 1996; Palmer et al., 2002). The aim of high density planting is to accommodate the maximum possible number of trees per unit area to get the highest possible profit per hectare as quickly as possible without having a negative effect on fruit quality, along with the effect of soil and other management factors that arise from high densities (Choudhary et al., 2020). In a cherry orchard, a high density planting would be considered to be 750+ trees per hectare, but with dwarfing rootstocks this could easily be higher (Robinson, 2007a). In New Zealand, modern high-density commercial apple planting systems intercept 55 to 60% of incoming light and yield 100 t/ha, with potential to yield ~130 t/ha (Breen et al., 2016; Breen et al., 2020). Increasing light interception has the theoretical potential to greatly increase yields (169 t/ha at 90% LI) (Palmer et al., 2002), but risks reducing yield and fruit quality through reduced within-canopy irradiance (Jackson, 1970; Palmer, 1981; Wünsche and Lakso, 2000; Wertheim et al., 2001). This has been found in other fruit crops, such as avocado, where for conventional planting systems there is no yield benefit from increasing canopy light interception above 80–84%, and there may be yield decline at higher rates of orchard light interception (Wilkie et al., 2019). Therefore, high within-canopy irradiance, or otherwise explained, the light transmission through a canopy, is central to achieving optimal spur function and high fruit quality. While this thesis will not focus on whole block yield, it will link light with flowering and return bloom, which are of course an integral part of yield.

Light interception in stone fruit orchards is far less understood than in apple orchards, and much of the research is focused on traditional planting systems of centre-leader or vase trees (Giuliani et al., 2000; Stanley et al., 2014; Tang et al., 2015). However, as more high-density or close-row planted, two-dimensional systems are being planted in New Zealand, it is valuable to understand the total light interception in these canopies in the New Zealand climate. The term two dimensional refers to any growing system that has little depth i.e. any thin canopy and a planar system is the preferred technical and descriptive name for a growing system that has upright fruiting shoots from a horizontal cordon (Hughes, 2020) which will be discussed in this thesis.

Large differences have been observed between two apple growing regions in the Netherlands and Denmark with 15% more light in the Netherlands producing 17% more fruit with same age trees, with similar spacing and training (Wertheim et al., 2001). Incoming radiation increases with decreasing latitude, with Wageningen, Netherlands, Aarsley Denmark and Lincoln NZ showing incoming global radiation of 1.93, 2.13 and 2.67 GJ m^{-2} in the same year (Wagenmakers, 1995). Mean temperature differences, and higher leaf areas common at lower latitudes may also lead to higher potential production at lower latitudes, provided there is a limit in excessive shading inhibiting flower bud formation. Hence, studies on planar systems done elsewhere may not be transferable to New Zealand climatic conditions.

Several factors contribute to the amount of light intercepted by trees. Including solar angle, row orientation, canopy dimensions and structure, leaf area index (LAI) and the diffuse proportions of incoming radiation, where maximum diffuse radiation values occur with partly clouded skies. This is where radiation originates from all parts of the sky (Castañer et al., 2012). PAR is the segment of light radiation which is in the 400 to 700 nanometre wavelength range and is the portion of the light spectrum utilised by plants for photosynthesis (Zhang et al., 2012). The visible light spectrum, including the photosynthetically active radiation (PAR), constitutes about 46% of the global radiation (Weiss and Norman, 1985). When PAR is expressed on a quantum basis, it is given the special term photosynthetic photon flux density (PPFD), with units expressed as µmol m^{-2} s^{-1} (Wünsche and Ferguson, 2005).

As sunlight continuously changes angle and intensity during the day, the amount of light interception by the same canopy varies with the time at which it is measured. Light interception measured around midday may not be representative of crop light interception characteristics, especially for compact fruiting wall architectures which have relatively low light interception around midday (Zhang et al., 2015) therefore the aim of this experiment was to employ light distribution measurements throughout the day over multiple days in order to have a better understanding of how light is intercepted and distributed in a planar canopy throughout the growing season.

4.2 Materials and methods

4.2.1 Data collection

The plant material and experimental layout are fully described in the introductory methods. Briefly, six plots of three trees of ‘Sweetheart’ grafted on ‘Colt’ rootstock, with two cordons and up to 12 shoots trained vertically, were selected, three in a 1.5 m row, and three in a 2 m row based on their similar number and size of upright shoots. Of these six plots, two were selected for a reflective mulch treatment, and the other four were left with no treatment, which will be discussed within this chapter.

Measurements of light distribution were made between flowering (20th September) and early December (full leaf), during the 2020-2021 season. Data were collected using two Campbell scientific data loggers (Campbell Scientific, CR800, USA), each fitted with 16 quantum sensors (Tranzflo NZ Ltd, Palmerston North, NZ) for each block of cherry trees situated in an array of 4 vertical X 4 horizontal positions. Vertically, sensors were situated at 1 m, 1.5 m, 2 m and 2.5 m above the ground (Figure 5: Vertical and horizontal canopy positions, numbered from 1 to 16 where PAR sensors were attached on horizontal wires within a planar cordon cherry block of three trees of ‘Sweetheart’ variety, planted in 2013 at the Clyde Research Centre, Plant & Food Research. Horizontally, positions were situated between paired upright fruiting shoots selected based on their similar length and diameter where possible. This gave 32 possible plant positions. Using clamps, sensors were fixed to horizontal wires (Figure 6). A reference sensor was placed above the canopy at 4m height to gain total incoming radiation values.

Each replicate consisted of two arrays of 16 sensors; one set in a plot in a 1.5 m row, the other in a plot in a 2 m row. After each set of recordings was completed for a replicate, the sensors were moved to the next replicate, so that full treatment replication was made over time.

Each replicate was completed over at least 24 hours, but in most cases 2-3 days continuously. By moving these sensor arrays, measurements of each replicate were able to be repeated at around 10-day intervals over the season.

Tranzflo PAR sensors were calibrated against a Licor reference sensor calibrated by ScottTech (Hamilton, NZ) at the beginning of the season, to record the amount of photosynthetically active radiation incident on their sensing surface as photosynthetic photon flux density PPFD (µmol m^{-2} s^{-1}). An instantaneous measurement of PPFD from every sensor was recorded every 5 seconds and then integrated to record a sensor average every 5 minutes. These data were then integrated further to provide the daily light integral (DLI, mol m^{-2} d^{-1}).The rate at which quanta of light in the PAR wavelengths hit a surface is known as the photosynthetic photon flux (PPF), measured in µmol s^{-1}. To achieve comparative values over different surface areas, this is often quoted as a density PPFD (µmol m^{-2} s^{-1}), which is what these sensors were calibrated to provide.

From the 288 PAR readings per sensor per day, the light distribution pattern throughout the canopy was calculated in the form of the daily light integral (DLI) per sensor. DLI is the amount of PAR that accumulates over a 24-hour period, and is measured in moles of light per square metre per day (mol m^{-2} d^{-1}). It is calculated by taking the average PAR per day and multiplying by 86,400 (the number of seconds in a day) and divided by 10^6 (the number of µmol in a mol). For average canopy values, all sensors were aggregated to give an average DLI over a day for all sensors in each position within a canopy (16 sensors). This was used to give a representation of average within-canopy DLI over the period from the beginning of flowering to harvest (19^{th} September – 19^{th} January).

4.2.2 Statistical analysis

All statistical analysis and graphing outputs were performed using R version 4.0.1. Some of the outputs are given in the appendix.

Three models were evaluated for within-canopy DLI over a season. The following equations were used:

- Linearfit <- lm(DLI ~ Date, data= data)
- Splinefit <- lm(DLI ~ splines::bs(Date, 3) , data= data
- Polyfit <- lm(DLI ~ poly(Date,2), data= data)

ANOVA was performed between these three models to compare the best fit. In the graphing of these three models, a 95% confidence level interval was used for predictions of standard error. The correlation coefficient was calculated using the stat_regline_equation function in R with the formulas from each model.

For the daily and solar noon PAR, averages were taken and *p*-values calculated from ANOVA and least significance comparisons were gained using the Fisher-LSD test.

4.3 Results and discussion

4.3.1 Seasonal light environment

4.3.1.1 Average in-canopy DLI throughout a season

To confirm that there was no reduction in DLI over a season, the above canopy DLI values are shown in Figure 9. The lack of relationship between date and DLI is somewhat unusual, as the seasonal comparison in Utah varies by around 40-61 mol m^{-2} d^{-1} between March and June at 41.7°N (Bingham, 2011). This potentially can be explained by a number of factors: The readings below were taken on a daily basis, regardless of whether it was full sun, overcast or partial cloud cover. The majority of days had at least partial cloud cover. Daily, the DLI varies significantly throughout the season which could explain why the large variation may be influencing this lack of relationship.

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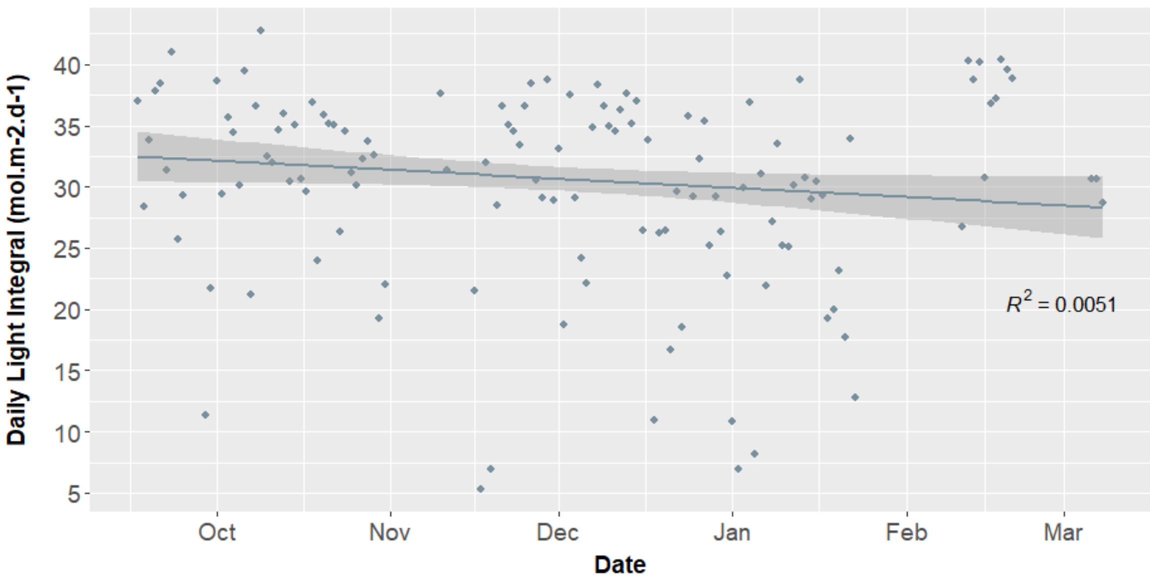

Figure 9: Linear model for daily light integral (DLI, mol m^{-2} d^{-1}) averaged daily from two sensors above the canopy measuring incoming radiation at the Clyde Research Centre over the 2020/21 season. The grey zone is the 95% confidence level interval for predictions from the model. R^2 is displayed for the coefficient of determination

By combining all the data points across the treatments of row spacing, and the vertical positions in the canopy, the average daily light integral (DLI) over the season decreased in what appeared to be a linear regression from late September through to late January (Figure 10: . Each point on the graph is an average DLI between all measurements taken on that day, including vertical position and horizontal position in the canopy, as well as across row spacing. This allowed a visual representation of what was happening across a whole block as an average in-canopy reading. The correlation co-efficient of determination of 0.32, while not high, does still show a downward trend.

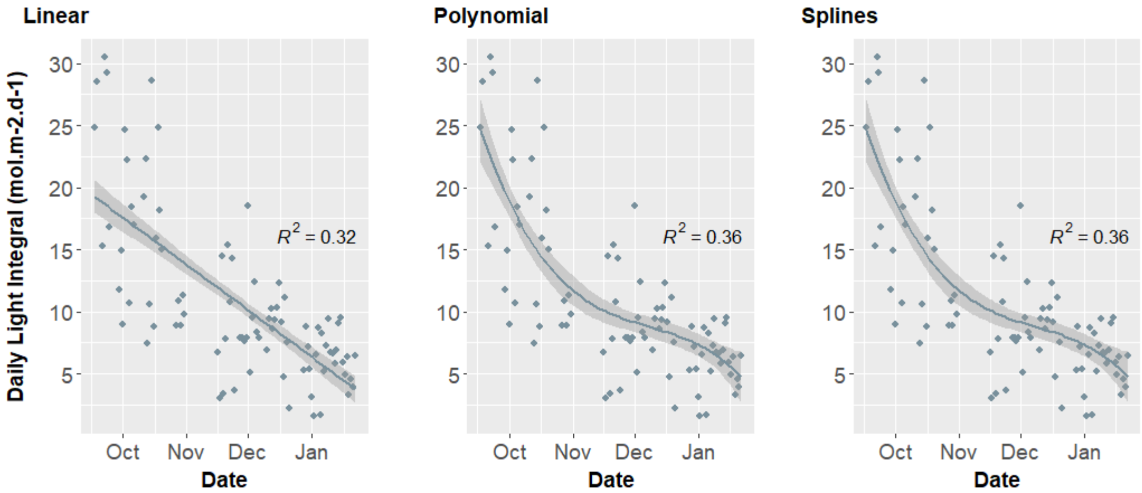

Figure 10: Linear, Polynomial and Splines models estimating differences in daily light integral (DLI, mol m^{-2} d^{-1}) averaged daily from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The grey zone is the 95% confidence level interval for predictions from the model. R^2 is displayed for the coefficient of determination

Given the variability throughout the vertical canopy, it is not surprising that the data do not show a strong fit with the model.

Given this variation between data points, to understand any other potential relationships, two other models were evaluated to understand if these data could be better interpreted using a spline model or a polynomial model were used to evaluate these same data. Figure 10: shows each model side by side, which both appear to have a slightly steeper reduction in the DLI early in the season, levelling out around

December once the trees are in full leaf, and then further dropping off after harvest as secondary shoot growth occurred.

These three models had a similar correlation coefficient, with R^2 values between 0.32 and 0.36, but with ANOVA, there was a significant difference between the linear model and both the spline and polynomial models ($p<0.001$), but no significance between the polynomial model and the spline model ($p=0.09$). Therefore the polynomial model was chosen for all further analyses.

4.3.1.2 Average light transmission throughout a season for different row spacings

When these data are divided into 1.5 and 2 m row spacing, the trend in light transmission through the canopy is very similar (Figure 11). It was predicted that the light transmission through the canopy would be higher in the 2 m row spacing, given that there is more opportunity over a day to be exposed to sunlight at various sun angles with wider row spacing. Generally over the season this is the case, but this is not statistically significant. Data collection after 12th December ceases for the 2 m row spacing due to logger malfunction, so unfortunately, it is unknown whether the light transmission trend continues, or whether differences occur between the DLI of canopies in different row spacings at around harvest.

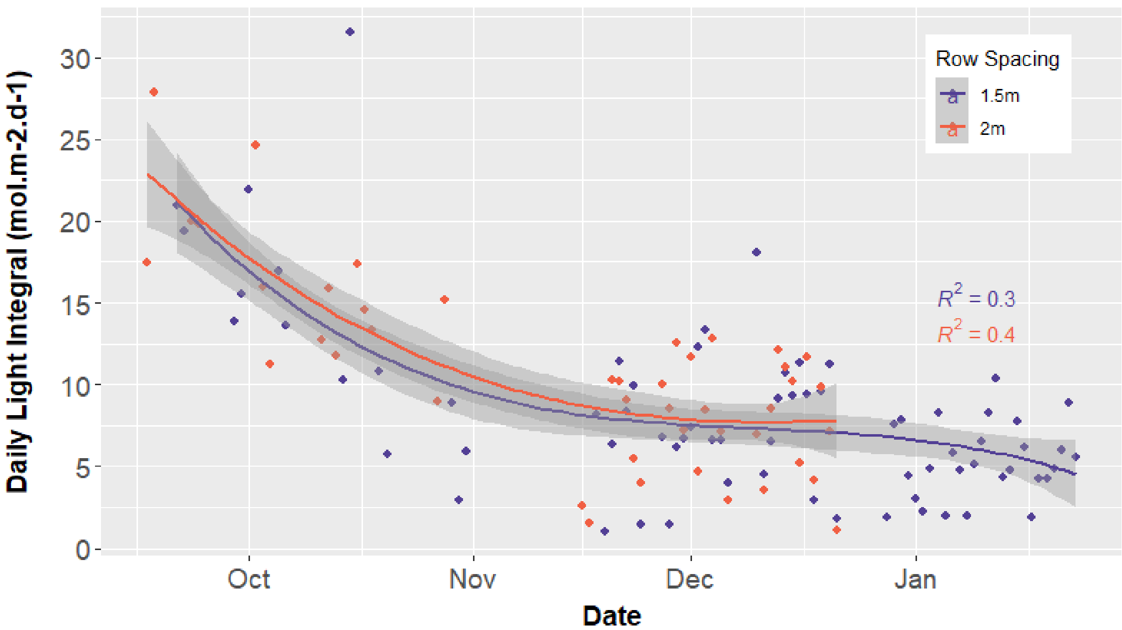

Figure 11: Polynomial fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) averaged daily from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The grey zone is the 95% confidence level interval for predictions from the model. R^2 is displayed for the coefficient of determination

Taking a monthly average of DLI gave a slightly clearer idea of whether there in fact were significant differences occurring between row spacings. October showed no significant differences between the 1.5 m and 2 m row spacings, but November and December did (Table 1 Average monthly daily light integral (DLI, mol m^{-2} d^{-1}) in October, November and December 2020 from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre. Means within a column that were significantly different based on LSD analysis are labelled with different letters. Meaning that early in the season, light penetration was not limited when leaf area was minimal, but as leaf area increased, the light penetration was affected more in the 1.5 m row spacing.

Table 1 Average monthly daily light integral (DLI, mol m^{-2} d^{-1}) in October, November and December 2020 from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre. Means within a column that were significantly different based on LSD analysis are labelled with different letters. The above canopy DLI reference is calculated on the average incoming readings for both row spacing sensor set ups.

Row Spacing (m)	**Month**		
	October	November	December
2	18.1 a	10.2 a	10.1 a
1.5	15.9 a	7.0 b	8.1 b
Above canopy DLI for reference	33.3	34.9	35.3

Average DLI was around 8 mol m^{-2} d^{-1} later in the season up to harvest in the 1.5 m rows. Given this timing is crucial for floral bud initiation, this low light environment may affect future potential fruiting. This will be discussed in the following chapter.

4.3.1.3 Average light transmission throughout a season for different canopy positions

Similar trends were demonstrated when the data were analysed within canopy positions over a season. (Figure 12). DLI was high early in the season, decreased rapidly as the canopy developed, before remaining relatively constant up until harvest. Early in the season, around flowering, the DLI is higher in the upper three canopy positions (2 m, 2.5 m and 1.5 m above the ground) and lower in the bottom of the canopy (1 m above the ground), but this difference is close, and not considered significantly different as can be seen by the 95% confidence interval.

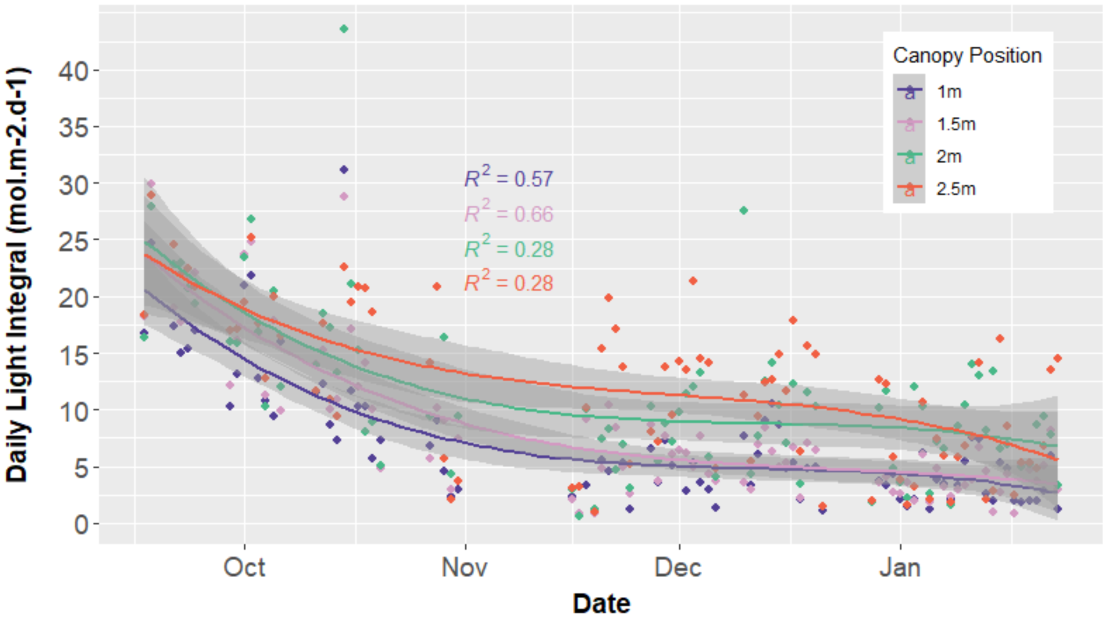

Figure 12: Polynomial fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each canopy position as meters from the ground. Averaged daily from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The grey zone is the 95% confidence level interval for predictions from the model. R^2 is displayed for the coefficient of determination

By mid-November, differences between canopy positions become more pronounced, the two upper canopy positions having significantly higher DLI than the lower two positions. This is then further confirmed with monthly average data in Table 2. While the DLI resulting from a 0.5 m increase in height may not be statistically significant at a single time-point, over an entire season, that slight increase in the DLI continuously may have a major impact on fruit quality, fruit set and/or return bloom. This could be particularly important when the two lowest canopy positions have a DLI of around 6 mol m^2 d^{-1} by mid-December. Whether this DLI is too low for each of these characteristics will be discussed in the following chapter.

Table 2 Average monthly daily light integral (DLI, mol m−2 d−1) from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre in October, November and December 2020. Means within a column that were significantly different based on LSD analysis are labelled with different letters. The above canopy DLI reference is calculated on the average incoming readings for both row spacing sensor set ups.

Canopy position (m)	Month		
	October	November	December
2.5	19.8 a	13.3 a	13.9 a
2	19.2 a	7.6 b	10.3 b
1.5	16.2 ab	6.4 b	5.5 c
1	13.1 b	6.1b	6.0 c
Above canopy DLI for reference	33.3	34.9	35.3

For those fruit quality attributes that are determined early in the season, there could be minimal differences between fruit from the upper and lower canopies. But for fruit quality attributes that are determined later in the season, for example total soluble solids, this difference in DLI may result in significant differences in fruit quality. Evaluation of light at critical time points may help to disseminate when light is most crucial for each fruit quality characteristic, and this will be done within chapter five.

Comparing R^2 values for the polynomial model of the DLI for each of the canopy positions, the models for the DLI of the two upper canopy positions have much lower R^2 values (0.28) than the two lower canopy positions (0.57 and 0.66). This shows that the upper portion of the canopy has considerably more variation in DLI values than the lower canopy. This variation may in fact carry through to fruit quality, and greater fruit quality variation might be expected within the upper canopy positions.

4.3.1.4 Average light transmission throughout a season for canopy position and row spacing

To tease out any row spacing effects, differences between the canopy positions in the two row spacings were examined (Figure 13). In both row spacings, the R^2 values for the model of DLI are lower in the upper canopy positions as observed in Figure 12, suggesting that the variability is high in the data from this region regardless of row spacing, and that variability in plant responses would be expected. This is particularly evident at the 2.5 m canopy position throughout the entire season in both row spacings. However, this could be partially explained by high variation in incoming radiation as can be seen in Figure 9.

Within Figure 13, the differences between the row spacings illustrated in Figure 11 is shown in more detail. The modelled DLI at each position are similar for the two row spacings in the early season, however, in late December the modelled DLI in the upper canopy positions are showing a difference of almost 10 mol.m^{-2}.d^{-1} between the 1.5 m and the 2 m row spacing. However, in late December the lower canopy positions are showing only a slightly higher DLI in the 2 m row spacing compared with the 1.5 m spacing. These larger differences in DLI the upper canopy may have consequences for fruit quality between row spacings, while the small differences in the lower canopy may not be great enough to show fruit quality reduction in the 1.5 m rows. Chapter five will cover whether these slight reductions were enough to influence fruit quality and return bloom.

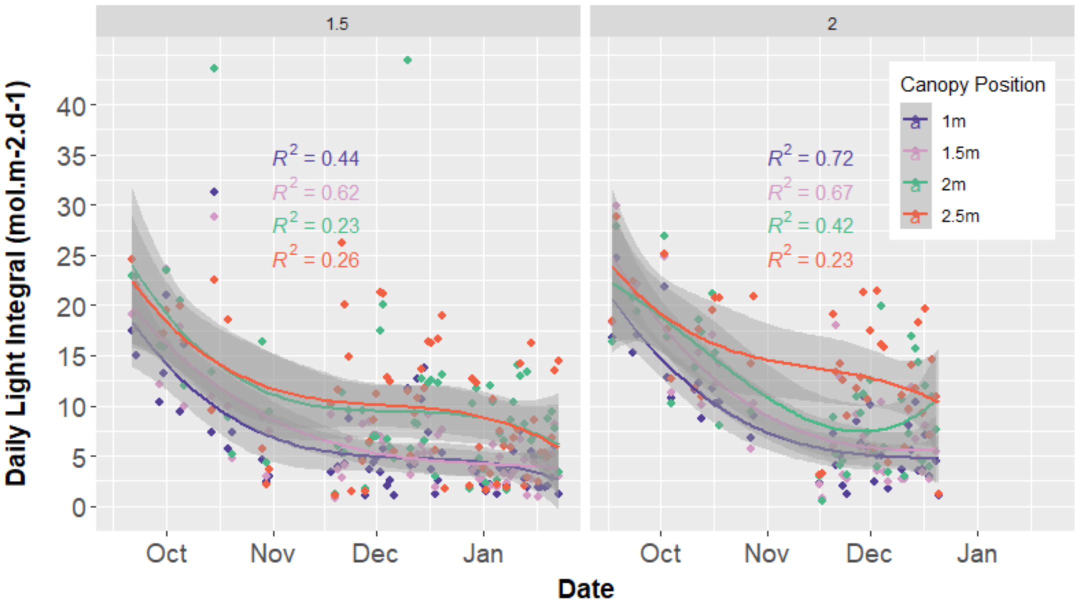

Figure 13: Polynomial fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each canopy position as meters from the ground, separated into either 1.5 m or 2 m row spacing. Averaged daily from 16 sensors at different locations within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The grey zone is the 95% confidence level interval for predictions from the model. R^2 is displayed for the coefficient of determination

4.3.2 Daily Light Environment

To understand the light environment in these canopies over a 24 hour period, all blocks were averaged across the season for each 5-minute period. This visual representation is shown in Figure 14. Total above canopy PAR increased from 0 µmol m^{-2} s^{-1} just before sunrise at 06:00 to around 1300 µmol m^{-2} s^{-1} at solar noon at approximately 13:00 before reducing to near 0 µmol m^{-2} s^{-1} at about 21:00.

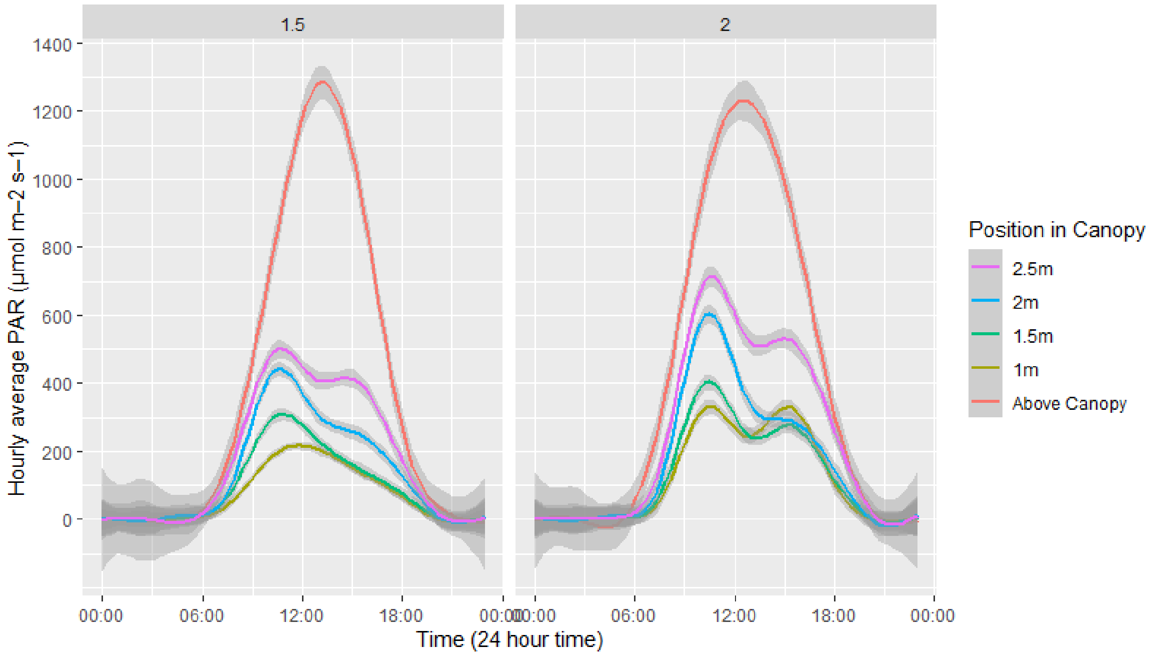

Figure 14: Hourly photosynthetically active radiation (PAR, µmol s^{-1} m^{-2}) at different heights (1 m, 1.5 m, 2.0 m, and 2.5 m) within planar cordon 'Sweetheart' trees grown at 1.5 m and 2 m row spacings. An average of PAR is presented every hour starting from midnight (00:00hr) to midnight (00:00hr) averaged from 19th September 2020 to 19th January 2021, normalised to a standard time. The canopy consisted of four sensors placed between two uprights. Each treatment was measured with four reps as well as an open sky sensor which was placed at 3 m in height recording above canopy radiation (open sky).

Within the canopies, each of the four canopy positions light environment behaved similarly, increasing up to 10:00, before reducing slightly around solar noon, and then increasing slightly again about 15:00 and further reducing up until 21:00. This however was more prominent in the upper canopy of the 2 m row.

The reduction in hourly PAR at solar noon is to be expected, because the sun is directly overhead at that point and the highest shading occurs as a result of the rows being planted NW-SE. However, in the lower canopy for the 1.5 m rows this variation in PAR at solar noon was less obvious, and is possibly due to the incidence of diffuse light intercepted in the lower regions of these canopies rather than direct sunlight and therefore was not as affected by solar noon shading.

The average PAR from a whole season confirms the data seen in Figure 13, where the upper canopy in the 2 m row spacing was receiving greater overall light in the later season than the 1.5 m row spacing, while the lower canopy differences were not as obvious. This translates over into the average values over the entire season too.

Table 3 gives these data as daily averages over the season from the 19th September 2020 to 19th January 2021. In both row spacings there is a significant difference in daily average PAR down through the canopy, but the lowest two canopy positions are not significantly different from each other. At each position in the canopy, there is a significant difference between row spacings, and in fact, in a 2 m row, the available light at 1 m is broadly similar to light at 2 m in a 1.5 m row.

Table 3: Daily average photosynthetically active radiation (PAR, μmol s^{-1} m^{-2}) for all sunlight hours with PAR>0 over a season from 19th September 2020 to 19th January 2021 for 4 vertical positions in the canopy. Including 1.5 m and 2 m row spacing. Means within a column, not between columns that were significantly different based on LSD analysis are labelled with different letters.

Position in canopy	**1.5 m**	**2 m**
2.5 m	219.6 a	263.5 a
2 m	159.0 b	189.5 b
1.5 m	119.2 c	139.9 c
1 m	101.1 c	142.8 c
P-value	<0.001	<0.001

From these daily averages, it is possible to speculate on what this might mean for fruit quality. Given the averages in each canopy position differ significantly, it could be assumed therefore that fruit quality will too. However, depending on the minimum light required for each of the fruit quality characteristics, this significant difference in light over a season may in fact not influence fruit quality or return bloom as greatly. Daily average PAR in the lower canopy is only 46% and 54% of the light captured in the upper canopy in 1.5 m and 2 m row spacings, so it would be likely that differences in fruit quality between the highest and lowest canopy positions will be observed, but as both the lowest canopy positions have no significant differences, that the fruit quality from these regions will be similar within a row spacing.

4.4 Conclusion

Throughout the season from flowering through to harvest, the light environment changes within all canopy positions. A rapid increase in leaf area from flowering through to fruit set, corresponds to a similar linear decrease in average within-canopy light transmission. This then levels off around the time of pit hardening around mid-November.

From these results, an understanding is gained of when leaf and shoot growth is occurring and how quickly. These figures do not give a total light interception figure, but rather an idea of how much light is being intercepted in all areas of the canopy over a whole day and a whole season.

The main findings from this experiment were:

- Row spacing did affect light transmission and higher total light was transmitted through the canopy, but only significant in the later season.
- The two highest vertical canopy positions (2 m and 2.5m from the ground) showed the greatest light capture in both row spacings.
- The highest light capture over the day was at 10.00am, and a dip in light was noticed at solar noon, particularly in trees with 2 m row spacing.

Chapter 5: Fruit set, fruit quality, and leaf area

5.1 Introduction

Sweet cherry (*Prunus avium* L.) is among one of the most widely grown and consumed temperate fruits in many parts of the world. The global production totals 2.2 million tonnes annually. Countries leading the production are Turkey, the USA, and Iran (Antognoni et al., 2020). New Zealand's production of sweet cherry is however significantly lower. In 2019 around 5000 tonnes were produced over an area of 1080 hectares, equating to around $50 million in exports, and a further $12 million in local market sales (Fresh Facts, 2020). The majority of cherry fruits grown in New Zealand are exported to Asia, with Taiwan and China making up a combined value of around $32 million in 2020 and $50 million in 2019 (The New Zealand Horticultural Export Authority, 2022). Cherries are also exported into the European Union, but in limited volumes, as tariffs on New Zealand stonefruit are high (12%) compared to those imposed on other Southern Hemisphere exporters, and this has led to decreased exports to the EU (The New Zealand Horticultural Export Authority, 2022). New Zealand's main competition for Southern Hemisphere-grown cherries in the export market is Chile, which produces nearly 90% of the total volume of cherries available. Because New Zealand cannot compete with Chile on volume, the marketing strategy focuses on producing fruit with exceptional quality characteristics (Whenua Māori, 2021).

Given the current labour shortages, increases in the costs of production, inflation, and wage increases, as well as costs of transporting goods doubling in the year to December 2021 (MFAT, 2022) it is important for the industry to find ways to grow productive, high-quality cherries in the most profitable ways. Two-dimensional growing systems have been developed because growers believe they may allow adaptation to these conditions. Rising harvest costs, estimated to be approximately 60% of the total yearly variable production costs (West et al., 2012), as well as the use of technologies such as platforms, robotics and other mechanised technologies to assist growers with labour efficiency require canopies that suit these technologies (Wilson, 2016). However, as high-quality fruit is New Zealand's primary advantage, the planar canopy systems endeavour to capitalise on physiological principles of energy capture to improve the uniformity of fruit quality through the canopy while retaining high yields.

Numerous studies across many temperate fruit crops in three-dimensional trees have shown that fruit quality is better in the upper canopy. Hamadziripi (2012) investigated the relationship between canopy position and various fruit quality parameters in three apple cultivars and concluded that fruit in the outer canopy was higher in TSS, reducing sugars and total carbohydrates but the size was not influenced. Feng et al. (2014) showed a similar outcome in their study on apples except, in this case, size was also greater in the outer canopy. Similarly, in apricot, Stanley et al. (2014) reported that fruit taken from the upper canopy locations resulted in higher SSC for a similar flesh firmness, alongside greater fruit size in the upper canopy positions. It was shown that light penetration into the canopy (30-70% in the upper canopy, and only 1-20% in the lower canopy using instantaneous PAR measurements) was closely linked to fruit quality. The effect of reduced light on fruit quality was also seen in peach, with artificial shading of trees resulting in fruits with lower soluble solids concentration (SSC) than those uncovered. They also looked at natural canopy shading, where smaller fruit, with less red colouration were found in the centre of the canopy compared with fruit from the canopy exterior (Lewallen, 2000). While there are fewer published data on cherry specifically, some work confirms that total soluble solids concentration was higher in the upper canopy, however fruit size was unaffected due to a significant yield difference (Scofield et al., 2021). Evidence suggests that fruit grown in low light zones may also be more susceptible to physiological postharvest disorders such as core flush, a form of internal senescent breakdown in apples (Blanke and Notton, 1992).

Consumer studies have shown a strong consumer preference for the largest cherry (Turner et al., 2008). From the economic analysis of fruit size in the United States of America, fruit size strongly reflects the price received in the market. A 24mm cherry would expect to receive USD 2.24 per kilogram, a 26mm cherry USD 3.20 and a >30mm cherry to receive USD 3.69/kg (Whiting et al., 2005). While this study is from 2005, and prices for New Zealand export cherries are considerably higher per kg overall at between NZD 11.69 and NZD 13.71/kg in 2022 (Selina Wamucii, 2022), the difference in price between size grades still stands. Therefore, there is greater incentive to produce larger fruit for greater overall returns to growers.

According to the consumer study by Turner et al. (2008), other than size, the second most important characteristic determining consumer choice was sweetness. In another consumer trial, consumer acceptance was highest for cherries with a total soluble solids concentration (SSC) above 20.0%, where acceptance was above 90%. Fruit below 16.1% was where it was deemed unacceptable by most. Cherry acceptance did not significantly increase for cherries with more than 20% SSC, suggesting that consumers had no preference for cherries with SSC >20% (Crisosto et al., 2003).

Flowering intensity, pollination and fruit set in sweet cherries play big roles in yield and fruit quality, yet are unpredictable and vary widely among cultivars and seasons. In

New Zealand, ‘Colt’ is the only commercially available rootstock (New Zealand Intellectual Property Office, 2022). It is a vigorous rootstock with low precocity. In ‘Lapins’, a variety with a common parent to ‘Sweetheart’, grafts on ‘Colt’ rootstock were found to have significantly lower cumulated yield than Mazzard, a popular rootstock throughout the Pacific Northwest (Milošević et al., 2014), and four varieties on Gisela 5 outperformed Colt on yields/tree (Stehr, 2005). However, in more dwarfing rootstocks such as ‘Gisela 5’ and ‘Krymsk 6’, there is a risk that these trees will often result in very high yields of small fruits. Fruit set percentage varies significantly year by year, but generally, it is expected that fruit set will be between 8-40% depending on the cultivar (Close, 2015). While ‘Sweetheart’ is considered a self-fertile cultivar, it does benefit from a pollinator (Békefi, 2004). In an open bee-mediated environment, fruit set in ‘Sweetheart’ was found to be 25.4%, while in a hand-pollinated situation it was as high as 55.7% (Zhang et al., 2018). This shows the potential for fruit set to be considerably higher given optimal conditions.

Flowers require a relatively large supply of carbon to support and maintain the growth of developing growth (Measham et al., 2013). The carbon can come from stored carbohydrates, such as from bulbs and tubers (Blanchard and Runkle, 2010), or in the case of cherry, in the period leading up to dormancy, the accumulation of total non-structural carbohydrates are translocated into storage areas including buds, trunk and roots (Measham et al., 2013). As is the case with cherries, flower buds develop earlier than vegetative buds, and therefore the plant relies on stored carbon reserves (Measham et al., 2013). However, when a stress factor is introduced, for example low light conditions, the carbon demands of the developing fruits are greater than the available carbon, and fruit abscission can occur. In other fruits, the introduction of shading in apple and grapevine shading during reproductive development dramatically increased inflorescence abscission and reduced overall fruit set (Ferree et al., 2001; Zhu et al., 2011).

In the two-dimensional systems, the optimisation of sunlight was the key objective. Given the flower timing in cherry occurs before vegetative bud break, these canopies give the best opportunity for optimum light to be available to all parts of the canopy during the initial stages of fruit development, therefore light should not be a limiting factor for fruit set. However, there is evidence to suggest that in other perennial fruits such as kiwifruit and apple, light intensity has a direct relationship with floral initiation, with shaded shoots producing fewer floral buds and inflorescences per shoot than exposed shoots (Wilkie et al., 2008), and similarly in olive (Stutte and Martin, 1986). As flower bud induction of cherry occurs between November and December in the

Southern hemisphere, and flower organ differentiation occurs in January/February when trees are in full leaf (Lang, 2011), flowering ability may be compromised due to shading within the canopies during this period.

The relationship between leaf area and fruit quality is by no means a new concept. Halleb (1933) states: “The supply of carbohydrates available to the fruit depends primarily on two factors—the amount of carbohydrates elaborated per fruit, and the transport of the carbohydrates to the fruit. The amount of carbohydrates elaborated per fruit will depend first upon the leaf area per fruit”

Fruit weight and diameter and the relationship to leaf area has been studied in many crops. In apple, Cittadini et al. (2008) found that fruit quality variables of size and SSC decreased linearly with increasing fruit number to leaf area ratio. They found that to gain a 1g increase in weight per fruit, an additional 32cm^2 of leaf area was needed. Additionally, relationships between leaf area and yield show positive correlations (Barritt et al., 1991). However, in kiwifruit, the reverse appears to be true. With an increase in the leaf area index, a decrease in mean fruit size was observed, with a decrease in mean fruit size at a rate of 5.8 g per unit LAI (Snelgar and Thorp, 1988). Studies in sweet cherries show a similar trend to apples, in that as leaf area to fruit ratios increase, the fresh weight, diameter and SSC increase (Penzel et al., 2021). When studied on a whole tree basis, (Penzel et al., 2021) found that the trees with the greatest percentage of fruit above 28mm in diameter was achieved at a leaf area to fruit ratio of 117 cm^2. However Neilsen et al. (2016) found that fruit size and sugar approached maximum levels around 210 to 250 cm^2, equating to around 4-8 spur leaves per fruit. They found that fruit size was greatly reduced when leaf area per fruit was less than 200 cm^2.

In cherry, spur leaf development develops rapidly after full bloom, reaching maxima around 50 days after full bloom. Fruiting spurs will generally have smaller leaves and less leaf area than vegetative spurs in apple (Barritt et al., 1991), this is true also for cherries where the total area of 2-3 shoot leaves equate to between 4-8 spur leaves (Lang, 2016a).

Nitrogen nutrition is a key modulator of sugar in fruit, as a core element involved in the processes of photosynthesis, respiration, and carbohydrate and signal transport in plants, and a low nitrogen supply can alter the assimilate distribution between various organs (Zhang, 2021). Fruit N concentration positively affects fruit sugar concentrations (Liao et al., 2019). In peach, it was found that leaf nitrogen content increases with exposure to photosynthetically active radiation, (Rosati et al., 2000).

Fruiting spur leaves have higher tissue levels of nitrogen than shoot leaves, and these will directly support the carbohydrate needs of developing fruits. As leaf area/ha and light interception are highly correlated (Barritt et al., 1991), if a planar cordon canopy system has well distributed light throughout a canopy, optimal leaf area per hectare, and dispersed fruiting spurs, there is the potential for high yields of optimal quality fruit.

Leaf area may also influence flowering. In apple, increased leaf area on individual spurs was found to increase flowering (Neilsen and Dennis, 1997). In almond, the greater the leaf area, the higher the probability for the spur to bear flowers in the following year, and both spur leaf area and spur longevity were strongly correlated with light. (Lampinen et al., 2011).

This chapter focuses on the fruit quality characteristics and their relationship to daily light integral, yield, fruit set, return bloom and leaf area.

5.2 Materials and methods

Refer to introduction for main materials and methods, including fruit quality assessments. Methods pertaining to this chapter will be included in more detail here.

5.2.1 Leaf area analysis

For this work, spur leaf area was estimated non-destructively. In order to do his, a relationship between leaf dimensions and leaf area was determined using a sample of leaves from trees adjacent to the experimental plots within the same orchard block. In (month), at full leaf maturity, 100 leaves were removed from spurs on ‘Sweetheart’ trees next to the experiment so as not to influence the leaf area of the experimental plots. Both width and length measurements were recorded on each leaf before placing the leaf on a white sheet with a scale and photocopied. Area analysis was then performed in the ImageJ software (IJ 1.46r, USA) and correlation of leaf length and width with leaf areas was investigated.

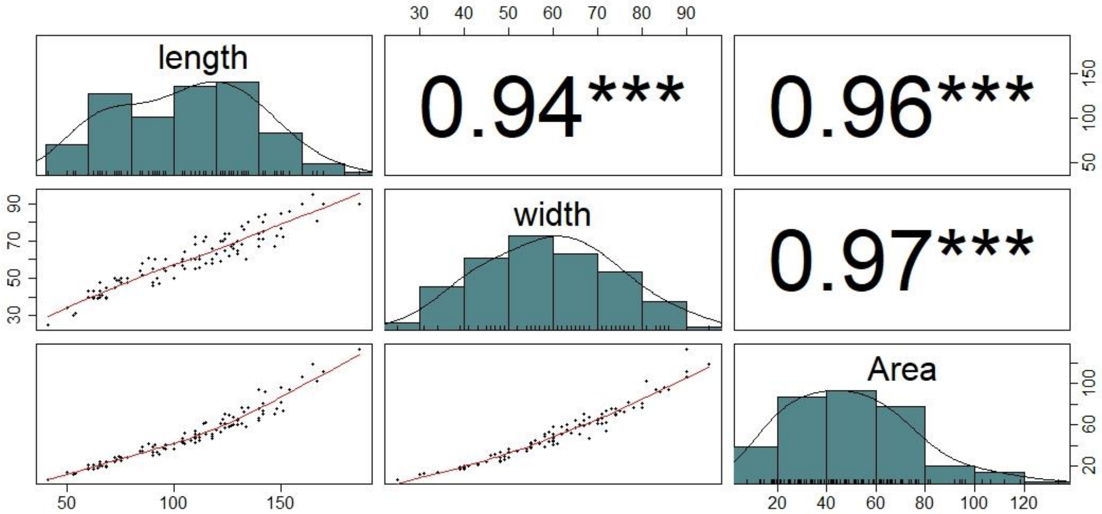

Figure 15: Correlation matrix for length (mm) and width (mm) to leaf area (cm^2) for individual spur leaves sampled randomly from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots with a fitted line. The top of the diagonal shows the value of the correlation and the significance value as *P-value* (0.001 = “”)

The correlation of area to both length and width were very high, with an R^2 value of either 0.96 or 0.97. Length was chosen as it was easier to measure, as width was slightly subjective to estimate which was the widest part of the leaf.

Once this relationship was established, all leaves from tagged spurs were measured for length, and then the equation of the regression ($y = 0.003x^2 + 0.098x + 2.2998$) was applied to all leaf lengths, and added to estimate the leaf area of each spur.

5.3 Results and Discussion

There were very few strong interactions between quality criteria and the other tree factors studied (

Figure 16: . However, seasonal average daily light integral (DLI), which represents the DLI from each position in each plot averaged across the season shows a clear positive relationship with the yield (Punnet_weight) in each of the vertical positions. This is not an unexpected finding, and is confirmed with many other crops (Sansavini and Corelli-Grappadelli, 1997; Whiting et al., 2005; Amarante et al., 2012; Wilson, 2020), however this basic analysis only confirms that there is a relationship between DLI and yield, and does not show where in the canopy these differences are occurring. For DLI, this relationship with punnet weight is the strongest correlation. Other weaker relationships are seen between DLI and SSC, fruit set percentage, and total spur leaf area. Unlike the others, the relationship with spur leaf area is negative. As DLI increases, the area of spur leaf decreases. This is also not unexpected, in other species of plants low light conditions can impose environmental stress on plants, and plants often respond adaptively by increasing their leaf area to intercept more sunlight (Francis and Gilman, 2019).

Some of the other strong relationships are between spur leaf area and individual fruit diameter, and return bloom. Each of these relationships will be discussed further in this chapter. Other strong relationships such as those between fruit quality characteristics SSC and FF are expected and will not be discussed, although, as can be seen in this correlation matrix, there is a large amount of variation between individual points, and even where straight line correlation would be expected, such as between flesh firmness and soluble solids concentration, the correlation coefficient is still only 0.53.

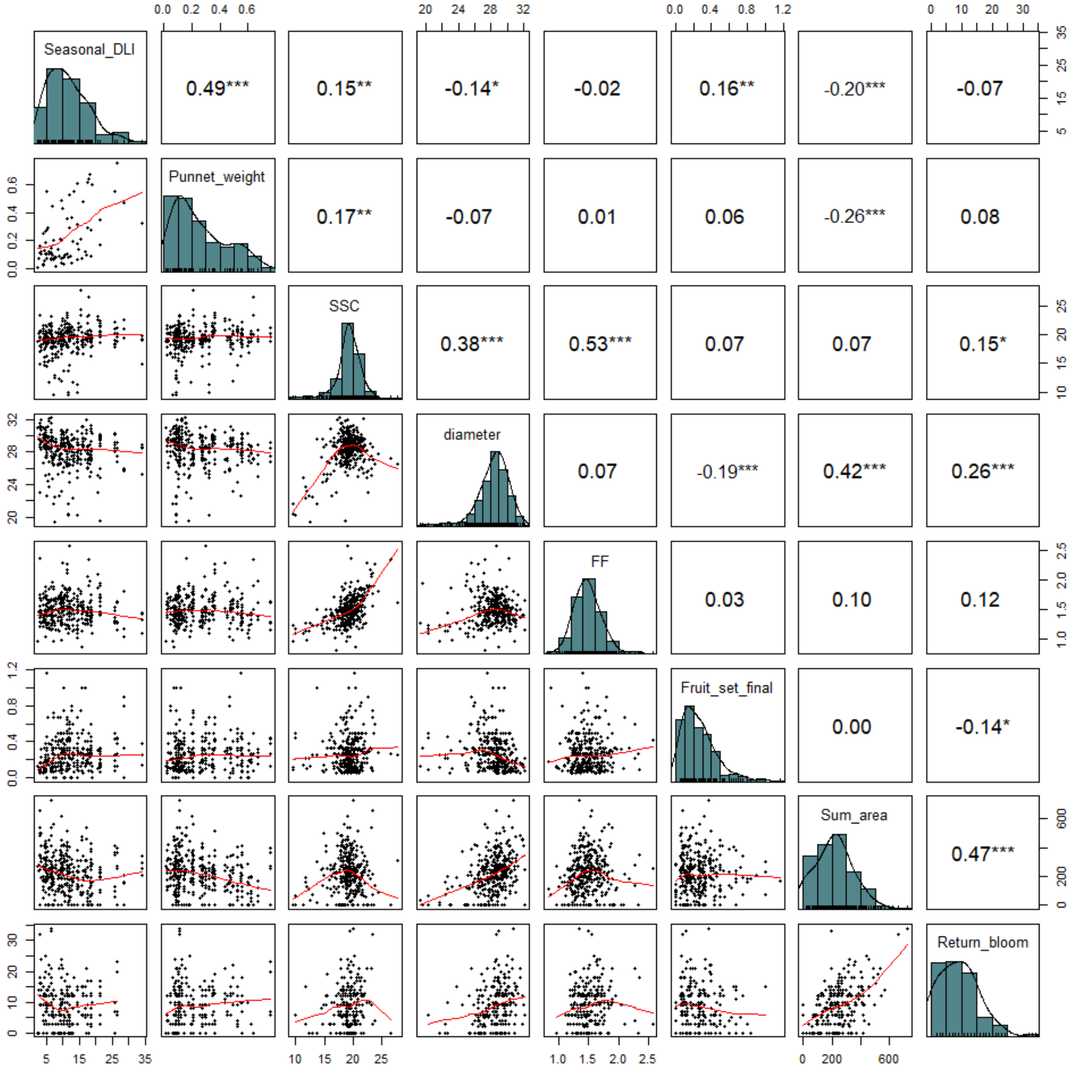

Figure 16: Correlation matrix of fruit quality characteristics soluble solids concentration (SSC), diameter, and flesh firmness (FF), and other tree information fruit set (Fruit_set_final), spur leaf area (Sum_area), return bloom, yield of each sensor position (Punnet_weight), a total weight of combined fruit from the 20cm surrounding area of a sensor,and the average seasonal daily light integral (Seasonal_DLI).from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots with a fitted line. The top of the diagonal shows the value of the correlation and the significance value as *P-values* (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols (“***”, “**”, “*”, “.”, " “).

5.3.1 Yield

The matrix in Figure 16 shows a strong relationship between the average seasonal daily light integral, and the harvested weight of fruit from each vertical canopy position. This was calculated as a "punnet weight", or the total fruit harvested within a 20 cm radius of the sensor on each single upright shoot. To gain more perspective on this correlation, the data were examined in two ways (Figure 18 and Figure 17). In Figure 18, the average seasonal DLI calculated from each sensor was plotted against the total weight of fruit harvested from that sensor position. In Figure 17 total fruit weight was is plotted with the approximate vertical position in the canopy to gain an insight into where the differences in yield are occurring.

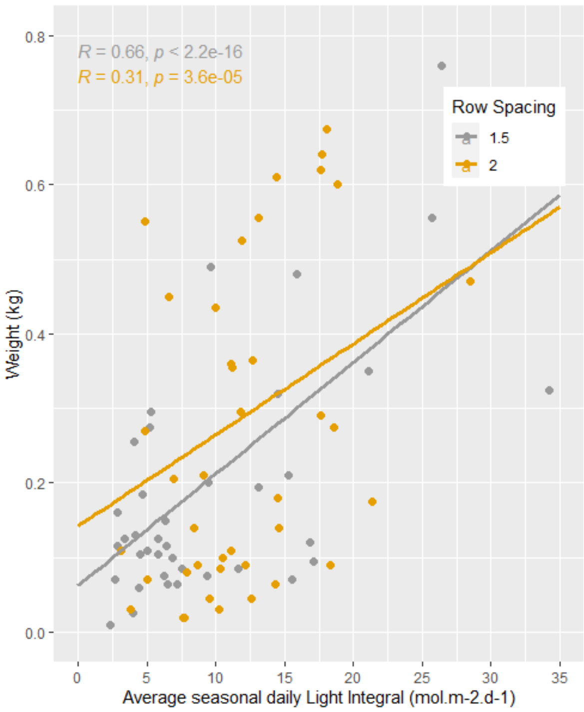

Figure 18: Linear fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the weight harvested from each upright associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

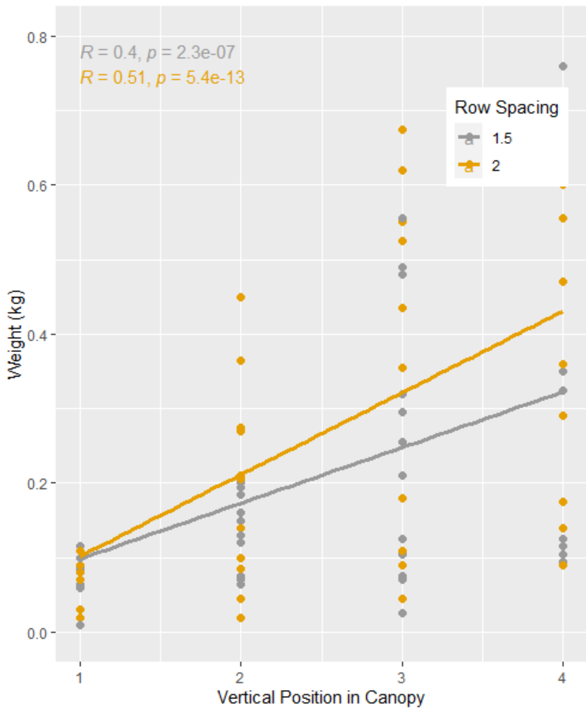

Figure 17: Linear fit of the difference in the vertical position in the canopy 1, 2, 3 and 4 corresponding to 1, 1.5, 2 and 2.5 m from the ground respectively for each sensor position within a block of three 'Sweetheart' cherry trees against the weight harvested from each upright associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

These two figures show a strong relationship between both DLI and weight ($p<0.001$), and sensor position and weight ($p<0.001$), and linear regression shows some separation between row spacings. This suggests that in low light environments the 2 m row spacing produced a greater yield (Figure 18: Linear fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the weight harvested from each upright associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.). However, as the R value is 0.31 for the 2 m row spacing, and there are few data points at low DLI in the 2 m spacing, more data points would be needed to increase this understanding. The other factor to consider is that this representation of light is an average over a whole season. It does investigate light environment during the periods of greatest fruit growth and did not take into effect times of day where there may have been higher direct light or light flecks, which may be the case in the two metre row spacing. This may begin to explain that slight variation in yield across row spacing. This will be discussed in further detail later in this chapter.

Figure 17 however, shows that in the base of the canopy, the yield between row spacings is the same, but increasing vertical height in the canopy increases yield in the 2 m row spacing at a greater rate than the yield in the 1.5 m row spacing. Chapter four confirmed that each vertical position within the canopy has a higher daily PAR from the average over the season in the 2 m row spacing. Looking at the data for percentage difference between them (Table 4), the canopy positions 2-4 (1.5 m – 2.5 m) all have a difference of 15-17% between row spacings, but almost 30% in position 1 (1 m). Therefore, based on these results, a greater yield difference should have theoretically been observed in the lowest canopy position.

Table 4: Daily average PAR (μmol s^{-1} m^{-2}) for all sunlight hours with PAR>0 over a season from 19th September 2020 to 19th January 2021 for the four vertical positions in the canopy measured 1, 1.5, 2 and 2.5 m from the ground. Including 1.5 m and 2 m row spacing, and the percentage difference between the row spacings in each vertical position.

Position in canopy (m)	Row spacing (m)		% Increase in average seasonal PAR
	1.5	2	
2.5	219.6	263.5	17%
2	159.0	189.5	16%
1.5	119.2	139.9	15%
1	101.1	142.8	29%

It is important to consider the impact of yield in all other fruit quality characteristics in this chapter. However, referring back to the matrix in Figure 16 there appears to be very little interaction with yield data and diameter or flesh firmness, and the weak interaction with SSC is positive, indicating that as yield in that position increases, so does SSC. This however is likely due to the higher yields being seen in the upper canopy, which generally have higher DLI and sugar accumulation.

5.3.2 Fruit Set

Fruit set percentage, calculated from fruit that made it to harvest per spur divided by the flower number per spur, showed a slight correlation in the initial matrix (Figure 16). However, when this is separated into row spacing, these correlations show no relationship in the 2 m row spacing, and only in the 1.5 m row spacing is there a correlation between seasonal average DLI and fruit set percentage (Figure 20). The lack of relationship in the 2 m row, could be explained by the reduction in flowers at low DLI, which can contribute to a higher fruit set percentage. When fruit set percentage is analysed in regard to vertical position in the canopy, while there is a very weak positive trend, there is no significant relationship (Figure 19). However, it is important to note the approximately 7% higher fruit set percentage in the 2 m row spacing compared with the 1.5 m rows.

The clustering of samples in the area of low DLI and low fruit set in the 1.5 m rows seen in Figure 20, combined with the lack of samples in the high DLI range in the 2 m row may have contributed to the difference between the row spacings. However this trend is also noticed among several other variables in this chapter.

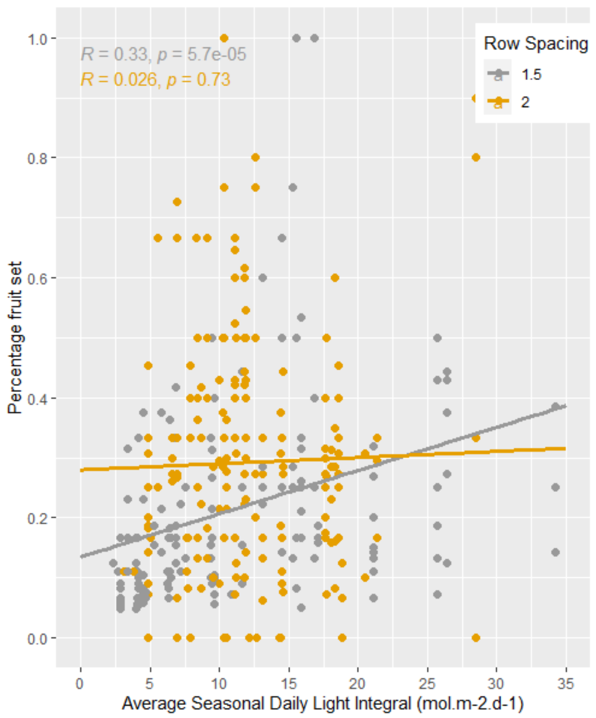

Figure 20: Linear fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three ‘Sweetheart’ cherry trees against the fruit set percentage from spur associated with the sensor position within planar cordon canopies of ‘Sweetheart’ cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

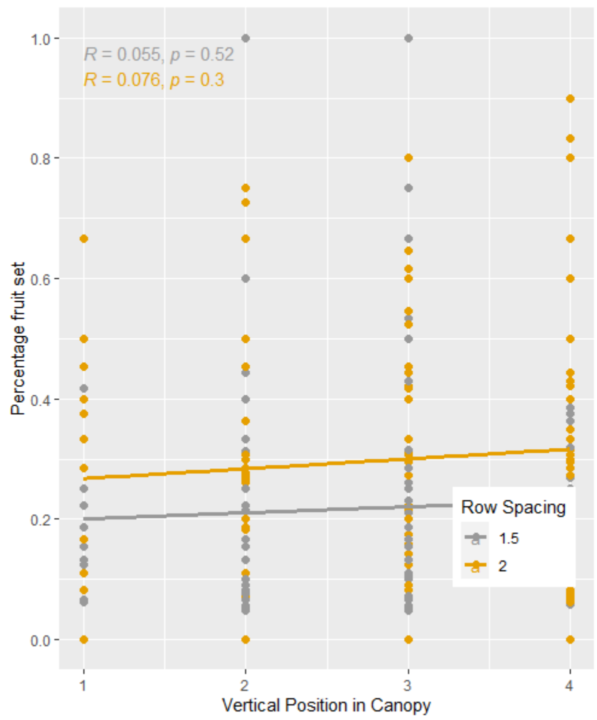

Figure 19: Linear fit of the difference in the vertical position in the canopy 1, 2, 3 and 4 corresponding to 1, 1.5, 2 and 2.5 m from the ground respectively for each sensor position within a block of three ‘Sweetheart’ cherry trees against the percentage of fruit set in each spur associated with the sensor position within planar cordon canopies of ‘Sweetheart’ cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

5.3.3 Soluble Solids Concentration

There was no relationship between DLI and SSC in the 1.5 m row spacing (*P*=0.2) and there was a weak relationship in the 2 m row spacing (*P*=0.002) (Figure 21). Both 1.5 m and 2 m row spacings had similar average SSC in low light environments, but the 2 m row spacing has higher average soluble solids in the higher light environments. It is possible that this difference was due to other factors such as leaf area, root competition and therefore competition for carbohydrate resources.

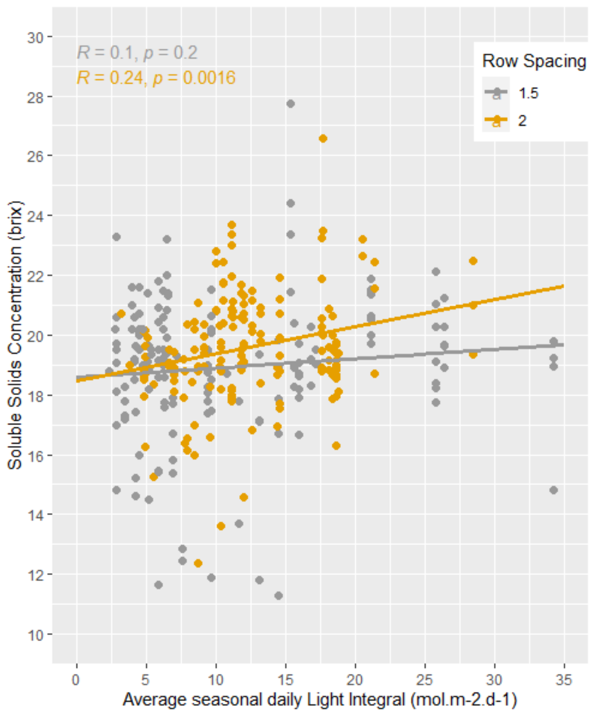

Figure 21: Linear fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the soluble solids concentration (SSC) from each spur associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

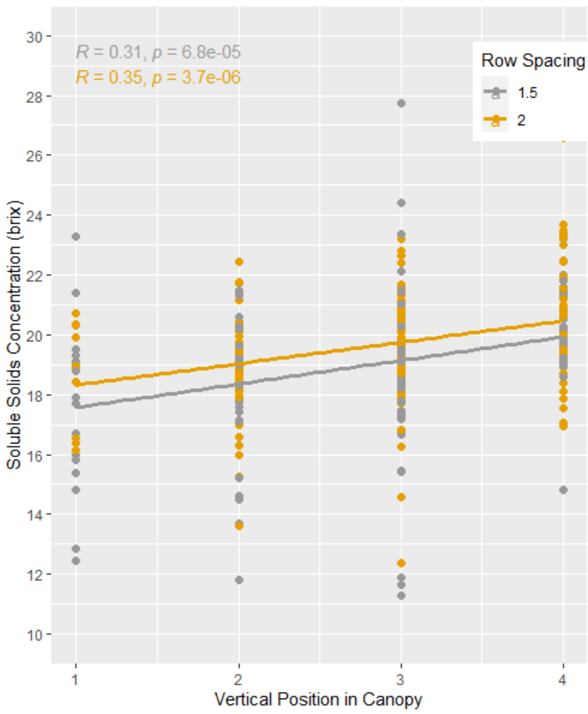

Figure 22: Linear fit of the difference in the vertical position in the canopy 1, 2 3 and 4 corresponding to 1, 1.5, 2 and 2.5 m from the ground respectively for each sensor position within a block of three 'Sweetheart' cherry trees against the soluble solids concentration (SSC) in each spur associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

When position is used instead of DLI, there appear to be stronger relationships between position and soluble solids concentration in 1.5 m (R=0.31) and 2 m row spacing (R=0.35), as the fruit position in the canopy gets higher, as does the soluble solids concentration, and this linear relationship is similar for both row spacings, although higher overall SSC is seen in the 2 m row spacing (Figure 22).

To understand any row spacing effect, Table 5 gives the average SSC down a row for both 1.5 m and 2 m row spacing. While SSC differed through the canopy as was expected based on Figure 22, differences between row spacings within the same vertical position were not significantly different. So, while PAR at the lowest canopy position was 29% higher in the lowest canopy position in the 2 m row, SSC did not differ.

Table 5 Average soluble solids concentration (SSC) from four vertical positions in the canopy measured 1, 1.5, 2 and 2.5 m from the ground, within either 1.5 m or 2 m row from within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Means that were significantly different based on LSD analysis are labelled with different letters.

Position in canopy (m)	**Row spacing (m)**		
	1.5	2	*P*-value
2.5	20.1 a	20.6 a	0.188
2	18.8 b	19.7 b	0.044
1.5	18.1 bc	19.0 c	0.049
1	17.1 c	18.7 c	0.049

When referring back to PAR, Table 3 in chapter four discussed the lower two canopy positions in both row spacing not being significantly different in average light conditions. It was speculated that the two lowest canopy positions would therefore not vary in quality, and for SSC it appears that this is true.

5.3.4 Fruit size

Fruit diameter data showed a different trend from the previously discussed variables, and it is important here to refer back to yield, where significantly higher ($P<0.002$) yields were observed in areas of upright shoots exposed to higher light over a season (Figure 18).

Figure 24 below shows the relationship between the average seasonal DLI and the average diameter of individual fruit in these environments. As the DLI increased, fruit diameter decreased from around 29 mm to 28 mm in the 1.5 m row, and from 28.5 mm to 27 mm in the 2 m row. With overall size higher in the 1.5 m row. This is unexpected, because as discussed in the introduction to this chapter, studies on many crops show that a higher light environment is associated with greater fruit size. As fruit numbers in the lower DLI positions were lower in the 1.5 m row spacing (Figure 18), the reduced fruit numbers may have resulted in larger fruit in those that remained, however in the higher DLI positions, fruit numbers did not differ between row spacings and yet fruit diameter still differed.

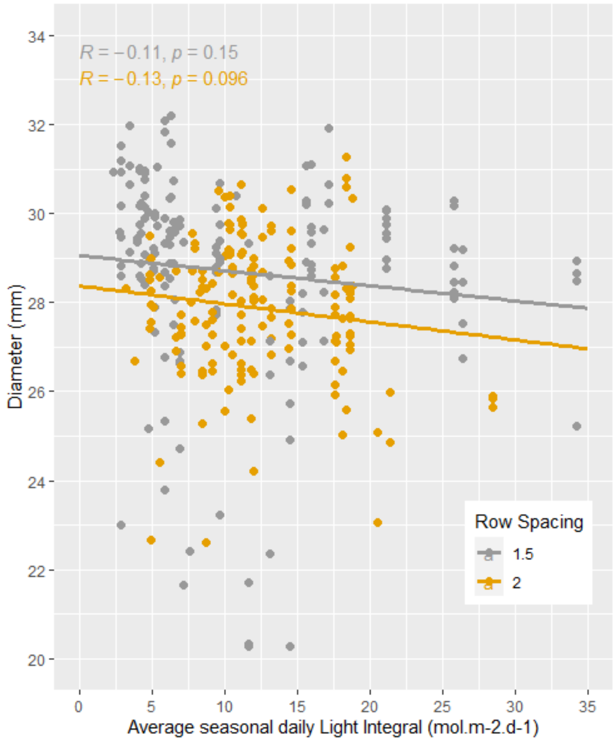

Figure 24: Linear fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the equatorial diameter (mm) from each spur associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

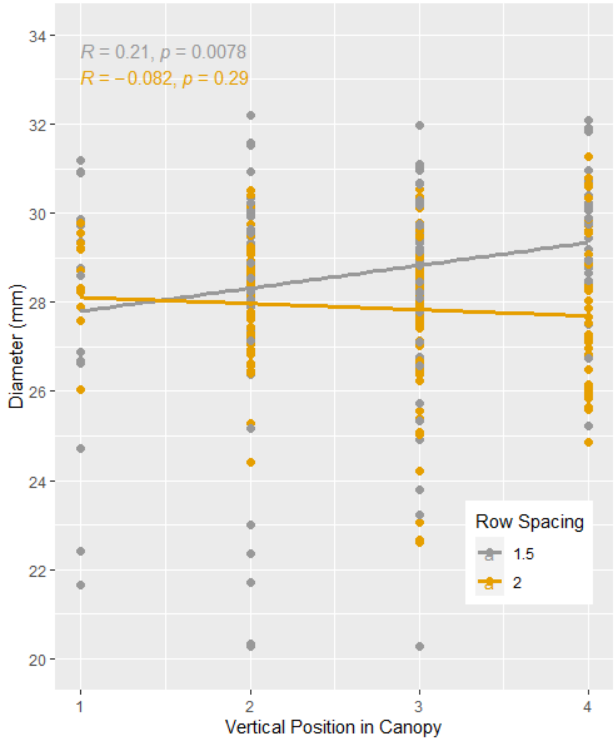

Figure 23: Linear fit of the difference in the vertical position in the canopy (1, 1.5, 2 and 2.5 m from the ground) for each sensor position within a block of three 'Sweetheart' cherry trees against the equatorial diameter (mm) in each spur associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

Therefore it may be that an individual tree is increasing the overall size. To assess this, these data were split into blocks, showing the relationship between DLI and diameter within each block. (Figure 25).

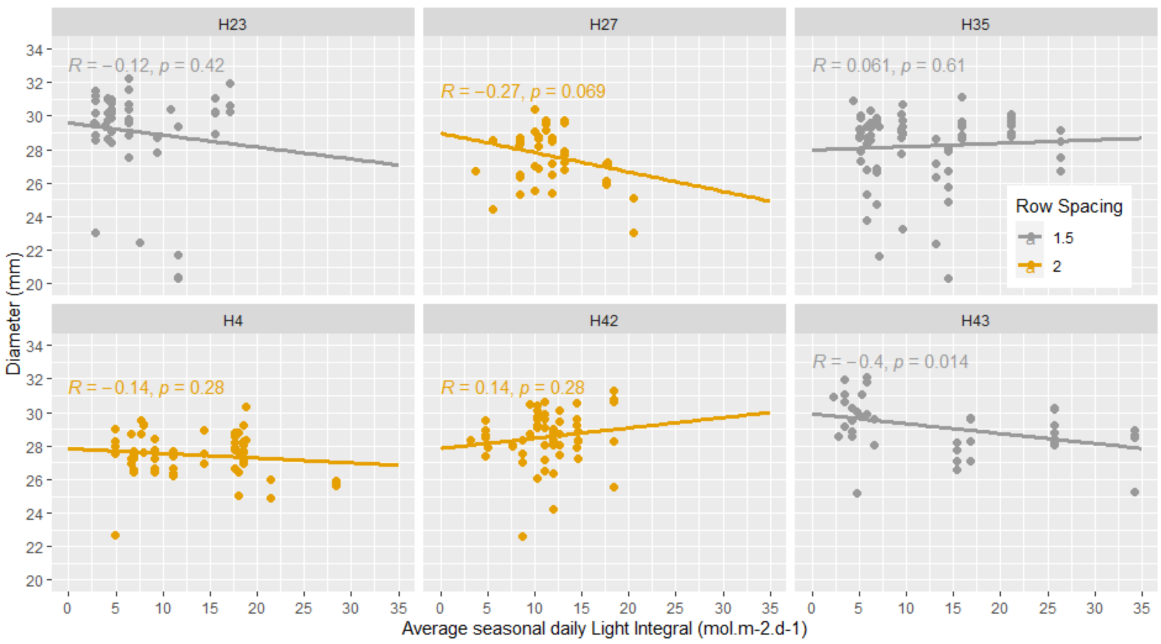

Figure 25: Linear fit of the difference in daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the equatorial diameter (mm) from each spur associated with the sensor position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Each graph represents one block, in either a 2 m row (orange) or 1.5 m row (grey). Correlation coefficients (R) and significance levels (p-value) are displayed.

Based on this figure, there were no clear trends, with no statistically significant correlations, but generally the 1.5 m rows had larger fruit size. However, there was no clear block that was producing fruit of greater diameter to explain why the 1.5 m row had overall higher diameter in all light environments. The relationships between DLI and diameter for each individual tree were weak.

From the initial matrix in Figure 16, diameter was more closely associated with leaf area than with DLI so this relationship, discussed below, may explain this result.

5.3.5 Leaf area

In the initial matrix in Figure 16, leaf area had a significant relationship with seasonal DLI, yield, diameter and return bloom (Figure 26).

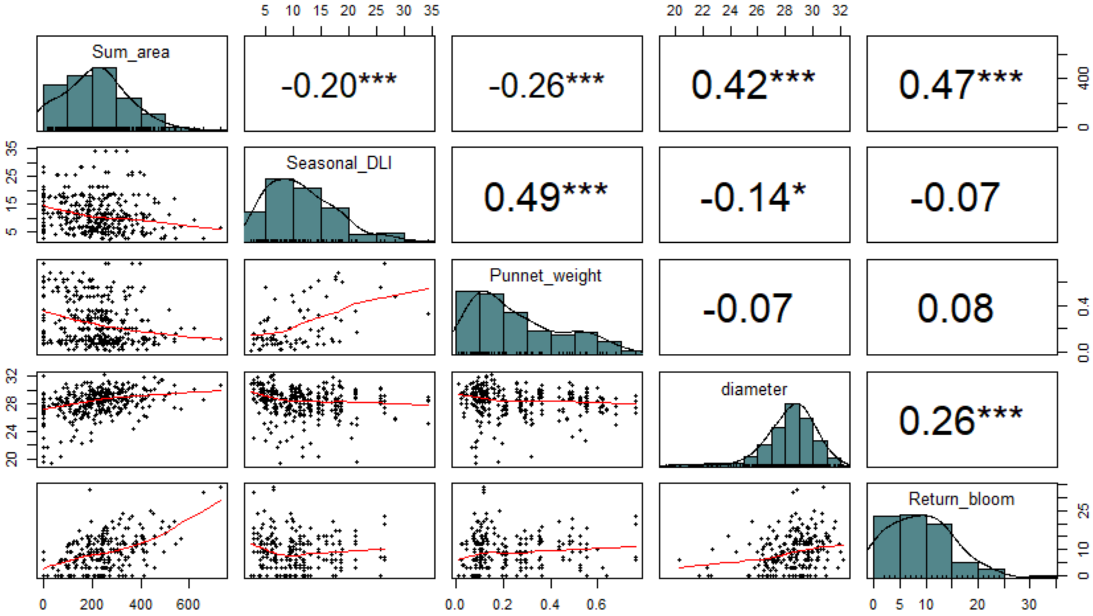

Figure 26: Correlation matrix of leaf area (Sum_area) and average seasonal daily light integral (Seasonal_DLI), yield of each sensor position (Punnet_weight), diameter (mm), and return bloom percentage (Return_bloom) from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots with a fitted line. The top of the diagonal shows the value of the correlation and the significance value as *P-values* (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols(“***”, “**”, “*”, “.”, " “).

As discussed above, the unexplained higher diameter in the 1.5 m rows, may be due to the strong relationship with spur leaf area rather than DLI. Firstly, looking at the average difference in leaf area between the two row spacings (Table 6), the leaf area per spur is significantly higher in the 1.5 m rows.

Table 6: Average spur leaf area (mm^2) by row spacing for 3 blocks in a 1.5 m row, and 3 blocks in a 2 m row from 16 sensor positions within planar cordon canopies of ‘Sweetheart’ cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Means that were significantly different based on LSD analysis are labelled with different letters.

Row Spacing (m)	Leaf area (mm2)
1.5	243.9 a
2	193.5 b

To know more about how the spur leaf area impacts on diameter, Figure 27: shows the relationship between leaf area and diameter for both 1.5 m and 2 m row spacing. While both had a significant positive relationship, the 1.5 m row spacing had a stronger relationship (R=0.45). When there are no spur leaves, both row spacings produce similar sized fruit, but as leaf area increases, size increases at a greater rate in the 1.5 m rows. This does not take into account yield however.

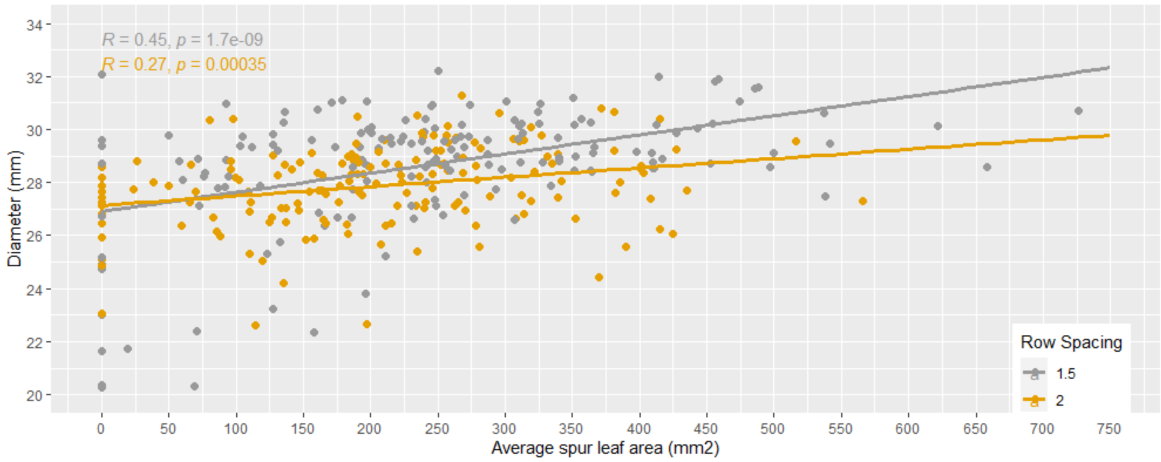

Figure 27: Linear fit of the relationship between average spur leaf area (mm^2) and fruit diameter (mm) averaged for each spur position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m (orange) or 1.5 m (grey) between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

To understand any yield effects, this correlation was separated into numbers of fruit per spur (Figure 28). While there were a few with more than 6 fruit per spur, the replication was too small to get any meaningful data. Interestingly, when the fruit per spur was lower (between 1 and 3 fruit per spur) the correlation coefficient was still steeper in the 1.5 m row spacing. Where, when the fruit number per spur was higher (between 4 and 6 fruit per spur) the difference between the row spacings were weaker.

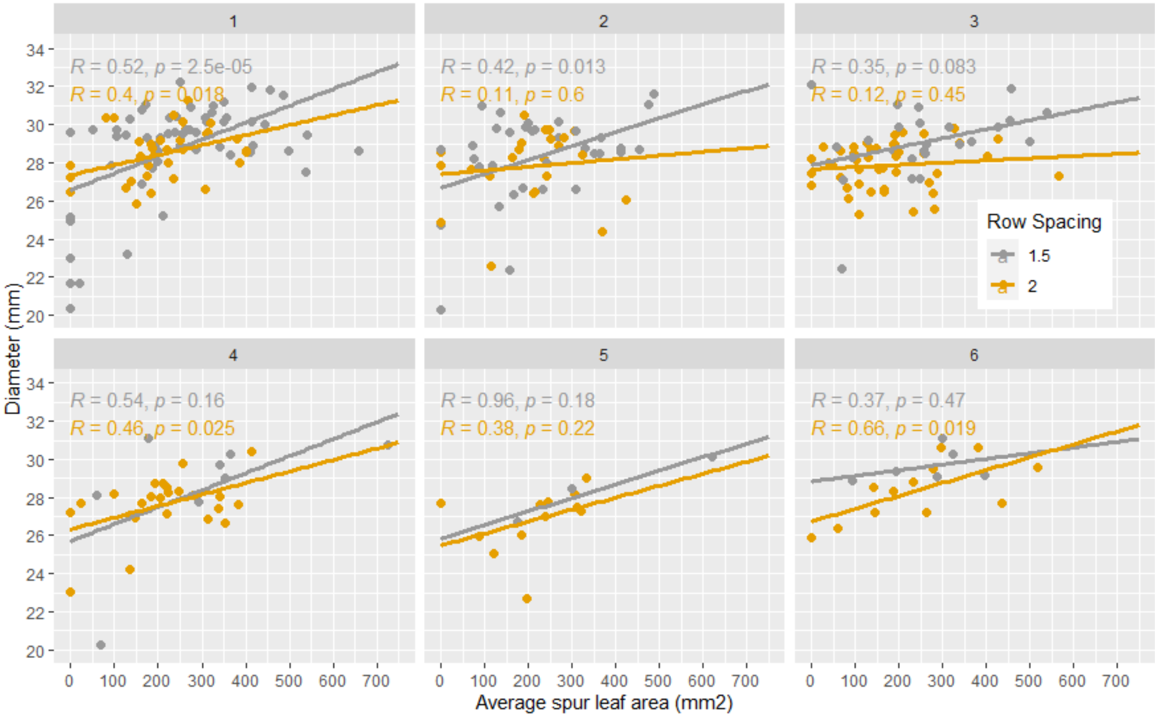

Figure 28: Linear fit of the relationship between average spur leaf area (mm^2) and fruit diameter (mm) averaged for each spur position within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m (orange) or 1.5 m (grey) between rows at the Clyde Research Centre over the 2020/21 season. Each graph represents number of fruit per spur between 1-6 fruit. Correlation coefficients (R) and significance levels (p-value) are displayed.

While this appears to be an important finding, it is also important to note that there are very few points where the 2 m row spacing has spurs with leaf area greater than 500 mm^2. It is possible that this lack of data is skewing the linear model where in fact the difference is due to overall lower leaf area per spur. If the light environment throughout the canopy in a 2 m row is higher, then it explains why the leaf area per spur is lower, as the necessary carbohydrates are available for fruit growth. Plotting average seasonal DLI by spur leaf area assesses the validity of this (Figure 29). Both 1.5 m and 2 m row spacing have a weak negative relationship, as the DLI increases, spur leaf area decreases. An explanation for this could be that as light availability increases, the need for larger leaves decreases as carbohydrate resources are not a limiting factor as discussed in the literature review.

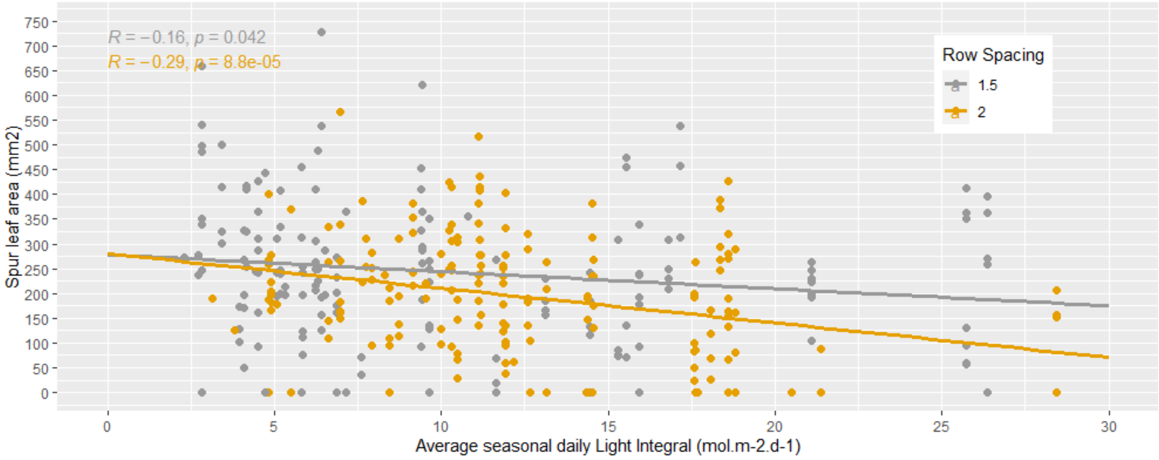

Figure 29: Linear fit of the daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the spur leaf area (mm2) associated with the sensor position within planar cordon canopy trees planted at 3 m between trees and 2 m (orange) or 1.5 m (grey) between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

However, this relationship is stronger in the 2 m row spacing (Figure 29). This difference may also be explained by the few points in the higher range of DLI, or that the seasonal DLI may not be reflecting the tree performance in any time point, and that points in time may differ a lot between positions and between row spacing. By separating these out into time periods this may be able to be understood more deeply. This will be discussed later in this chapter.

While there is no relationship between seasonal average DLI and return bloom, there is a relatively strong relationship between spur leaf area and return bloom percentage (Figure 30). While overall return bloom average is higher in the 1.5 m row spacing, the trends are very similar.

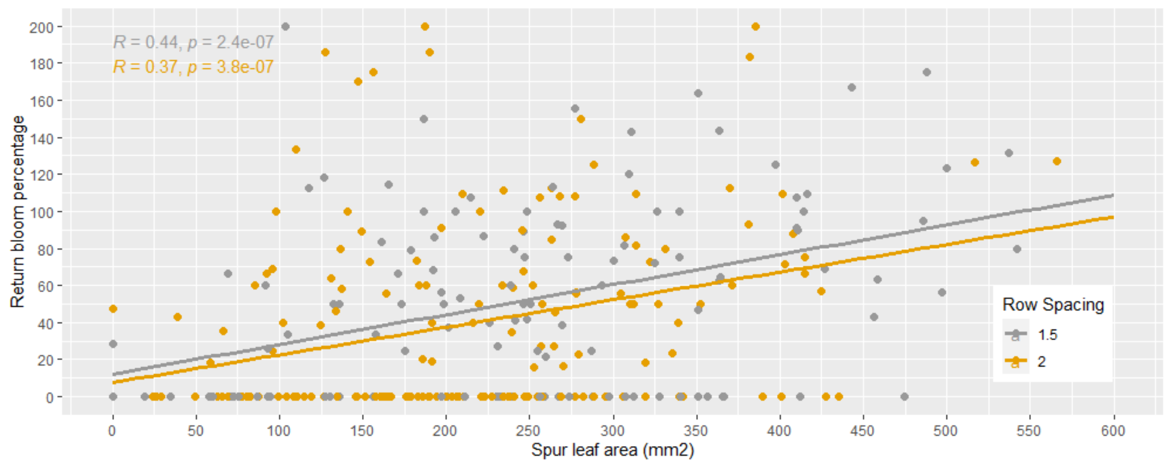

Figure 30: Linear fit of the spur leaf area for each sensor position within a block of three 'Sweetheart' cherry trees against the return bloom percentage within planar cordon canopy trees planted at 3 m between trees and 2 m (orange) or 1.5 m (grey) between rows at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

These data show that spur leaf area has a greater influence on return bloom than seasonal average daily light. Noting however, that there are also a significant number of spurs with varying degrees of spur leaf area with no return bloom as well.

5.3.6 Seasonal Variability in DLI

By understanding that seasonal average DLI is a broad measure of total light captured over the season, there are three distinct time periods at which light distribution through the canopy will be important for flower development and fruit set, fruit development, and then at harvest when floral initiation is occurring simultaneously with final fruit development.

To understand the light environment and the relationship between this and fruit quality, the light data were split into three time periods:

1.) Flowering and fruit set

2.) Pit hardening

3.) Leading up to harvest

5.3.6.1 Flowering and fruit set

During this time (29 August-26 October), light was relatively evenly distributed through the canopy at this early stage of seasonal development, apart from in the lowest part of the canopy (Table 7). At this time, most of the tree carbon is going into flower and shoot development.

Table 7: Average daily light integral (DLI, mol m^{-2} d^{-1}) between the period of 29th August and 26th October when trees are flowering and flowers are going through fruit set for 4 vertical positions in the canopy. Data are averaged over 3 blocks in a 1.5 m row, and 3 blocks in a 2 m row from 16 sensor positions within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Means that were significantly different based on LSD analysis are labelled with different letters.

Position in canopy (m)	Average Daily light integral
2.5	14.7 a
2	16.4 a
1.5	15.6 a
1	10.1 b

A correlation matrix with flowering and fruitset DLI (Figure 31) showed that SSC and diameter were no longer correlated with DLI, whereas fruit number per spur (Fnl_fruit_count) and yield per position (Punnet_weight) are correlated. Fruit set however had no relationship with DLI during this period.

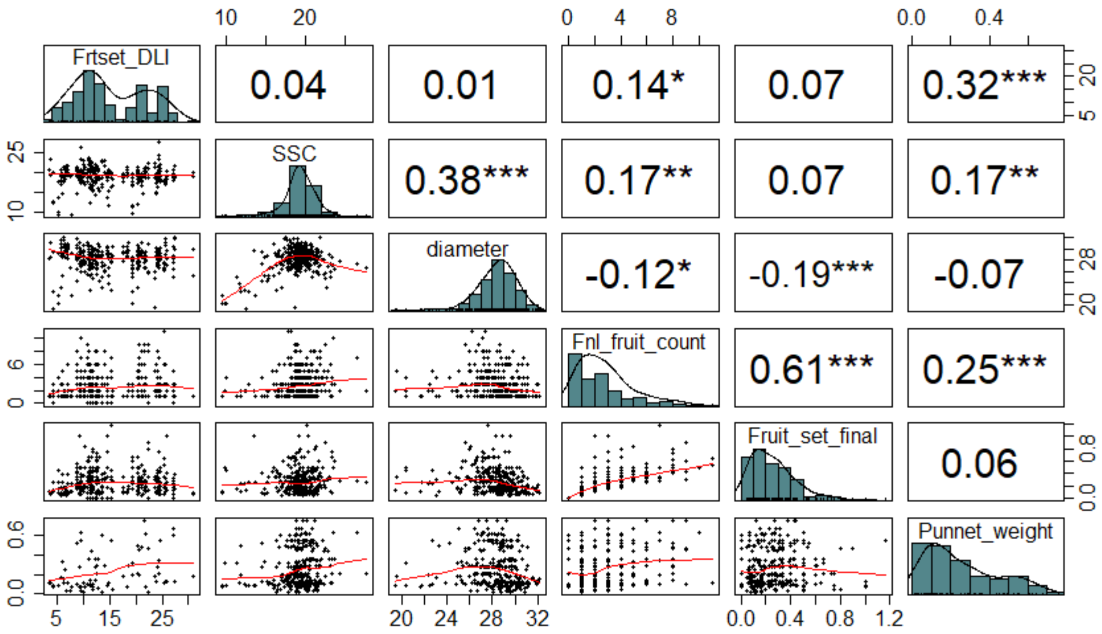

Figure 31: Correlation matrix of average daily light integral (DLI, mol m^{-2} d^{-1}) between the period of 29th August and 26th October, and fruit set and fruit quality characteristics; soluble solids concentration (SSC), fruit equatorial diameter (diameter), fruit spur number (Fnl_fruit_count), fruit set percentage (Fruit_set_final) and yield at each sensor position (Punnet_weight) from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots with a fitted line. The top of the diagonal shows the value of the correlation and the significance value as *P-values* (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols ("***", "**", "*", ".", " ").

Based on these results it can be concluded that the light in the early fruit development stage has the greatest impact on yield, but no influence on fruit quality. While there are numerous studies around light and yield and fruit quality on other fruits, few are focused on the time period of light and its influence. However, one study in apples found that the cell expansion stage (which in cherries is up to 30 days after full bloom (DAFB)) (Alkio et al., 2014) is the most important stage for determining final fruit weight in (Boini et al., 2022). But it is generally accepted that many other environmental factors are involved.

5.3.6.2 Pit hardening

Around pit hardening (Average readings from 10th Oct – 10th Nov), the trees have reached full leaf and there is now a significant difference between upper and lower canopy positions in terms of DLI. At this time, the tree carbon is being focused mainly on fruit development, and chapter four showed a slowing in canopy growth over this time.

Table 8: Average daily light integral (DLI, mol m^{-2} d^{-1}) between the period of 10th October – 10th November when fruit are at pit hardening stage for 4 vertical positions in the canopy. Data are averaged over 3 blocks in a 1.5 m row, and 3 blocks in a 2 m row from 16 sensor positions within planar cordon canopies of ‘Sweetheart’ cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Means that were significantly different based on LSD analysis are labelled with different letters.

Position in canopy (m)	Average Daily light integral
2.5	20.4 a
2	16.5 b
1.5	14.5 b
1	9.5 c

The correlation matrix for the month over pit hardening showed that the fruit number per spur did not appear to be affected by DLI and yield per position was still significant, but less so than at flowering and fruit set. However, a strong relationship between DLI during this time and SSC can be seen, but no other fruit quality metric.

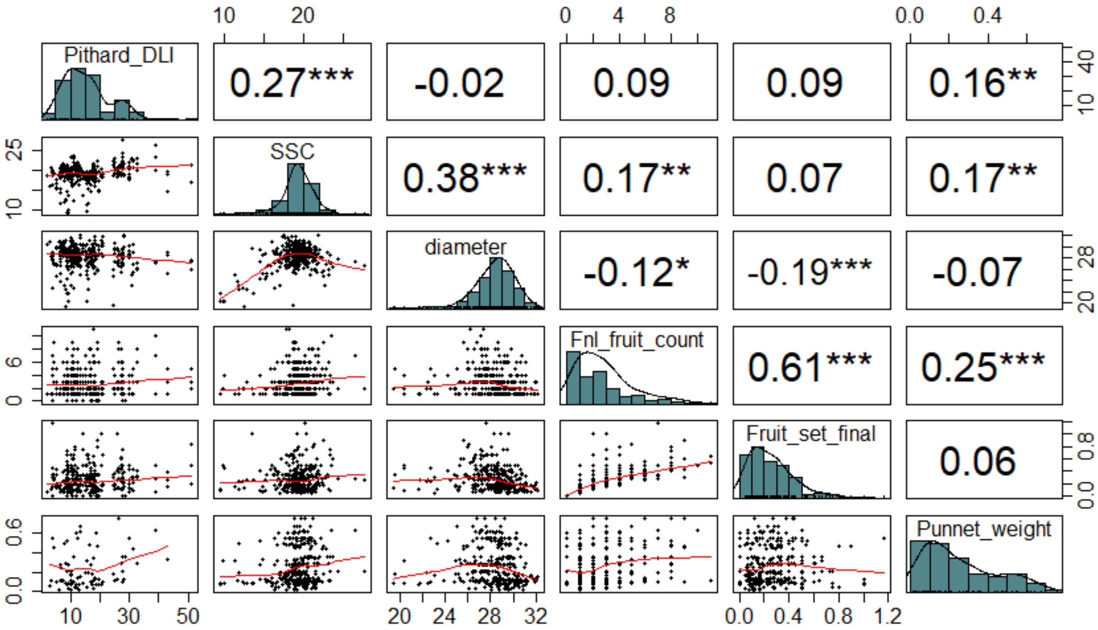

Figure 32: Correlation matrix of average daily light integral (DLI, mol m^{-2} d^{-1}) between the period of 10th October – 10th November, and fruit set and fruit quality characteristics; soluble solids concentration (SSC), fruit equatorial diameter (diameter), fruit spur number (Fnl_fruit_count), fruit set percentage (Fruit_set_final) and yield at each sensor position (Punnet_weight) from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots with a fitted line. The top of the diagonal shows the value of the correlation and the significance value as *P-values* (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols(“***”, “**”, “*”, “.”, " “).

Therefore, this time period around pit hardening is most important for soluble solids concentration accumulation as well as yield, but not for other factors. Stage two of cherry fruit development is categorised as 30-50 days after full bloom (Alkio et al., 2014), during this time the events occurring are the thickening and hardening of the cell walls, which is generally why GA3 is applied for improved fruit firmness at this stage (Einhorn et al., 2013). However, during this time there is only a slight enlargement of the cells (Vignati et al., 2022) which may explain the lack of influence on fruit size during this time.

5.3.6.3 Pre harvest

Similar to the full leaf at pit hardening, DLI is reduced down the canopy (Table 9 , but at this time the lower middle canopy was now showing a greater reduction in DLI, likely due to the shoot development that has occurred throughout the season.

Table 9 Average daily light integral (DLI, mol m^{-2} d^{-1}) between the period of 10th December – 10th January when fruit are at pit hardening stage for 4 vertical positions in the canopy. Data are averaged over 3 blocks in a 1.5 m row, and 3 blocks in a 2 m row from 16 sensor positions within planar cordon canopies of 'Sweetheart' cherries trees planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. Means that were significantly different based on LSD analysis are labelled with different letters.

Position in canopy (m)	Average Daily light integral
2.5	21.5 a
2	16.7 b
1.5	9.2 c
1	9.4 c

From the matrix, it appeared that this time point had very little influence on either yield or fruit quality characteristics, with only weak relationships between DLI and SSC and yield per position (Figure 33).

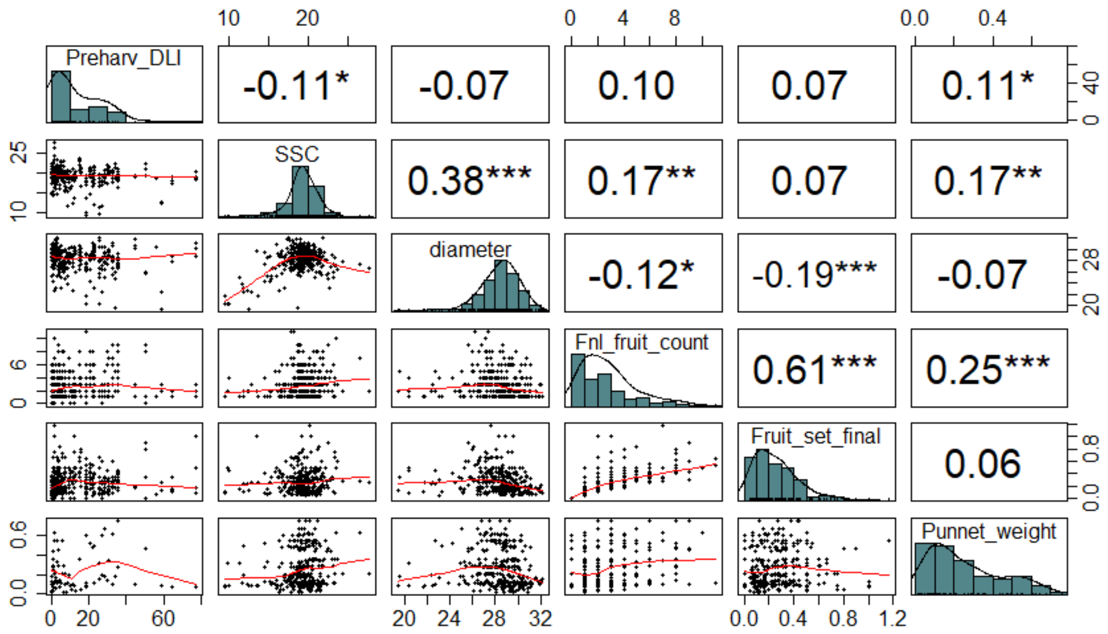

Figure 33 Correlation matrix of average daily light integral (DLI, mol m^{-2} d^{-1}) between the period of 10th December – 10th January, and fruit set and fruit quality characteristics; soluble solids concentration (SSC), fruit equatorial diameter (diameter), fruit spur number (Fnl_fruit_count), fruit set percentage (Fruit_set_final) and yield at each sensor position (Punnet_weight) from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season. The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots with a fitted line. The top of the diagonal shows the value of the correlation and the significance value as *P-values* (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols("***", "**", "*", ".", " ").

5.4 Conclusions

The hypothesis for this thesis was that the bud position in the planar cordon canopy does not affect fruit set or fruit quality. While there is significant variation within the samples, some clear trends were found.

The main findings from this experiment were:

- Yield of cherries is directly positively influenced by average seasonal daily light.
- There is a strong correlation between DLI and return bloom, as well as SCC. However fruit diameter is not affected when tree influence is accounted for.
- Spur leaf area decreased as DLI increased.
- Fruit size is more strongly correlated with spur leaf area than DLI or canopy position.
- The time period where light has the most influence on fruit quality is around flowering and fruit set.

Chapter 6: The use of reflective mulch to reduce variation in light and fruit quality in planar canopy cherries

6.1 Introduction

The use of reflective mulch in commercial operations to improve colour in apples has been commonplace for a number of years. Higher prices are gained for fruit with a high percentage of red blush, and therefore it has been found that the cost of installing reflective mulch is outweighed by the increase in profits for highly blushed fruit. Installing reflective mulch in cherries however is unusual in a commercial setting.

In New Zealand, rain and birds are two of the main factors that damage cherry crops, and therefore in many orchards bird netting and/or rain covers are installed. These are usually installed around early December for a mid-January harvest. In the lead up to harvest, this can reduce the amount of available light by up to 22% (Solomakhin and Blanke, 2007). Most of the reflective mulch research has been done in apples, particularly as hail nets used commercially in apple production throughout the world is in place for most of the growing season are known to reduce photosynthetically active radiation levels (PAR) by 12-27% (Widmer, 2001), prompting the need for reflective mulch . At 1 m above ground, use of reflective mulch has been found to increase reflected light in apple canopies by up to 3.9 times compared with uncovered grass alleys (Weber et al., 2019), or 30-40% reflection of incoming radiation vs 5-10% in grass control (Bastías and Corelli-Grappadelli, 2012). In some studies, this has been found to be even higher at 6.3 fold (Solomakhin and Blanke, 2007). A number of studies have shown that this increase in reflected light improves colouration in apples, particularly in the shaded side of the tree, and the lower inner part of the canopy (Solomakhin and Blanke, 2007; Hanrahan et al., 2011; Robinson, 2017). Solomakhin and Blanke (2007) showed the fruit in the lower canopy with reflective mulch had a darker red hue, as well as a 12% increase in the percentage of class I fruit than the grassed control, which equated to financial gains of up to €1300 ha^{-1}. However, Meinhold et al. (2011) suggested that €200 ha^{-1} was a more likely financial return.

In apples, between four to six weeks prior to harvest was considered the optimal installation time (Funke and Blanke, 2004; Meinhold et al., 2011). However mulch has been shown to be effective with exposure for as little as two weeks prior to harvest for improved fruit colouration (Layne et al., 2001; Funke and Blanke, 2021). While blush coverage is not an important consideration in most cherry varieties due to their even colouration, colour change to dark red is one of the main harvest timing criteria (Long, 2005). The increase in light availability in the lower portions of the canopy might reduce the amount of variation through the canopy in the timing of colouration. In apples, this may result in fewer picks (Hanrahan et al., 2011), or at least increase the amount of fruit harvested in the first pick (Layne et al., 2001; Funke and Blanke, 2021). Reducing the number of picks in cherry would be advantageous, as harvest costs make up an estimated 69% of the cost of production (Grant et al., 2011).

Other important fruit quality characteristics such as firmness, variation in fruit ripening and sugar accumulation have also been studied in apples with reflective mulch installed. Solomakhin and Blanke (2007) found that while there were no differences in fruit maturity and firmness, fruit from trees with reflective mulch contained 2.4% more SSC than those without reflective mulch, but also found that fruit in the lower canopy developed higher vitamin C contents compared with those without mulch. Research done by Ntagkas et al. (2019) in tomato showed similar results with vitamin C , and suggested this may contribute to public health. As well as greater colour, and higher soluble solids, (Vangdal et al., 2007) have found apple and pear trees grown with reflective mulch were larger than those from control trees.

There may also be long term effects of using reflective ground covers. Hanrahan et al. (2011) found that in apple, reflective mulch treatments increased fruit set and yield over multiple seasons. They, attributed this to increased light availability at each level in the canopy during floral initiation and bud differentiation.

In cherries, the first signs of floral initiation occur at 49 d after anthesis (Watanabe, 1982), and bud differentiation in sweet cherries ranges from 86 to 112 days after anthesis (Charlotte et al., 1998). In apple, floral initiation is occurs at around 80 to 90 days after anthesis (Milyaev et al., 2017). Later introduction of reflective mulch might be ok at lifting the light environment close to harvest to help during the period of bud initiation. Where in cherries this would need to be slightly earlier depending on cultivar to cover the floral initiation period.

Most of the detailed research into the use of reflective mulch has been conducted on conventionally grown central leader trees, particularly in apple. However, it is hypothesised that reflective film might greatly increase total canopy light interception in vertical or V shaped canopies. In vertical fruiting walls, which have a ratio of tree height to between row spacing of 1, the use of reflective films could increase total light interception to 80% (Robinson, 2017).

There is limited research on the use of reflective mulch in stone fruit, and in particular reflective mulch in two-dimensional cherry systems. However, Whiting et al. (2008) examined reflective ground covers on ‘Bing’ cherry in the USA and Chile. They found that the reflective mulch treatments increased mean shoot length and fruit matured ~5 days earlier. Given this earlier maturity, the number of picks were also able to be reduced from five to three (Hansen, 2006) . For fruit quality measurements, at a comparable maturity, fruit from the Extenday treated trees had 9% greater firmness, and 8% high total soluble solids than the untreated controls. Fruit size also increased by roughly the equivalent of 1-1.5 mm (Hansen, 2006). This increase in size while it may appear small, can make a ~30% difference in price received at market (Menzies, 2004).

In the USA, work on ‘Sweetheart’ on ‘Mazzard’ rootstock, when reflective mulch was applied before flowering and remained in place all season, average yield increased from 12.5kg to 20kg per tree. Differences in yield were still observed when the mulch was laid down later in the season, but not as prominent (Warner, 2008).

Most of the research on the use of reflective mulch is limited to fruit quality, in particular fruit colour, and some on yield. However, there are some studies that refer to summer pruning and reflective mulch treatments increasing leaf photosynthetic activity, specific leaf weight, and flower bud diameter (Bhusal et al., 2017).

From chapter four, it was confirmed that light transmission through a planar canopy is limited, particularly in the very narrow 1.5 m row spacing. The two lowest canopy positions show significantly lower light transmission than the upper canopy. While the 2 m row spacing showed improved transmission compared with the 1.5 m spacing, there was still a reduction in the daily light integral (DLI) through the canopy. Chapter five then confirmed that both canopy position, and average seasonal light were strong contributing factors in both yield and soluble solids concentration. Therefore, the aim of this chapter is to assess whether the introduction of reflective mulch may be useful in lifting the amount of transmitted light through reflection into the lower canopy light in order to improve soluble solids concentration and return bloom which would consequently improve yields.

6.2 Methods

6.2.1 Mulch installation

Using a block within the same experimental block as the larger trial. White Extenday™ (Extenday New Zealand Ltd, Auckland, New Zealand) reflective mulch was installed on the 27th of November 2020, approximately 60 days post anthesis (Figure 34).

This mulch was installed on one block of 3 trees in 1.5 m row spacing and one block of three trees in 2 m row spacing, andstayed in place through the growing season until leaf fall.

It was laid down on either side of the row, and filled the entire inter-row space for the 9 metres of tree length down the row. This meant that the width of the mulch was 1.5 m and 2 m depending on row spacing.

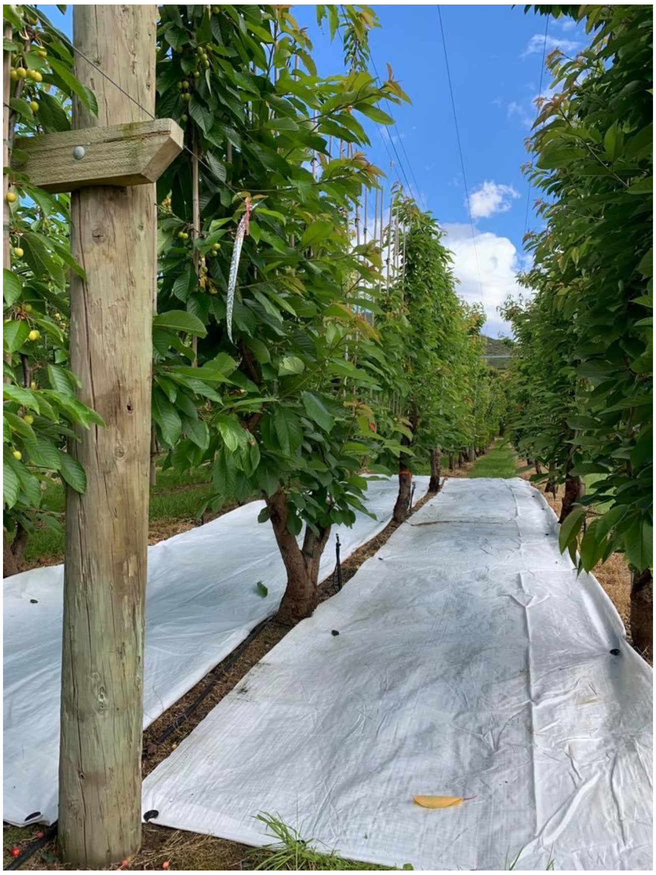

Figure 34: Extenday™ cloth laid down in a 1.5 m row spacing plot of 3 'Sweetheart' planar cordon trees within the larger trial planted in 2013 at the Clyde Research Centre on the 27th November 2020.

Mulch was cleared of falling plant debris throughout the season.

6.2.2 Quantification of light environment

Light was measured using the methods explained in chapter four, however only one time point was used for the analysis of the impact of Extenday mulch on the light environment. This gave the ability to measure both income radiation from above, as well as reflected light from below over at least a 24 hour period.

Light sensors were placed in all 16 vertical and horizontal positions within the canopy as explained in chapter four, with sensors in the same positions facing downwards.

6.2.3 Fruit quality measurements

Fruit set measurements were carried out using individual tagged spurs in each of the 32 positions within a canopy, with eight vertical upright shoots used within each of three trees. Flower counts were done around ‘popcorn’ stage ~20th September 2020. An initial fruit set count was then done on the 19th of October 2020 (Figure 35), and then a final fruit number at harvest on the 3rd January. From these data, a final fruit set count per spur was calculated. A severe -5°C frost on the 29th September (Figure 36) resulted in the deaths of many spurs, and therefore numbers of fruit available were less than originally planned.

Figure 35: Aborted fruitlets on the 19th of October 2020 on ‘Sweetheart’ planar cordon trees at the Clyde Research Centre.

Figure 36: Overhead frost fighting on the 29th September 2020, with a -5C frost, resulting in spur deaths on ‘Sweetheart’ planar cordon trees at the Clyde Research Centre.

Fruit were harvested into individual Plix® trays with barcoded labels with spur numbers to be taken back to the lab for an immediate assessment (Figure 37).

Figure 37: Harvesting ‘Sweetheart’ fruit from individual spurs from planar cordon trees at the Clyde Research Centre into Plix® single layer trays

The three fruit quality measurements used for the reflective mulch experiment were diameter, flesh firmness and soluble solids concentration. These were all measured immediately post-harvest. Diameter was measured using callipers to measure a single equatorial diameter at the widest position, flesh firmness was measured with a compression test with the fruit texture analyser (GÜSS, South Africa) with a flat metal plate commonly used in kiwiberry, and soluble solids concentration was measured using 3 drops of juice from a slice of an individual fruit using an Atago Pal-1 refractometer (Atago Co Ltd, Japan).

6.2.4 Statistical analysis

- All statistical analysis and graphing outputs were performed using R version 4.0.1.
- For multiple comparisons, averages were taken and p values calculated from analysis of variance (ANOVA) and least significance comparisons were gained using the Fisher-LSD test.
- Daily light integral was calculated as the µmol m−2 s−1 multiplied by 86,400 (number of seconds in a day) and divided by 106 (number of µmol in a mol).

6.3 Results and Discussion

6.3.1 Daily light environment

32 sensors per three tree block were set up, 16 facing upwards and 16 facing downwards to intercept both incoming light from above the canopy, and reflected light from the ground. This was repeated for all Extenday and no-Extenday treatments.

Between the 6th and the 19th of March, all treatments were measured for at least a 24 hour time period. Each sensor recorded single point PAR in μmol m^{-2} s^{-1}, every five minutes.

Using this data, the daily light integral (DLI) was calculated. This value integrates intensity and duration of light over an entire day. These data are shown in Table 10: Average daily light integral (DLI, mol m^{-2} d^{-1}) between the 6th and the 19th of March for Extenday™ treatment and control (no Extenday™) for all four canopy positions 1, 1.5, 2 and 2.5 metres from the ground, in both 1.5 m and 2.0 m row spacings.

Table 10: Average daily light integral (DLI, mol m^{-2} d^{-1}) between the 6th and the 19th of March for Extenday™ treatment and control (no Extenday™) for all four canopy positions 1, 1.5, 2 and 2.5 metres from the ground, in both 1.5 m and 2.0 m row spacings. Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different within a column.

	Control		Extenday™	
	Row Spacing (m)			
Vertical Canopy Position (m)	**1.5**	**2.0**	**1.5**	**2.0**
4 (2.5)	6.5 a	15.9 a	15.7 a	16.4
3 (2)	3.5 b	7.0 b	6.6 b	9.0
2 (1.5)	2.0 bc	2.9 c	2.8 b	8.6
1 (1)	0.9 c	1.7 c	1.9 b	7.9
P-value	< 0.001	< 0.001	= 0.001	n.s
Above canopy DLI for reference	27.3	25.2	24.5	25.1

In the control (no mulch) treatment, both 1.5 m and 2 m row spacings showed significant differences in DLI between positions in the canopy. There was also an obvious trend in reducing DLI down the canopy, with as little as 0.9 mol m^{-2} d^{-1} in the lowest part of the canopy. (Armitage et al., 1981) reported that seed geraniums required 1.94 mol m^{-2} d^{-1} for flower initiation and 3.25 mol m^{-2} d^{-1} for flower development. While this of course is a different species, it may be that the lowest canopy positions in both row spacings had light environments that are too low for optimum flowering and flower development. In the Extenday treatment, while there still appeared to be a trend for reducing light availability down the canopy, differences between positions were generally not significant. However, in the two lowest canopy positions in the 1 m row spacing, DLI is still very low, and well below the 3.25 mol m^{-2} d^{-1} needed for optimal development suggested by Armitage et al. (1981).

Figure 40 and Figure 42 illustrate this more clearly. In the 1.5 m row spacing, there is almost no difference between the treatments at either the 1 m and 1.5 m vertical positions within the canopy (Figure 38). Further up the canopy at 2 m and 2.5 m, differences between the Extenday and no Extenday treatments were visible, with higher DLIs and more variability among records in reflective mulch treatments. While it may appear that the treatments in the highest canopy position are significantly different from each other, when the errors of replications are included in the analysis, it is not considered significantly different, therefore the differences are more likely due to variation in tree architecture between treatments.

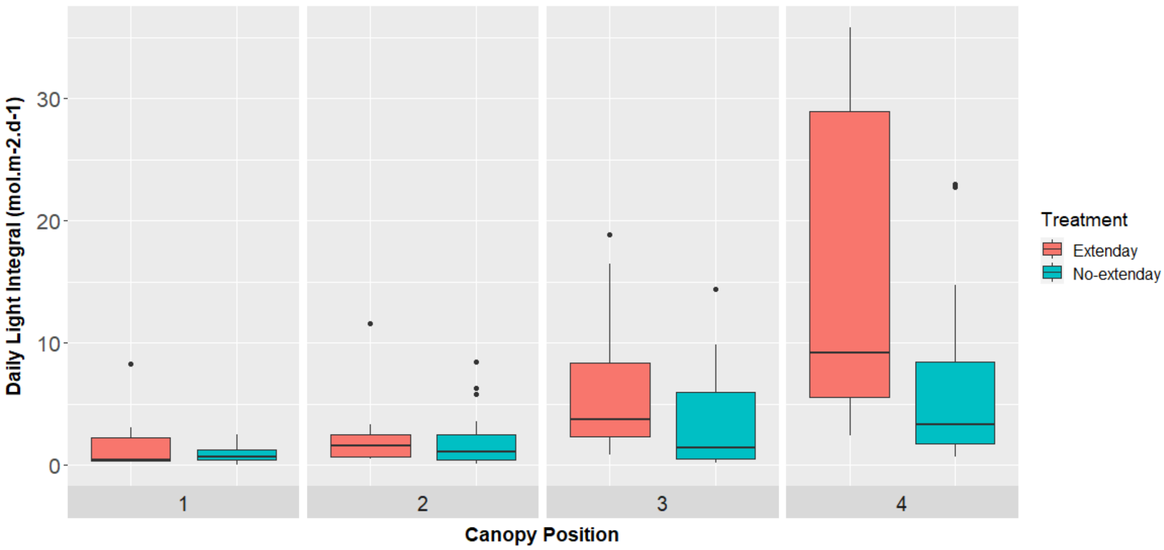

Figure 38: Average seasonal daily light integral (DLI, mol m^{-2} d^{-1}) for incoming radiation for Extenday™ treatment and control (no Extenday™) for all four canopy positions, in 1.5 m rows of planar cordon 'Sweetheart' trees. Boxplots include the minimum, the first quartile, the median, the third quartile and the maximum.

In the 2 m row spacing however, differences between reflective mulch treatments are more obvious (Figure 39). In the higher levels of the canopy, at 2 m and 2.5, no significant differences are seen between treatments, while in the lower canopy DLI is significantly higher in the Extenday treatment at 1 m ($p<0.001$) and 1.5 ($p=0.0128$). By increasing the DLI in the lower two canopy positions, the variation within the tree is greatly reduced. Theoretically, by creating a more even distribution of light, both fruit set and fruit quality should be more evenly distributed through the canopy, particularly as the light reaching the lower portions of the canopy in the Extenday treatment trees is four times that of the non-treated controls for the 2 m row spacing.

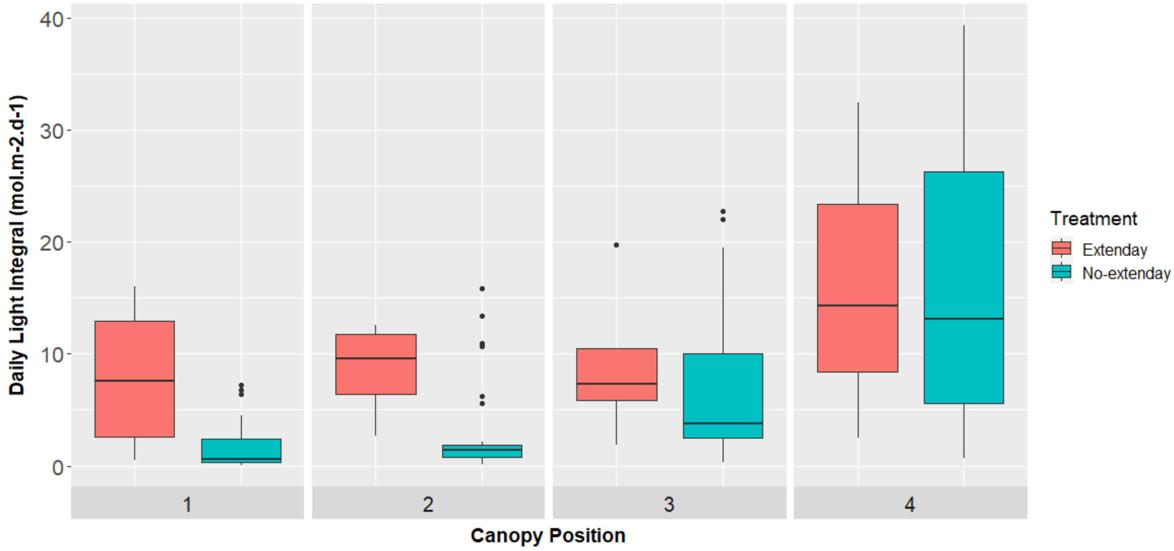

Figure 39: Average seasonal daily light integral (DLI, mol m^{-2} d^{-1}) for incoming radiation for Extenday™ treatment and control (no Extenday™) for all four canopy positions, in 2 m rows of planar cordon 'Sweetheart' trees. Boxplots include the minimum, the first quartile, the median, the third quartile and the maximum.

Given the increase in DLI in the lower canopy positions in the 2 m row spacing, but not in the 1.5 m row spacing, it may be that in the 1.5 m rows, there is not enough light getting through the canopy over a full day to be able to reflect the light back into the lower canopy. To find out whether this is in fact the case, the PAR readings from the sensors that were facing downwards to intercept the amount of reflected light were used to calculate reflected DLI. Figure 40 shows both row spacings 1.5 m and 2 m and the reflected DLI in the blocks lowest canopy position for each Extenday or no Extenday treatment. In, both row spacings mulch increased reflected DLI, however, only the 1.5 m row spacing is statistically significant (p=0.004), (2 m row spacing p= 0.061). While not statistically significant between treatments, the amount of light reflected in the 2 m row spacing is higher than that of the 1.5 m overall in both the Extenday treatment and control.

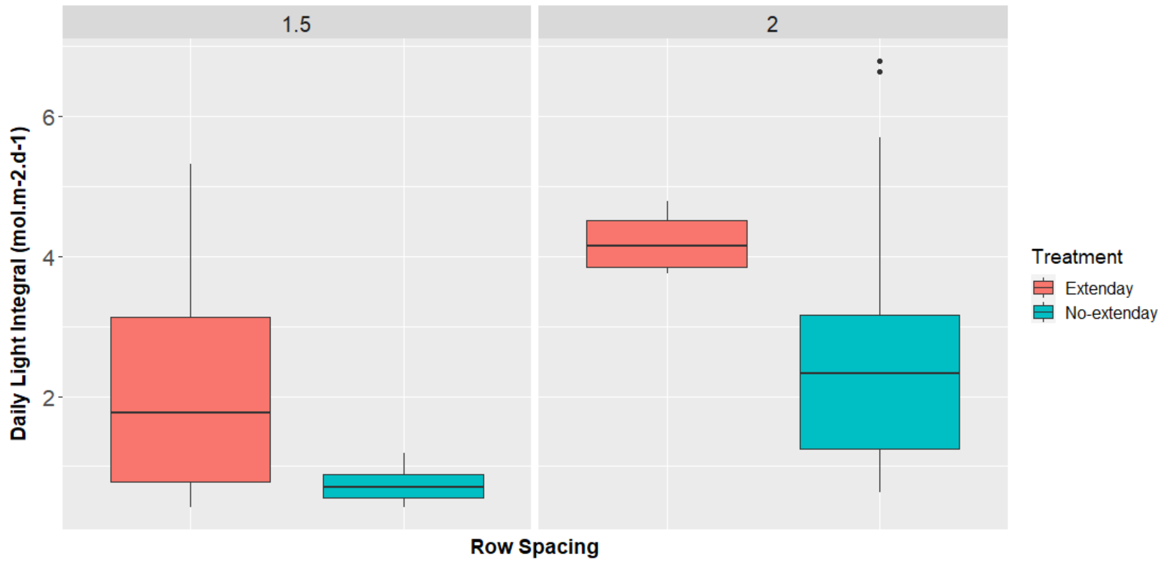

Figure 40: Average seasonal daily light integral (DLI, mol m^{-2} d^{-1}) for reflective radiation from sensors facing downwards, for Extenday™ treatment and control (no Extenday™) for the lowest canopy position (1 m), in 1.5 m and 2 m rows of planar cordon 'Sweetheart' trees. Boxplots include the minimum, the first quartile, the median, the third quartile and the maximum.

Therefore, by introducing Extenday into these narrow row planar cordon systems, it appears that DLI can be improved, but only in 2 m row spacing, where more light is able to reach the reflective mulch for it to be fully effective at reflecting enough light into the lowest canopy.

6.3.2 Hourly light environment

While the DLI provides an overview of how much light a plant is receiving over the course of the day, it does not explain what is happening within a day. To gain an idea of how the light environment changes over a day, PAR readings were averaged every hour for each treatment and row spacing and averages of multiple days plotted over a 24 hour time period for the lowest canopy position (Figure 41). Other than the expected higher PAR in the Extenday, and higher overall PAR in the 2 m row spacing, the only unexpected result was the difference in the time in which Extenday increased the available PAR in the lower canopy. For the 1.5 m row spacing, the increase in PAR was evident in the morning hours, up until approximately 13:00. Whereas in the 2 m row spacing, the increase in PAR was most noticeable after 13:00. Whereas for most of the day in both row spacings, either the morning or afternoon PAR was very similar between treatments. The rational for this is unclear, but it may be a simple explanation of tree architecture in the rows to the East and West of the measured trees having either porous or dense canopies. Another possibility is the sensor position and leaf shading from the East or West side.

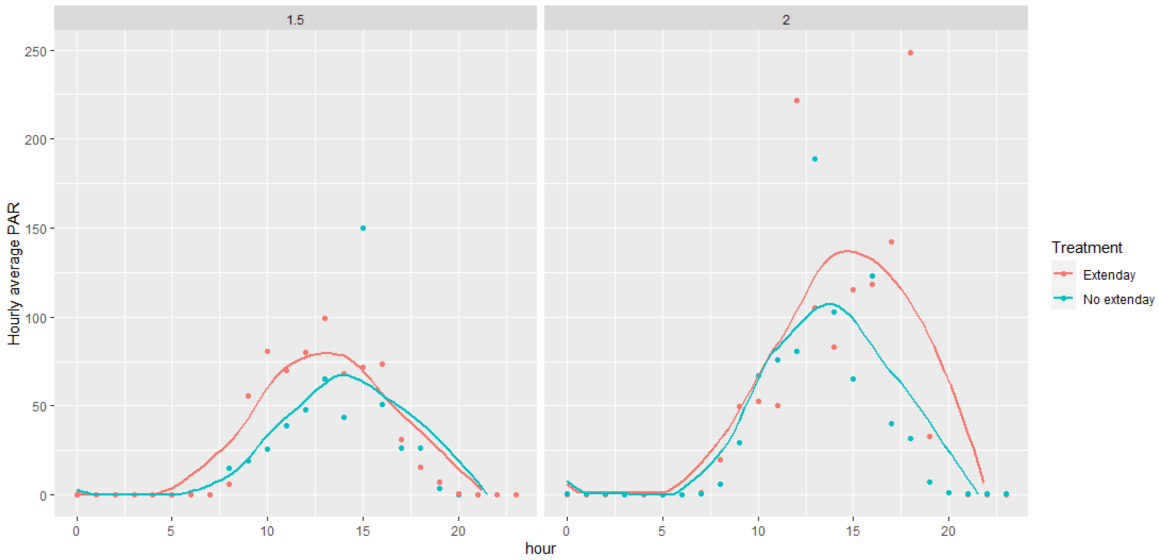

Figure 41: Hourly PAR (μmol s^{-1} m^{-2}) for Extenday™ and control (No-Extenday™) between the 6th and the 19th of March treatments in the lowest canopy position (1 m) within planar cordon 'Sweetheart' trees grown at 1.5 m and 2 m rowing spacings. Light measurements are presented every hour starting from midnight (0) to midnight (24).

6.3.3 Fruit Quality

6.3.3.1 Size

In cherries, size is one of the most important criteria for fruit quality. The larger the fruit, the higher the price. Therefore, growers will aim for fruit with a diameter above 28mm. Looking at the average diameter for each row spacing with and without Extenday mulch, there was no significant difference when averaged over the canopy between treatments (Table 11A). Given the increase in DLI in the lower canopy with the use of Extenday described earlier, an increase in size might be expected if there is a direct relationship. However this was not observed in the 2 m row spacing (Table 11).

Table 11: Average fruit size (mm) for treatments in each row spacing (A) for Extenday™ and control (No-Extenday™) treatments, and then for just the 1 m canopy position (B) Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different.

A	Row Spacing	
	1.5 m	2 m
No Extenday	28.5 a	27.9 a
Extenday	29.1 a	27.6 a

B	Row Spacing	
	1.5 m	2 m
No Extenday	27.2 a	28.5 a
Extenday	29.8 a	27.5 a

If the distribution of data is examined more closely, size distribution is wider in the no-Extenday treatments, particularly in the 1.5 m row. In this case around 5% of the fruit harvested under 26mm, while less than 1% of the fruit are under 26mm in the Extenday treatments (Figure 42). So while adding reflective mulch may not have an overall lift in average diameter, it contributed to reducing the variability of fruit quality within a canopy.

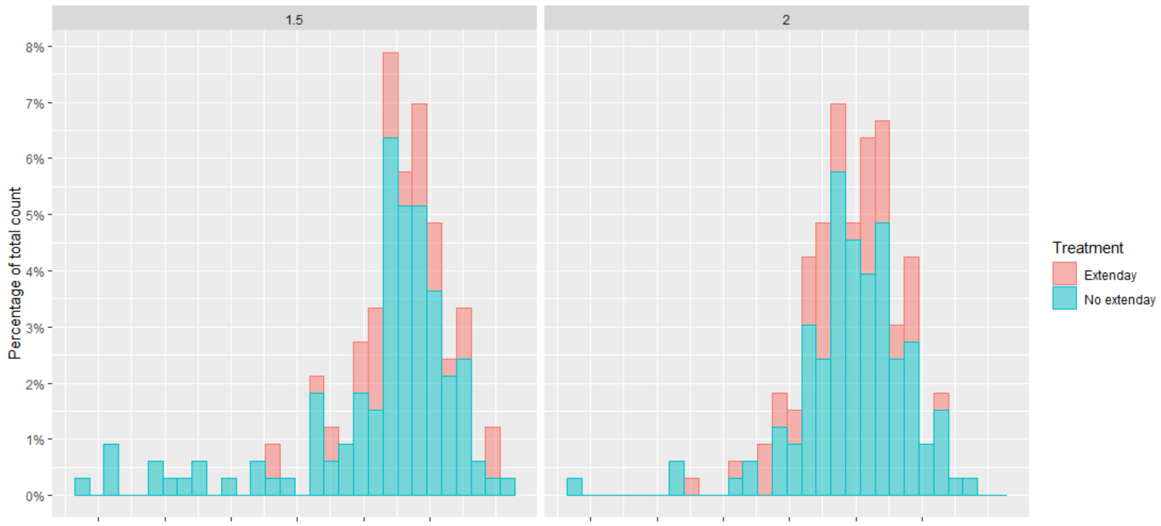

Figure 42: Frequency graph of the percentage of fruit that fell within each diameter for Extenday™ and control (No-Extenday™) treatments across 1.5 m and 2 m row spacing from planar cordon 'Sweetheart' trees at the Clyde Research Centre in the 2020-21 season.

This can be quantified further by breaking down the average diameters of the fruit into canopy positions to see if the variability can be reduced. Table 12 gives the average diameter of fruit from each vertical position within the canopy for both treatments at both row spacings. While there is a little variability, only the 1.5 m row spacing with no-Extenday shows statistically different means between canopy positions. So while within 2 m row spacings, there is an environment in which diameter has low variability, by adding Extenday mulch into a 1.5 m row, the light environment is able to be lifted enough to create better uniformity of fruit size.

Table 12: Average diameter for each canopy position in both row spacings with and without Extenday™ reflective mulch. Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different within a column.

	1.5 m		**2 m**	
Position in canopy	Extenday	No-Extenday	Extenday	No-Extenday
2.5 m	29.3 a	29.5 a	27.4 a	27.8 a
2 m	29.2 a	28.5 ab	27.8 a	27.7 a
1.5 m	28.7 a	28.2 b	27.5 a	28.1 a
1 m	29.8 a	27.2 b	27.5 a	28.6 a

6.3.3.2 Soluble Solids Concentration

If these same principles are applied to soluble solids concentration, a measure of fruit maturity, average soluble solids concentration over the entire canopy was slightly higher in both row spacings with the Extenday treatment, but only significantly so in the 2 m row spacing (p=0.0002). When just narrowing the data to the lowest canopy position at 1 m from the ground, there was no difference between treatments for soluble solids concentration in either row spacing (Table 13B).

Table 13: Average soluble solids concentration for treatments in each row spacing (A), and then for just the 1 m canopy position (B.) Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different.

A	Row Spacing	
	1.5 m	2 m
No Extenday	18.5 a	19.3 b
Extenday	19.3 a	20.4 a

B	Row Spacing	
	1.5 m	2 m
No Extenday	17.1 a	18.7 a
Extenday	16.8 a	18.7 a

However, looking at the distribution of data for all fruit (Figure 43), there was a similar distribution to the diameter data. While averages are similar, there is wider distribution of data between treatments. The no-Extenday control trees in the 1.5 m row spacing showing fruit with very low SSC down to 9°brix, and the Extenday treatment in the 2 m row spacing having a higher proportion of fruit above 20°brix. This suggests that while the averages between the two treatments are similar, the Extenday mulch is helpful to lift the proportion of fruit above a minimum brix level.

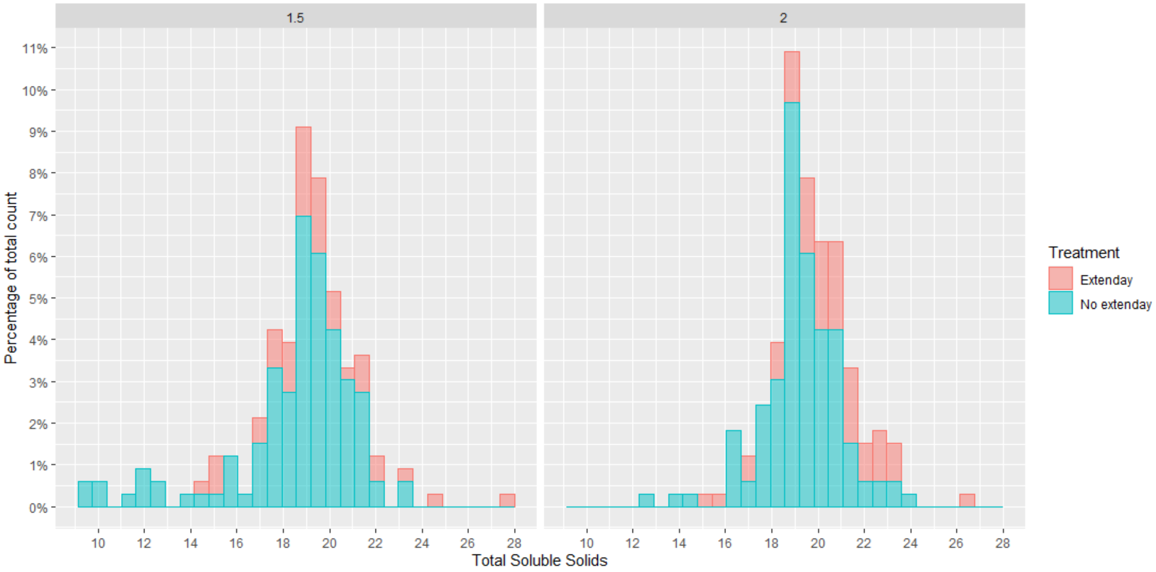

Figure 43: Frequency graph of the percentage of fruit that fell within each soluble solids concentration range for Extenday™ and control (No-Extenday™) treatments across 1.5 m and 2 m row spacing from planar cordon 'Sweetheart' trees at the Clyde Research Centre in the 2020-21 season.

If then is broken down into canopy positions, for each treatment and row spacing (Table 14) in both row spacings, there was a trend to decreasing SSC down the canopy ($p<0.001$). When Extenday is added, this difference was not as great, particularly due to an increase in the 1.5 m and 2 m positions within the canopy for both row spacings.

Table 14: Average soluble solids concentration for each canopy position in both row spacings with and without Extenday™ mulch. Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different within a column.

	1.5 m		2 m	
Position in canopy	Extenday	No-Extenday	Extenday	No-Extenday
2.5 m	18.9 a	20.3 a	21.0 a	20.4 a
2 m	20.2 a	18.3 b	20.8 a	19.1 b
1.5 m	18.8 a	17.9 b	19.5 a	18.8 b
1 m	16.8 a	17.1 b	18.7 a	18.7 b

6.3.4 Fruit quality in relation to DLI

Investigating the relationships between seasonal DLI and fruit quality, may allow better understanding of whether it is just the light environment impacting the fruit quality, or where other factors involved in canopy position are having a greater affect, for example wood age, leaf area or wood diameter.

A correlation matrix of seasonal average DLI and the fruit quality characteristics (diameter, flesh firmness and soluble solids concentration) (Figure 44) showed relationships between DLI and SSC and diameter but not flesh firmness. However when these data were split into treatments, there was little to no effect.

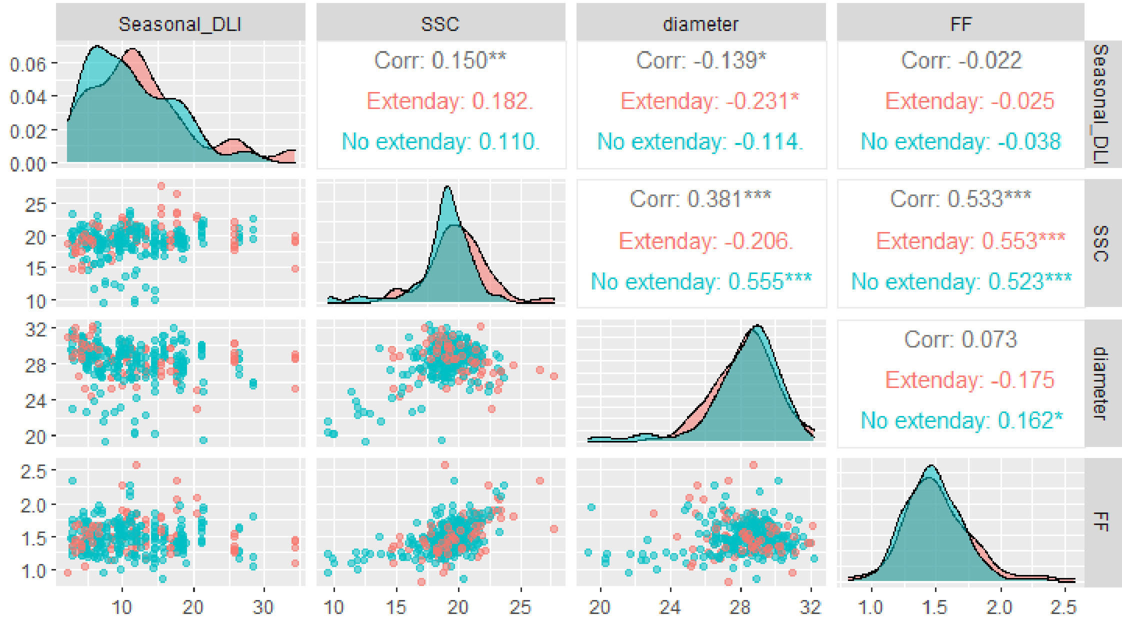

Figure 44: Correlation matrix of average seasonal daily light integral (DLI, mol m^{-2} d^{-1}), and fruit quality characteristics; soluble solids concentration (SSC), fruit equatorial diameter (diameter), and flesh firmness (FF) from 'Sweetheart' cherry trees trained as planar cordon canopies planted at 3 m between trees and 2 m or 1.5 m between rows at the Clyde Research Centre over the 2020/21 season with Extenday™ (orange) or control (No-Extenday™) treatments (green). The distribution of each variable is shown on the diagonal. The bottom of the diagonal shows bivariate scatter plots. The top of the diagonal shows the value of the correlation and the significance value as *P-values* (0, 0.001, 0.01, 0.05, 0.1, 1) <=> symbols ("***", "**", "*", ".", " ").

For example, the correlation matrix data appear to show size having a weak negative relationship associated with DLI (-0.139), with increasing DLI, diameter decreases. The linear relationship between both the Extenday and control treatments showed a very similar trend, however, Figure 45 shows the greater number of fruit with diameter below 24mm. So while the average diameter may be similar, the range of diameters at any given DLI is narrower in the Extenday treatment.

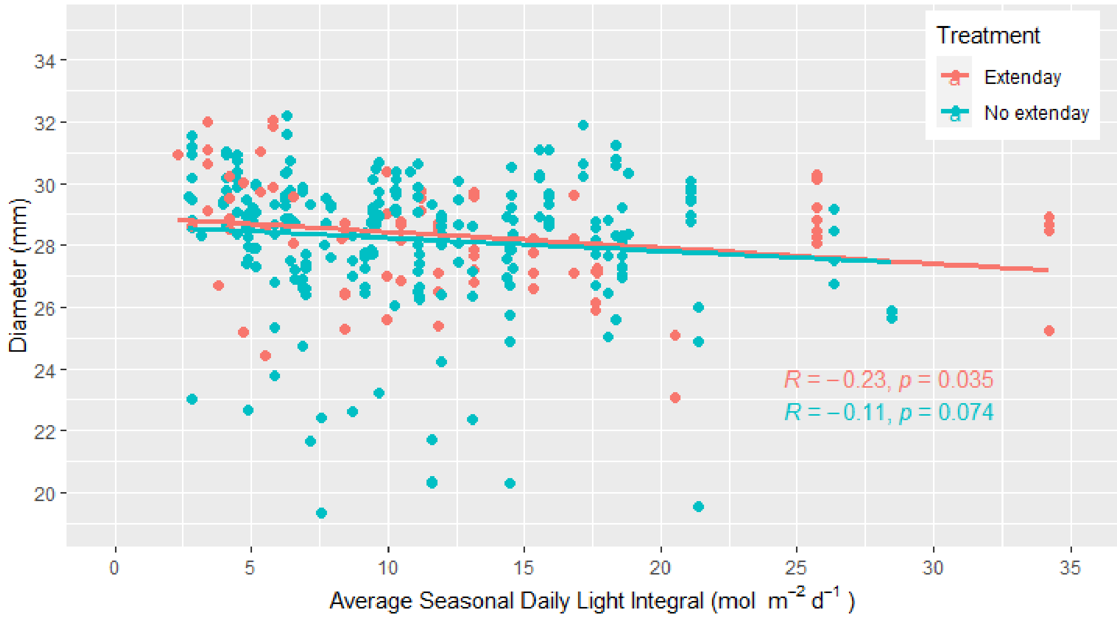

Figure 45 Linear fit of the season average daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the diameter (mm) associated with the sensor position within planar cordon canopy trees planted at 3 m between trees and 2 m or 1.5 m between rows for Extenday™ (orange) and control No-Extenday™ treatment (blue), at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

It is possible that the apparent unexpected reduction in diameter with an increase in DLI is probably explained by the presence of greater fruit numbers in the upper canopy where the high DLI usually occurs, although this is not immediately obvious with fruit number per spur (Figure 46), with a significant relationship in the control treatment (P<0.001) but not with the Extenday treatment (P=0.13). More replications with fruit from higher DLI positions would be needed to clarify whether there is a relationship here.

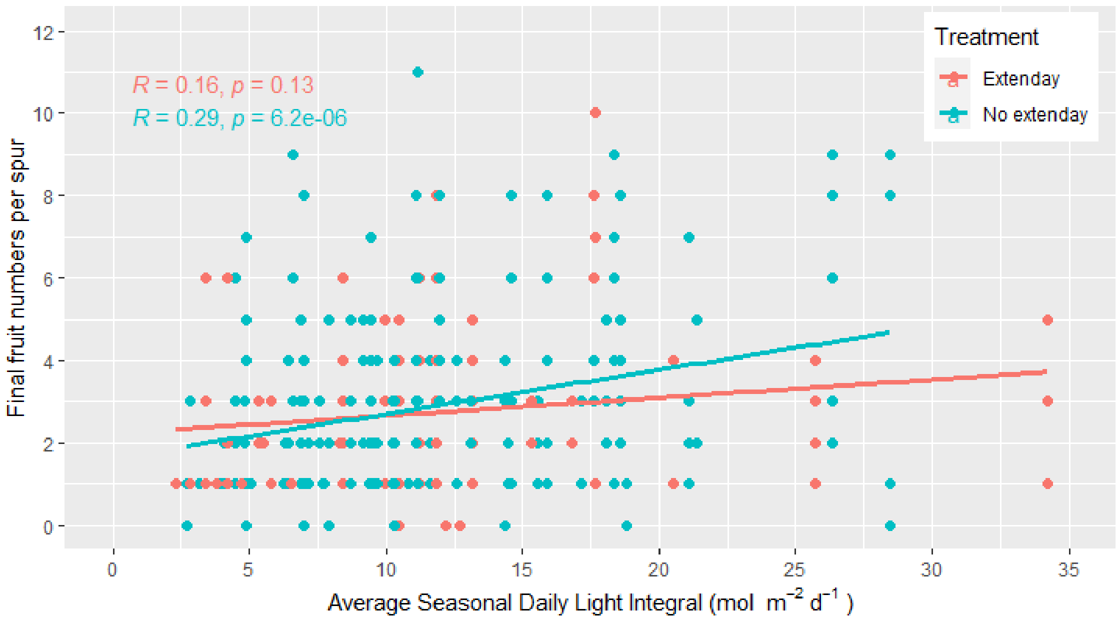

Figure 46: Linear fit of the season average daily light integral (DLI, mol m^{-2} d^{-1}) for each sensor position within a block of three 'Sweetheart' cherry trees against the final fruit numbers per spur associated with the sensor position within planar cordon canopy trees planted at 3 m between trees and 2 m or 1.5 m between rows for Extenday™ (orange) and control No-Extenday™ treatment (blue), at the Clyde Research Centre over the 2020/21 season. Correlation coefficients (R) and significance levels (p-value) are displayed.

6.3.5 Return bloom

The hypothesis of including Extenday day to improve the light environment within very narrow row planar cordon cherry systems was to understand whether yield could be improved by increasing the flower numbers in the lowest canopy.

However, this was not the case. Flower counts from the same spurs tagged in the previous season associated with a canopy position, showed that flower counts decreased between seasons, and Extenday treated trees show significantly fewer flowers than the untreated controls in the second season (Table 15).

Table 15: Average flower number per spur in both row spacings with and without Extenday™ mulch in the 2020 season and the 2021 season. Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different within a column.

	Average number of flowers per spur	
	2020 season	2021 season
Control	12.0	9.4
Extenday	11.5	6.7
p-value	n.s	n.s

When separated into row spacing (Table 16), flower numbers are similar in the 1.5 m row, but much lower in the 2 m row spacing. This again is an unexpected result, particularly as the Extenday was able to improve the light in the lower canopy in the 2 m rows. It is possible there is something else going on with tree health, particularly as these trees were affected by heavy late frost as described in chapter three.

Table 16: Average flower number per spur in either a 1.5 m or 2 m row, with and without Extenday™ mulch in the 2020 season and the 2021 season. Least Significant Difference (LSD) at 5% level of significance used within treatment + row spacing groups. Means followed by a common letter are not significantly different within a column.

	Average number of flowers per spur			
	2020 season		2021 season	
	1.5 m	2 m	1.5 m	2 m
Control	12.6	11.5	11.3	7.7
Extenday	11.5	11.5	10.7	6.7
p-value	n.s	n.s	n.s	n.s

6.4 Conclusions

While there is a lot of research on the use of Extenday in apple systems for the positive improvement of colour and soluble solids concentration, work on cherries is very limited. It is particularly useful to know that the use of reflective mulch can improve the light conditions within the lower canopies of planar cordon cherry systems. However, in this work, there appeared to be very few flow on effects on fruit quality and repeat bloom of this increased light.

The main findings from this experiment were:

- The available light in the lowest canopy with both row spacings was very low.
- An improvement in DLI was seen in the lower canopy, but only significant in 2 m rows.
- There was a reduction in SSC variability, and a reduction in the number of fruit below 14% SSC.
- There was a reduction in variability of fruit diameter in the 1.5 m row spacing, with a reduction in fruit <26mm in diameter.
- No other fruit quality improvements were found, nor return bloom.

Chapter 7: General discussion and conclusions

Sweet cherry is a fast-growing crop for New Zealand, with production area hectares increasing by more than 50% between 2017 and 2020 (Fresh Facts, 2022). With an industry goal to increase the value to $250 million by 2035, new ways of growing are having to be implemented that will improve both economic and ecological sustainability.

Economic constraints, compounded by increased costs due to the covid19 pandemic, as well as more environmental constraints are continually being placed upon growers.. Therefore systems that cut down input costs while simultaneously improving yields are desirable. With this in mind, two-dimensional systems have been designed, using the physiological driver of apical dominance to improve current growing systems.

However, in New Zealand, uptake of two-dimensional systems for cherry has been slow. A report by (Palmer, 2007) for the apple industry states that drivers for change within the industry include a demonstrated advantage over existing methods, as well as a having a reliable proven skill base to call on to help growers understand the system.

The previous chapters in this thesis begin to elicit knowledge and understanding of the planar cordon growing system for cherries to be able to demonstrate an advantage over conventional growing methods. This now has the option of being used in knowledge transfer for the industry, and as a basis for further research and development.

The main principle in the design of these systems is the improvement of light, both total light interception, as well as light distribution through a canopy. It is well documented that crop yields are positively related to total light interception (Monteith, 1977; Robinson and Lakso, 1991; Palmer et al., 2002). It is also well documented that fruit quality is positively related to light distribution (Halleb, 1933; Hamadziripi, 2012; Feng et al., 2014; Stanley et al., 2014). However, there are gaps in knowledge related to two-dimensional systems for cherry, or more specifically the planar-cordon system for cherry. While these systems were originally designed to improve light interception and distribution, those factors had not yet been quantified for cherry.

Based on the understanding that improved light distribution through the canopy should produce more even distribution of carbon resources, the outcome would be highly uniform fruit quality throughout the canopy. This assumption formed the basis of the hypothesis of this thesis.

The research for the thesis examined the light environment within planar cordon canopies and how this light environment affected particular fruit quality traits, fruit set and return bloom.

Three research objectives were set to achieve the aim above.

Light within planar cordon cherry canopies

The first objective was to quantify the light environment at points within a canopy, both over a day and across an entire season. Total light interception in perennial crops is well documented with literature published for many fruit crops (Grossman and DeJong, 1998; Palmer et al., 2002; Robinson, 2007b). However, limited for cherry, and even more limited for two-dimensional cherry systems. By measuring light within various positions in a planar cordon canopy, a greater understanding of light transmission through the canopies was able to be achieved. By evaluating the light environment both within a 1.5 m and a 2 m row, which are considerably lower than current three-dimensional and two-dimensional plantings, and understanding of row spacing effect on light could also be gained.

Row spacing did have an effect on average within-canopy light transmission. While the 2 m row showed slightly higher daily DLI over the majority of the season, this was not statistically significant. However, when averaged month by month, significant differences were seen. Due to a sensor malfunction, the 2 m row spacing is missing data from late December, so were unable to discuss late season DLI differences.

Light transmission varied throughout the vertical canopy, but this was only statistically significant in mid-December onwards, once canopies were in full leaf. This was particularly noticeable between the upper two and the lower two canopy positions.

When looking at the daily light curves, the highest total incident PAR on all sensors (the time when penetration of light into the canopy was greatest) occurred not at solar noon, but at around 10:00am. At solar noon, if the sun was directly overhead where there is a very narrow shadow, essentially the width of the canopy, with the lowest amount of canopy exposed. Either side of this there is an increase in sun exposure on one side of the tree and therefore, in these narrow canopies, an increase in light penetration. But as the angle of the sun changes, the neighbouring rows begin to interfere, and PAR would be expected to drop. Therefore, at 10am the sun angle at its most beneficial for optimal light penetration into the canopy in these rows.

Examining PAR at each of the vertical canopy positions averaged over an entire season showed significant differences down a canopy with around a 50% reduction in light from the top to the bottom of the canopy. However, the lowest two canopy positions in both row spacings were not significantly different from each other. The row spacing effect is evident in all vertical canopy positions, with the 2 m row spacing having significantly higher daily average PAR.

Significant differences in light between both row spacings and positions within a canopy may affect fruit quality and return bloom. However, even though mean PAR values were 100-150 μmol·s-1·m-2 in the lowest parts of the canopy, at various time points over a day and a season, there are periods where these lower canopies are receiving higher PAR, particularly during the early season with an open canopy. From literature, it is known that in conventional apple systems it has been estimated that only 2-12% of the available light penetrates into the centre of the canopy (Tustin et al., 1998; Fouché et al., 2010; Kviklys et al., 2022). Data presented here show that in these cherry canopies, even the lowest canopy position is receiving around 15% of the available light in full leaf. This slight increase may be enough to reap the benefits of improved fruit quality. However, literature also shows that shading of more than 55% of visible light reduces fruit quality, and in particular fruit size (Jackson, 1970; Musacchi and Serra, 2018). So this increased light penetration compared to conventional systems still may not be enough to improve these characteristics.

Fruit quality and fruit set

The second objective was to quantify fruit quality traits SSC, diameter and flesh firmness, as well as fruit set, return bloom and leaf area at different bud positions in the canopy, and investigate the relationship of these with positions in the canopy and with light received by the bud over a season. It is well documented in many crops that light is correlated with various fruit quality traits, in particular SSC and fruit weight (Hamadziripi, 2012; Feng et al., 2014; Stanley et al., 2014) as well as fruit set (Tustin et al., 1988).

Based on the results from this study, it can be confirmed that fruit yield of cherries is directly influenced by whole seasonal daily light. While there is a substantial variation, it is considered a significant effect, as DLI increases, so does yield. This is of course not a new concept, and has been studied across many crops. This is also evident in return bloom, where there is a strong correlation between DLI and return bloom the following season. While not as clear, trends also exist between DLI and fruit SSC and diameter. However, when tree influence is included, fruit diameter effects are more variable and clear trends are not obvious.

Spur leaf area though, appears to play a significant role in fruit size, more so than position or light, with the position in canopy having little effect at all on fruit size.

Spur leaf area decreased as DLI increased, as the tree appears to compensate for low light conditions by increasing leaf area, however, an unexpected finding in this study was that as spur leaf area increased, fruit size increased at a greater rate in 1.5 m rows than 2 m rows when there were low fruit numbers per spur. While this may be due to low fruit replication, a repeat of this study would be beneficial to tease out whether this is a true effect.

From chapter four, it is known that the DLI integral changes through the season, particularly early on with rapid leaf development. By separating the average DLI into three time periods, the timing when greatest influences on fruit quality were occurring could be observed. The strongest influence on yield occurred early in the season, which may in fact be a carry-over effect from the previous season, as it is known that DLI has a strong influence on return bloom. During this early season development, the DLI had very little influence on fruit quality, and this appears to be most relevant at the mid fruit development stage around pit hardening, where the strongest relationship is seen between DLI and SSC. Fruit size however shows no relationships, but as mentioned before, spur leaf area appears to be the greatest predictor of size.

Fruit size was not affected by canopy position, and appeared to be much more significantly affected by spur leaf area than either position in the canopy or DLI at any time during the season. However, SSC was strongly correlated to both DLI and canopy position, and the strongest correlation was seen with DLI at pit hardening.

Returning to the hypothesis for this thesis, that the bud position in the planar cordon canopy does not affect fruit set or fruit quality, these findings show that while bud position does not appear to significantly impact fruit set percentage, there is a difference between row spacings. This suggests that there is more going on than just the effect of position on fruit quality. This is particularly evident from the fact that there is a relationship between DLI and fruit set percentage, but only in a 1.5 m row where there is more variation in DLI throughout the canopy.

Reflective mulch

The third objective was to determine if the use of reflective mulch technologies could improve fruit quality traits should the light be limited in the lower canopy bud positions. Reflective mulch has been used in the apple industry for a number years, with many reports stating that reflective mulch is able to improve fruit quality traits by reflecting incoming light to increase available light by up to 6 fold (Solomakhin and Blanke, 2007; Bastías and Corelli-Grappadelli, 2012; Weber et al., 2019). The use of reflective mulch in cherries is however not commonplace, and there are no reports of reflective mulch being used in 2-dimensional cherry systems.

In this experiment, the available light in the lowest parts of the canopy in both 1.5 m and 2 m row spacings were very low, less than 1 mol m^{-2} d^{-1} in the 1.5 m row and less than 2 mol m^{-2} d^{-1} in the 2 m row. The addition of reflective mulch was able to double the DLI in the 1.5 m row, and quadruple it in the 2 m row. In both cases, the variation through the canopy was also reduced, with no statistical difference observed between the four canopy positions in the 2 m row spacing after the addition of reflective mulch.

From these data, it is clear that the 2 m row benefited the most from the introduction of a reflective mulch, as more light gets through the canopy to be able to be reflected back into the lower canopy. While an improvement was observed in the very narrow 1.5 m row, it was not significant in any vertical position in the canopy.

Fruit quality appeared not the change greatly with the addition of reflective mulch. Considering mean values of fruit SSC and fruit size, the only significant increase occurred in an increased SSC in fruit from the 2 m row spacing trees. However, examining population data for fruit SSC and size showed clear treatment differences. Regarding brix, there was a clear reduction in the percentage of fruit in the very under-ripe or low sugar fruit (<14%) in the harvest sample, and a decline in the variability of SSC through the canopy, with increased fruit SSC in fruit from the middle (1.5 m and 2 m) canopy positions. Similarly, this was noticed for fruit size. In this case, Extenday mulch reduced the percentage of fruit in the very small (<26mm diameter) range. As with SSC, there was also a reduction in variability of fruit size through the canopy in the 1.5 m row spacings by increasing the size in the lowest canopy position.

In regard to return bloom statistics, not only was there no increase in the number of flowers per spur in the lowest canopy positions with the introduction of Extenday mulch over the flower initiation period, there was also a reduction in average numbers between seasons suggesting some other influences, such as disease, frost or another seasonal effect such as alternate bearing. However, a reduction in the number of flowers per spur may not always be detrimental; if those flowers all produce fruit, those fruit might have optimal fruit quality. This should be investigated in further research. Chapter five discussed the relationships between DLI at different points in the season and fruit characteristics. It was found that early season DLI had the greatest effect on yield. It is possible therefore that the installation of Extenday should have occurred much earlier than November to see a greater effect.

7.1 Conclusions

In summary, the research aim and objectives set at the start of this thesis have been met. The first objective was to quantify light within canopies. It is now understood that light transmission through the canopies declines naturally as the canopy leaf area develops over a growing season. This decline occurred rapidly in the early season, and later slowed. Throughout the growing season, the average daily light integral tended to be higher in the 2 m row spacings, although not enough to be significant. However, when this daily difference was viewed across an entire season, row spacing effect was proven to be prominent in the later growing season when the canopy was in full leaf.

Within vertical canopies, the transmission of light was highest in the upper two canopy positions, and lowest in the bottom two canopy positions, but this was significant mainly in the latter part of the season once full leaf had developed. Hence in the early season the differences between canopy positions ware relatively small, although other physiological factors may be influenced.

Switching from seasonal to average daily light curves showed greater differences both between row spacings, and among canopy positions. Seasonal average PAR showed that the lowest vertical position in a 2 m row had the equivalent average light environment of approximately the third vertical position in a 1.5 m row spacing.

The second objective was to determine if the light environment was impacting fruit set and fruit quality. A correlation matrix showed that yield, SSC, fruit set and leaf area were all positively influenced by increasing DLI, and diameter was slightly negatively influenced by increasing DLI. This was generally true also for canopy position.

By separating the data into early, middle and late season DLI, it was found that early season DLI had the greatest influence on yield, the middle season DLI had greatest influence on SSC, and late season DLI had little influence on either fruit set/number or on fruit quality. Therefore for optimal orchard outcomes with sweet cherry, improving light penetration in the early and mid-season would provide the greatest benefits.

The third objective was to determine if low light levels in the bottom of the canopy were in fact impacting yield, fruit set and soluble solids concentration. If so, the implementation of reflective mulch could result in significant improvement in the light penetration into the lower canopy positions. There was an improvement in light penetration into the bottom of the canopy from using reflective mulch, but only in the 2 m row spacing. Possibly the 1.5 m row canopies were too dense for enough light to penetrate to the ground and be reflected back into the canopy. While the implementation of reflective mulch was useful for improving light in 2 m rows, the only improvement seen in fruit quality was a reduced variation of soluble solids concentration from comparing fruit taken throughout a canopy. While this would be an important improvement, the cost and time involved in implementing the reflective mulch technology could possibly not be justified.

Overall this thesis aimed to test the hypothesis that the bud position in the planar cordon canopy does not affect fruit set or fruit quality. Based on the outcomes from these three objectives outlined above, there is sufficient evidence to partially reject the hypothesis. The light environment through the vertical canopies was highly variable, as was fruit quality, but trends showed that some fruit quality factors were affected by canopy position (SSC) and others were not (diameter). Many other factors contribute to fruit quality within these canopies, particularly the yield influence, with the upper canopy having increased fruit numbers. However, light is still the driving factor. This research has initiated an early understanding of the light environment, fruit set and fruit quality and how each is distributed through these planar cordon canopies for cherry. However, to understand more about where the limits are for creating a system that has much more evenly distributed light, fruit quality and fruit set, as well as improve limitations from the previous research the following future work is proposed:

- Due to sensor malfunction, light measurements were not taken for the 2 m row spacing through to after harvest. Therefore, valuable data about the light environment during floral bud initiation was missed. It would be beneficial to complete light sampling right through to leaf fall to get a clearer picture of what happens during the whole season, including after harvest.
- From chapter five, it is known that early season light is the most important for fruit numbers. As reflective mulch was laid down only after full leaf had developed, this pre-flowering window of opportunity was captured. Greater benefit from using reflective mulch may have been demonstrated then, particularly in the 1.5m rows, and a repeat experiment with a longer implementation period would be desirable.
- Although planar cordon canopies at 1.5 m and 2 m row spacings have been shown to improve light interception and light penetration compared with three-dimensional canopies, light into the lower canopy regions was still lower than

the upper canopy regions, and this affected fruit quality and fruit numbers. Besides using reflective mulches, other methods to improve light in these lower regions could include increasing the row spacing, reducing tree height or reducing the number of vertical uprights per tree from 12 to 10 or 11. Whilst these options may reduce the amount of canopy available for fruit production, it may be offset by improved productivity and fruit quality in the lower canopy. While these options may have a slight effect on yield they could reduce variability. More testing would be needed to prove outcomes

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Appendix

Some statistical outputs

Chapter 5:

```
library(readxl)

library(agricolae)

library(ggplot2)

library(dplyr)

library(ggpubr)

hrly <- read_excel("K:/Claire Scofield/Old Docs/MSc/2020-2021/total_light_data.xlsx",
sheet = "hourly_light")


hrly<- filter(hrly, DLI > 0.5, DLI<60)

hrly1<-  subset(hrly, subset = Treatment == "No Extenday"&Position==c(1,2,3,4))
summary(hrly1)

##     Block            Row_spacing         Date
##  Length:4835        Min.   :1.500   Min.   :2020-09-17 00:00:00
##  Class :character   1st Qu.:1.500   1st Qu.:2020-10-29 00:00:00
##  Mode  :character   Median :1.500   Median :2020-12-03 00:00:00
##                     Mean   :1.704   Mean   :2020-11-27 05:50:50
##                     3rd Qu.:2.000   3rd Qu.:2020-12-19 00:00:00
##                     Max.   :2.000   Max.   :2021-01-23 00:00:00
##       Time                          Treatment           Values
##  Min.   :1899-12-31 02:00:00   Length:4835        Length:4835
##  1st Qu.:1899-12-31 10:00:00   Class :character   Class :character
##  Median :1899-12-31 13:00:00   Mode  :character   Mode  :character
##  Mean   :1899-12-31 13:08:02
##  3rd Qu.:1899-12-31 16:00:00
##  Max.   :1899-12-31 23:00:00
##     Position          PAR            Sunlight Hours      DLI
##  Min.   :1.000   Min.   :  10.69   Min.   :13     Min.   : 0.5004
##  1st Qu.:2.000   1st Qu.:  39.39   1st Qu.:13     1st Qu.: 1.8435
##  Median :3.000   Median : 100.95   Median :13     Median : 4.7245
##  Mean   :2.537   Mean   : 216.09   Mean   :13     Mean   :10.1128
##  3rd Qu.:4.000   3rd Qu.: 278.47   3rd Qu.:13     3rd Qu.:13.0324
##  Max.   :4.000   Max.   :1281.40   Max.   :13     Max.   :59.9695

hrly2 <-aggregate(cbind(DLI) ~ Date + Row_spacing +Position +Block, data = hrly1, mean, na.rm =
TRUE)


Splines <- ggplot(hrly2, aes(x = Date, y = DLI))+
  stat_summary(
    geom = "point",
    fun = "mean",
    col = "#78909C",
    size = 3,
    shape = 20,
    fill = "#78909C")+
  geom_smooth(col = "#78909C",method = "lm",formula = y ~ splines::bs(x, 3))+
  ylab("Daily Light Integral (mol.m-2.d-1)")+
  xlab("Date") +
  scale_y_continuous(breaks=seq(0, 40, 5))+
  theme(axis.text=element_text(size=14),
        axis.title=element_text(size=14,face="bold"),
        axis.title.x = element_text(margin = margin(t = 5, r = 0, b = 5, l = 0)),
        axis.title.y = element_text(margin = margin(t = 0, r = 15, b = 0, l = 5)))+
  stat_regline_equation(label.x.npc = 0.7, label.y.npc = 0.3, size=4.5,
                        formula = y ~ splines::bs(x, 3),
                        aes(label =  paste(..rr.label..)))

Linear<-ggplot(hrly2, aes(x = Date, y = DLI))+
```

```
  stat_summary(
    geom = "point",
    fun = "mean",
    col = "#78909C",
    size = 3,
    shape = 20,
    fill = "#78909C")+
  geom_smooth(col = "#78909C",method = "lm")+
  ylab("Daily Light Integral (mol.m-2.d-1)")+
  xlab("Date") +
  scale_y_continuous(breaks=seq(0, 40, 5))+
  theme(axis.text=element_text(size=14),
        axis.title=element_text(size=14,face="bold"),
        axis.title.x = element_text(margin = margin(t = 5, r = 0, b = 5, l = 0)),
        axis.title.y = element_text(margin = margin(t = 0, r = 15, b = 0, l = 5)))+
  stat_regline_equation(label.x.npc = 0.7, label.y.npc = 0.3, size=4.5,
                        aes(label =  paste(..rr.label..)))

Polynomial<-ggplot(hrly2, aes(x = Date, y = DLI))+
  stat_summary(
    geom = "point",
    fun = "mean",
    col = "#78909C",
    size = 3,
    shape = 20,
    fill = "#78909C")+
  geom_smooth(col = "#78909C",method = "lm", formula = y~poly(x,2))+
  ylab("Daily Light Integral (mol.m-2.d-1)")+
  xlab("Date") +
  scale_y_continuous(breaks=seq(0, 40, 5))+
  theme(axis.text=element_text(size=14),
        axis.title=element_text(size=14,face="bold"),
        axis.title.x = element_text(margin = margin(t = 5, r = 0, b = 5, l = 0)),
        axis.title.y = element_text(margin = margin(t = 0, r = 15, b = 0, l = 5)),
        plot.margin=margin(1,0,0,0, "cm"))+
  stat_regline_equation(label.x.npc = 0.5, label.y.npc = 0.3, size=4.5,
                        formula = y~poly(x,2),
                        aes(label =  paste(..rr.label..)))


library(ggpubr)

ggarrange(Linear, Polynomial+rremove("ylab"), Splines+rremove("ylab"),
          labels= c("Linear", "Polynomial", "Splines"),
          ncol=3, nrow=1, align="hv")

## `geom_smooth()` using formula 'y ~ x'
```

```
#Row spacing

ggplot(hrly2, aes(x = Date, y = DLI, colour=as.factor(Row_spacing)))+
  stat_summary(
    geom = "point",
    fun = "mean",
    size = 3,
    shape = 20)+
  geom_smooth(method = "lm", formula = y~poly(x,3))+
  ylab("Daily Light Integral (mol.m-2.d-1)")+
  xlab("Date") +
  scale_y_continuous(breaks=seq(0, 40, 5))+
  theme(axis.text=element_text(size=14),
        axis.title=element_text(size=14,face="bold"),
        axis.title.x = element_text(margin = margin(t = 5, r = 0, b = 5, l = 0)),
        axis.title.y = element_text(margin = margin(t = 0, r = 15, b = 0, l = 5)),
        legend.position = c(.95, .95),
        legend.justification = c("right", "top"))+
  stat_regline_equation(label.x.npc = 0.85, label.y.npc = 0.35, size=4,formula = y~poly(x,3),
                        aes(label =  paste(..rr.label..)))+
  labs(color = "Row Spacing") +
  scale_color_manual(labels = c("1.5m", "2m"), values = c("#523F95", "#F15F43"))
```

```
#Position in canopy

ggplot(hrly2, aes(x = Date, y = DLI, colour=as.factor(Position)))+
  stat_summary(
    geom = "point",
    fun = "mean",
    size = 3,
    shape = 20)+
  geom_smooth(method = "lm", formula = y~poly(x,3))+
  ylab("Daily Light Integral (mol.m-2.d-1)")+
  xlab("Date") +
  scale_y_continuous(breaks=seq(0, 40, 5))+
  theme(axis.text=element_text(size=14),
        axis.title=element_text(size=14,face="bold"),
        axis.title.x = element_text(margin = margin(t = 5, r = 0, b = 5, l = 0)),
        axis.title.y = element_text(margin = margin(t = 0, r = 15, b = 0, l = 5)),
        legend.position = c(.95, .95),
        legend.justification = c("right", "top"))+
  stat_regline_equation(label.x.npc = 0.35, label.y.npc = 0.7, size=4,formula = y~poly(x,3),
                        aes(label =  paste(..rr.label..)))+
  labs(color = "Canopy Position") +
  scale_color_manual(labels = c("1m", "1.5m", "2m", "2.5m"), values = c("#523F95", "#D399C2", "#
48B888", "#F15F43"))
```

```
#Position in canopy and row spacing

ggplot(hrly2, aes(x = Date, y = DLI, colour=as.factor(Position)))+
  stat_summary(
    geom = "point",
    fun = "mean",
    size = 3,
    shape = 20)+
  geom_smooth(method = "lm", formula = y~poly(x,3))+
  ylab("Daily Light Integral (mol.m-2.d-1)")+
  xlab("Date") +
  scale_y_continuous(breaks=seq(0, 40, 5))+
  theme(axis.text=element_text(size=14),
        axis.title=element_text(size=14,face="bold"),
        axis.title.x = element_text(margin = margin(t = 5, r = 0, b = 5, l = 0)),
        axis.title.y = element_text(margin = margin(t = 0, r = 15, b = 0, l = 5)),
        legend.position = c(.98, .95),
        legend.justification = c("right", "top"))+
  stat_regline_equation(label.x.npc = 0.35, label.y.npc = 0.8, size=4,formula = y~poly(x,3),
                        aes(label =  paste(..rr.label..)))+
  labs(color = "Canopy Position") +
  scale_color_manual(labels = c("1m", "1.5m", "2m", "2.5m"), values = c("#523F95", "#D399C2", "#
48B888", "#F15F43"))+
  facet_grid(~Row_spacing)
```

Chapter 6:

```
library(readxl)

total_data <- read_excel("K:/Claire Scofield/Old Docs/MSc/2020-2021/total_data.xlsx",
                           sheet = "consolidated")

summary(total_data)

##     Block            Row_spacing        Spur_no          Code          
##  Length:346         Min.   :1.500   Min.   : 1.00   Length:346        
##  Class :character   1st Qu.:1.500   1st Qu.:22.00   Class :character  
##  Mode  :character   Median :2.000   Median :43.00   Mode  :character  
##                     Mean   :1.766   Mean   :44.01                     
##                     3rd Qu.:2.000   3rd Qu.:66.00                     
##                     Max.   :2.000   Max.   :94.00                     
##                                                                       
##   Treatment            Position       Sensor_no         Sensor         
##  Length:346         Min.   :1.000   Min.   : 1.000   Length:346        
##  Class :character   1st Qu.:2.000   1st Qu.: 5.250   Class :character  
##  Mode  :character   Median :3.000   Median : 8.000   Mode  :character  
```

```
##                    Mean   :2.725   Mean   : 8.922
##                    3rd Qu.:3.000   3rd Qu.:14.000
##                    Max.   :4.000   Max.   :16.000
##
##  Block_sensor       Upright_no       Flr_count     Intl_fruit_count
##  Length:346         Mode:logical   Min.   : 2.00   Length:346
##  Class :character   NA's:346       1st Qu.: 8.00   Class :character
##  Mode  :character                  Median :12.00   Mode  :character
##                                    Mean   :11.84
##                                    3rd Qu.:15.00
##                                    Max.   :30.00
##                                    NA's   :20
##  Fnl_fruit_count  Fruit_set_initial Fruit_set_final    Frt_weight
##  Min.   : 0.000   Min.   :0.0000    Min.   :0.0000   Min.   : 4.019
##  1st Qu.: 1.000   1st Qu.:0.1429    1st Qu.:0.1111   1st Qu.: 9.895
##  Median : 2.000   Median :0.2667    Median :0.2308   Median :11.184
##  Mean   : 2.853   Mean   :0.2962    Mean   :0.2651   Mean   :10.846
##  3rd Qu.: 4.000   3rd Qu.:0.4000    3rd Qu.:0.3333   3rd Qu.:12.079
##  Max.   :11.000   Max.   :1.0000    Max.   :1.1667   Max.   :14.942
##  NA's   :20       NA's   :25        NA's   :21       NA's   :16
##     diameter           FF              SSC        Punnet_weight
##  Min.   :19.35   Min.   :0.815   Min.   : 9.50   Min.   :0.0100
##  1st Qu.:27.27   1st Qu.:1.325   1st Qu.:18.31   1st Qu.:0.1000
##  Median :28.59   Median :1.474   Median :19.30   Median :0.2050
##  Mean   :28.21   Mean   :1.487   Mean   :19.15   Mean   :0.2609
##  3rd Qu.:29.56   3rd Qu.:1.627   3rd Qu.:20.45   3rd Qu.:0.3600
##  Max.   :32.20   Max.   :2.579   Max.   :27.75   Max.   :0.7600
##  NA's   :16      NA's   :16      NA's   :16      NA's   :10
##   Seasonal_DLI     Pithard_DLI      Preharv_DLI         Frtset_DLI
##  Min.   : 2.309   Min.   : 2.082   Min.   : 0.07493   Min.   : 3.376
##  1st Qu.: 6.404   1st Qu.: 9.640   1st Qu.: 2.37948   1st Qu.:10.087
##  Median :10.472   Median :14.449   Median : 8.71989   Median :12.627
##  Mean   :11.625   Mean   :16.098   Mean   :14.76288   Mean   :15.147
##  3rd Qu.:15.555   3rd Qu.:19.141   3rd Qu.:23.02190   3rd Qu.:20.981
##  Max.   :34.233   Max.   :51.218   Max.   :77.42268   Max.   :31.010
##  NA's   :3
##    DLI_March       LeafLength1      LeafLength2      LeafLength3
##  Min.   : 0.000   Min.   :  0.00   Min.   :  7.94   Min.   :  6.625
##  1st Qu.: 1.097   1st Qu.: 21.34   1st Qu.: 23.86   1st Qu.: 26.525
##  Median : 3.490   Median : 35.42   Median : 42.10   Median : 42.100
##  Mean   : 5.390   Mean   : 35.78   Mean   : 42.82   Mean   : 44.978
##  3rd Qu.: 7.684   3rd Qu.: 49.38   3rd Qu.: 57.26   3rd Qu.: 61.425
##  Max.   :32.467   Max.   :105.66   Max.   :117.14   Max.   :117.140
##  NA's   :143                       NA's   :43       NA's   :54
##   LeafLength4      LeafLength5      LeafLength6      LeafLength7
##  Min.   :  5.46   Min.   : 6.625   Min.   : 11.02   Min.   :  7.94
##  1st Qu.: 23.86   1st Qu.:21.345   1st Qu.: 26.52   1st Qu.: 23.86
##  Median : 42.10   Median :42.100   Median : 38.68   Median : 38.68
##  Mean   : 43.22   Mean   :41.903   Mean   : 42.93   Mean   : 41.82
##  3rd Qu.: 60.58   3rd Qu.:57.260   3rd Qu.: 57.26   3rd Qu.: 57.26
##  Max.   :105.66   Max.   :94.780   Max.   :105.66   Max.   :100.14
##  NA's   :81       NA's   :117      NA's   :175      NA's   :241
##   LeafLength8      LeafLength9      LeafLength10    LeafLength11
##  Min.   :  7.94   Min.   :  7.94   Min.   :16.76   Min.   :18.98
##  1st Qu.: 21.34   1st Qu.: 17.87   1st Qu.:26.52   1st Qu.:28.97
##  Median : 42.10   Median : 32.92   Median :35.42   Median :44.78
##  Mean   : 44.12   Mean   : 35.40   Mean   :38.65   Mean   :47.03
##  3rd Qu.: 65.74   3rd Qu.: 45.66   3rd Qu.:57.26   3rd Qu.:62.84
##  Max.   :117.14   Max.   :105.66   Max.   :57.26   Max.   :79.58
##  NA's   :298      NA's   :319      NA's   :341     NA's   :342
##   LeafLength12    LeafLength13    LeafLength14    LeafLength15
##  Min.   :23.86   Min.   :57.26   Min.   :35.42   Min.   :42.10
##  1st Qu.:30.24   1st Qu.:59.38   1st Qu.:37.09   1st Qu.:49.13
##  Median :36.62   Median :61.50   Median :38.76   Median :56.15
##  Mean   :36.62   Mean   :61.50   Mean   :38.76   Mean   :56.15
##  3rd Qu.:43.00   3rd Qu.:63.62   3rd Qu.:40.43   3rd Qu.:63.18
##  Max.   :49.38   Max.   :65.74   Max.   :42.10   Max.   :70.20
##  NA's   :344     NA's   :344     NA's   :344     NA's   :344
##     Sum_area      Count_leaves     1yr_shoots         Return_bloom
##  Min.   :  0.0   Min.   : 1.000   Length:346         Min.   : 0.000
##  1st Qu.:126.7   1st Qu.: 4.000   Class :character   1st Qu.: 4.000
##  Median :217.7   Median : 5.000   Mode  :character   Median : 9.000
##  Mean   :217.1   Mean   : 5.211                      Mean   : 9.186
##  3rd Qu.:297.1   3rd Qu.: 7.000                      3rd Qu.:13.000
##  Max.   :726.6   Max.   :15.000                      Max.   :34.000
```

```
##                                                                NA's   :115
##  Return_bloom_perc
##  Min.   :  0.00
##  1st Qu.:  0.00
##  Median : 27.92
##  Mean   : 56.32
##  3rd Qu.: 82.95
##  Max.   :500.00
##  NA's   :20

library(agricolae)

library(dplyr)

library(ggpubr)



ggplot(total_data, aes(x=Fnl_fruit_count, y=diameter))+
  geom_point()+
  geom_smooth(method=lm, se=FALSE)+
  facet_wrap(~Block)

## `geom_smooth()` using formula 'y ~ x'
```

```
#leaf area to all

library(dplyr)

Data.num =
  select(total_data,
         FF, SSC, diameter, Sum_area)

Data.DLI =   select(total_data,
                     Sum_area, Seasonal_DLI)


Data.num

## # A tibble: 346 x 4
##       FF   SSC diameter Sum_area
##    <dbl> <dbl>    <dbl>    <dbl>
##  1 NA     NA       NA       277.
##  2  1.46  20.2     29.6     238.
##  3  1.58  21.6     29.4     103.
##  4  1.39  20.8     29.8     127.
##  5  1.43  22       29.6     156.
##  6  1.89  23.2     27.5     538.
##  7  1.5   19.4     28.9     193.
##  8  1.34  19.9     30.7     727.
##  9  1.36  21       29.4     127.
## 10  1.76  20.2     29.4     173.
## # ... with 336 more rows

library(PerformanceAnalytics)

library(psych)

chart.Correlation(Data.num,
                  method="pearson",
                  histogram=TRUE,pch=16,
                  hist.col= "blue")
```

```
pairs.panels(Data.num[1:4],
method = "pearson", # correlation method
hist.col = "cadetblue4",
density = TRUE,  # show density plots
ellipses = FALSE, # show correlation ellipses,
stars=TRUE,
cex.labels=3, cex.axis=1.5)
```

```
# Regression for fruit count/position by diameter per block

ggscatter(total_data, x = "Fnl_fruit_count", y = "diameter", add = "reg.line", color="Treatment"
,
          xlim = c(0, 10), ylim=c(18,32)) +
 scale_x_continuous(breaks = seq(from = 0, to = 10, by = 2))+
  facet_wrap(~Treatment~Row_spacing+Block)+
stat_cor(label.x = 6, label.y = 22) +
stat_regline_equation(label.x = 6, label.y = 20)

## `geom_smooth()` using formula 'y ~ x'
```

```
# Regression for fruit count/position by tree position per block

ggscatter(total_data, x = "Fnl_fruit_count", y = "Position", add = "reg.line", color="Treatment"
,
          xlim = c(0, 10), ylim=c(1,4)) +
  scale_x_continuous(breaks = seq(from = 0, to = 10, by = 2))+
  facet_wrap(~Treatment~Row_spacing+Block)+
  stat_cor(label.x = 6, label.y = 1.5) +
  stat_regline_equation(label.x = 6, label.y = 1.1)

## `geom_smooth()` using formula 'y ~ x'
```

```
# Regression for fruit count/position by DLI per block

ggscatter(total_data, x = "Fnl_fruit_count", y = "Seasonal_DLI", add = "reg.line", color="Treatm
ent",
          xlim = c(0, 10), ylim=c(1,20)) +
  scale_x_continuous(breaks = seq(from = 0, to = 10, by = 2))+
  facet_wrap(~Treatment~Row_spacing+Block)+
  stat_cor(label.x = 6, label.y = 1.5) +
  stat_regline_equation(label.x = 6, label.y = 6)

## `geom_smooth()` using formula 'y ~ x'
```

```
# Regression for SSC by leaf area

ggscatter(total_data, x = "SSC", y = "Sum_area", add = "reg.line",
          xlim = c(8, 30), ylim=c(1,800)) +
  scale_x_continuous(breaks = seq(from = 0, to = 30, by = 2))+
  facet_wrap(~Row_spacing)+
  stat_cor(label.x = 600, label.y = 750) +
  stat_regline_equation(label.x = 9, label.y = 800)

## `geom_smooth()` using formula 'y ~ x'
```

```
# Regression for diameter by leaf area

ggscatter(total_data, x = "Sum_area", y = "diameter", add = "reg.line",
          xlim = c(0, 800), ylim=c(18,34)) +
  scale_x_continuous(breaks = seq(from = 0, to = 800, by = 100))+
  scale_y_continuous(breaks = seq(from = 0, to = 34, by = 2))+
  facet_wrap(~Row_spacing)+
  stat_cor(label.x = 400, label.y = 20) +
  stat_regline_equation(label.x = 400, label.y = 19)

## `geom_smooth()` using formula 'y ~ x'
```

```
ggscatter(total_data, x = "diameter", y = "Sum_area", add = "reg.line",
          xlim = c(18, 34), ylim=c(1,800)) +
  scale_x_continuous(breaks = seq(from = 0, to = 34, by = 2))+
  facet_grid(~Position)+
```

```
  stat_cor(label.x = 19, label.y = 750) +
  stat_regline_equation(label.x = 19, label.y = 800)

## `geom_smooth()` using formula 'y ~ x'
```

Chapter 7:

```
library(readxl)

extenday_PAR <- read_excel("K:/Claire Scofield/Old Docs/MSc/2020-2021/extenday_light.xlsx",
                                             sheet = "PAR_long")

summary(extenday_PAR)

##     Block             Treatment              Hour                    
##  Length:101296      Length:101296      Min.   :2021-03-06 14:10:00  
##  Class :character   Class :character   1st Qu.:2021-03-09 08:05:00  
##  Mode  :character   Mode  :character   Median :2021-03-12 04:10:00  
##                                        Mean   :2021-03-12 20:55:12  
##                                        3rd Qu.:2021-03-16 17:40:00  
##                                        Max.   :2021-03-19 11:35:00  
##                                                                     
##       Date                          Time                      Row_spacing   
##  Min.   :2021-03-06 00:00:00   Min.   :1899-12-31 00:00:00   Min.   :1.500  
##  1st Qu.:2021-03-09 00:00:00   1st Qu.:1899-12-31 05:55:00   1st Qu.:1.500  
##  Median :2021-03-12 00:00:00   Median :1899-12-31 11:45:00   Median :2.000  
##  Mean   :2021-03-12 08:59:44   Mean   :1899-12-31 11:55:28   Mean   :1.795  
##  3rd Qu.:2021-03-16 00:00:00   3rd Qu.:1899-12-31 18:00:00   3rd Qu.:2.000  
##  Max.   :2021-03-19 00:00:00   Max.   :1899-12-31 23:55:00   Max.   :2.000  
##                                                                             
##     Facing             Values             Position         PAR         
##  Length:101296      Length:101296      Min.   :1.00   Min.   : -13.390  
##  Class :character   Class :character   1st Qu.:1.75   1st Qu.:   0.000  
##  Mode  :character   Mode  :character   Median :2.50   Median :   1.732  
##                                        Mean   :2.50   Mean   :  64.845  
##                                        3rd Qu.:3.25   3rd Qu.:  29.805  
##                                        Max.   :4.00   Max.   :2792.000  
##                                                       NA's   :733

library(ggplot2)

library(lubridate)

library(tidyverse)

library(dplyr)
library(scales)

extenday_PAR$PAR[extenday_PAR$PAR<5] <- 0

#Measuring only hourly

hours <- extenday_PAR %>%
  mutate(hour = hour(Time)) %>%
  group_by(hour, Position, Row_spacing,Block, Facing, Treatment)%>%
  summarise(
    PAR = mean(PAR, na.rm = TRUE),
    n = n())

## `summarise()` has grouped output by 'hour', 'Position', 'Row_spacing', 'Block', 'Facing'. You
can override using the `.groups` argument.

up_1.5m<-  subset(hours, subset = Facing == "up"&Row_spacing==1.5&Position==1)
up_2m<-  subset(hours, subset = Facing == "up"&Position==1)

down_1m <-  subset(hours, subset = Facing == "down"&Position==c(1))

down_1m$PAR[down_1m$PAR<10] <- 0


ggplot(down_1m, aes(hour, PAR, colour=as.factor(Treatment))) +
  facet_wrap(~Row_spacing)+
```

```
  geom_point()+
  stat_smooth(se=FALSE)+
  scale_y_continuous(limits = c(0,NA), breaks = seq(0, 140, by = 20)) +
  ylab("Hourly average PAR")+
  scale_color_discrete(name="Treatment")

## `geom_smooth()` using method = 'loess' and formula 'y ~ x'
```

```
ggplot(up_2m, aes(hour, PAR, colour=as.factor(Treatment))) +
  facet_grid(~ Row_spacing)+
  geom_point()+
  stat_smooth()+
  scale_y_continuous(limits = c(0,NA), breaks = seq(0, 2000, by = 50)) +
  ylab("Hourly average PAR")+
  scale_color_discrete(name="Treatment")

## `geom_smooth()` using method = 'loess' and formula 'y ~ x'
```

```
#Measuring every 5 mins

extenday_PAR$PAR[extenday_PAR$PAR<10] <- 0

summary(extenday_PAR)

##      Block              Treatment              Hour
##  Length:101296      Length:101296      Min.   :2021-03-06 14:10:00
##  Class :character   Class :character   1st Qu.:2021-03-09 08:05:00
##  Mode  :character   Mode  :character   Median :2021-03-12 04:10:00
##                                        Mean   :2021-03-12 20:55:12
##                                        3rd Qu.:2021-03-16 17:40:00
##                                        Max.   :2021-03-19 11:35:00
##
##       Date                          Time                     Row_spacing
##  Min.   :2021-03-06 00:00:00   Min.   :1899-12-31 00:00:00   Min.   :1.500
##  1st Qu.:2021-03-09 00:00:00   1st Qu.:1899-12-31 05:55:00   1st Qu.:1.500
##  Median :2021-03-12 00:00:00   Median :1899-12-31 11:45:00   Median :2.000
##  Mean   :2021-03-12 08:59:44   Mean   :1899-12-31 11:55:28   Mean   :1.795
##  3rd Qu.:2021-03-16 00:00:00   3rd Qu.:1899-12-31 18:00:00   3rd Qu.:2.000
##  Max.   :2021-03-19 00:00:00   Max.   :1899-12-31 23:55:00   Max.   :2.000
##
##     Facing              Values              Position         PAR
##  Length:101296      Length:101296      Min.   :1.00   Min.   :   0.00
##  Class :character   Class :character   1st Qu.:1.75   1st Qu.:   0.00
##  Mode  :character   Mode  :character   Median :2.50   Median :   0.00
##                                        Mean   :2.50   Mean   :  64.25
##                                        3rd Qu.:3.25   3rd Qu.:  29.80
##                                        Max.   :4.00   Max.   :2792.00
##                                                       NA's   :733

subset(extenday_PAR, PAR > 10)

## # A tibble: 38,572 x 10
##    Block Treatment Hour                Date                Time
##    <chr> <chr>     <dttm>              <dttm>              <dttm>
##  1 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  2 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  3 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  4 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  5 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  6 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  7 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  8 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
##  9 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
## 10 H27   Extenday  2021-03-06 14:10:00 2021-03-06 00:00:00 1899-12-31 14:10:00
## # ... with 38,562 more rows, and 5 more variables: Row_spacing <dbl>,
## #   Facing <chr>, Values <chr>, Position <dbl>, PAR <dbl>

up_1 <-  subset(extenday_PAR, subset = Facing == "up"&Position==1&PAR>2)
up_1$PAR[up_1$PAR < 10] <- 0
```

```
ggplot(up_1, aes(Time, PAR, colour=as.factor(Treatment))) +
  facet_wrap(~Row_spacing)+
  stat_smooth()+
scale_x_datetime(labels = function(Time) format(Time, format = "%H:%M"))+
  scale_y_continuous(limits = c(0, NA))+
  ylab("Hourly average PAR")+
  scale_color_discrete(name="Treatment")

## `geom_smooth()` using method = 'gam' and formula 'y ~ s(x, bs = "cs")'
```