

The Effect of Pre-Harvest Tree Management on Postharvest Fruit Quality

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Contents

Contents.....	II
List of Figures	II
1.0 Background	1
2.0 Carbohydrates.....	2
2.1 Effects of source availability on fruit quality	3
2.1.1 Crop load.....	4
2.1.2 Climate Effects on fruit quality	6
2.2 Carbohydrate Manipulation.....	6
2.2.1 Source Manipulation.....	7
2.2.2 Sink Manipulation	7
3.0 Nitrogen	9
3.1 Nitrogen Management.....	9
3.2 Effects of N nutrition on Fruit Quality.....	10
4.0 Conclusion.....	11
Cited References.....	12

List of Figures

		Page
1	Diagram of carbohydrate partitioning model (Génard et al., 1998)	3
2	Diagram of cherry fruit development pattern (Kupferman, 1986)	4
3	Tree trunk girdling (Mertes, 2013)	8

1.0 Background

The Australian sweet cherry (*Prunus avium*, referred to hereafter as cherry) industry is a relatively small producer by world standards, only producing approximately 0.5% of the world's total cherry production (James, P. (2011)). The cherry sector had a strong season in production terms in the 2012/13 year, with total production reaching approximately 15,500T - an increase of more than 35 per cent on the 2011/12 year (HAL, 2013; FGT, 2013b; ABS, 2013). Approximately 80% of cherries produced are for the domestic market, although exports are steadily increasing. 3,256T of cherries were exported in the 2012/2013 season, with 1,920T (59% of total exports) exported from Tasmania (HAL, 2013; FGT, 2013b; ABS, 2013). Production provides a counter seasonal advantage over producers in the northern hemisphere, however strong competition exists with other southern hemisphere producers, in particular New Zealand and Chile. The industry is increasingly looking to export markets in order to sell fruit, and with this there is a need to move from air-freight to sea-freight for export of larger volumes of fruit to Asia (FGT, 2013a).

It is essential that export markets are maintained or expanded to meet increased production, and that prices obtained compensate for the high cost of production in Australia. This requires high quality fruit that attract a premium price in export markets. It is commonly understood that pre-harvest management (Eg. Crop load, irrigation and nutrition, tree canopy and light relations, use of GA prior to harvest, harvest date etc) and external variables, particularly seasonal climate variation, impact on fruit quality in the market place. Previous studies suggested links between fruit mineral nutrition, fruit quality and shelf life (Whiting and Close unpublished) with nitrogen content in particular affecting fruit firmness and storability (Swarts et al., unpublished). Quentin et al. (2013) and Bound et al. (2013) determined that competitive sink limitation (girdling and thus removing the roots of the tree as a competitive sink) can lead to decreased fruit abscission and increased fruit set and quality characteristics in cherries. Understanding the mechanisms that underpin these issues could assist in enabling the production of high quality fruit with improved postharvest shelf life. This review focusses on the topic of my PhD project: the effect of tree carbohydrate and nitrogen-nutrition relations in the orchard on postharvest fruit quality, in particular firmness, and consumer perception of quality.

2.0 Carbohydrates

In perennial woody plants there is a highly integrated system of competing carbohydrate sinks (utilization sites). Internal competition for carbohydrates (carbohydrate partitioning) is shown by changes in rates of carbohydrate movement from sources to sinks and reversals in direction of carbohydrate transport as the relative sink strengths of various organs change (Kozłowski, 1992). Carbohydrate partitioning is an important process in trees and depends on the strength of sinks and the availability of sources during the season. As reserves of carbohydrates, stored in roots from the previous season and subsequently mature green leaves are the main sources but are spatially separated from the sinks (i.e. new shoots and fruit), assimilates must be translocated via the phloem from source to sink (Atkinson et al., 2001). Sugars actively accumulate in the phloem and move passively to sinks along a concentration gradient (Fig. 1). Thus the growth rate of fruit (sink tissues) can be limited by an insufficient supply of photoassimilates from the source leaves (source-limited) or by the inability of the sink tissues to fully utilise the available photoassimilates from the source leaves (sink-limited) (Patrick, 1987 (Atkinson et al., 2001). In cherries, carbohydrates partitioned to fruit are mainly provided by root sourced carbohydrates initially followed by leaves of reproductive and vegetative spurs and current season shoots (Ayala, 2004). During the growing season carbohydrate sequestration, remobilisation and allocation throughout a growing season changes. Generally, carbohydrate accumulation in the reserve organs (roots, branches and trunk) occurs mainly after harvest (Keller and Loescher, 1989; Beppu et al. 2003). Flower development relies on the carbohydrate reserves accumulated the previous year as flowering occurs before leaf expansion, and thus fruit set is strongly related to flower development. Therefore the production and partitioning of carbohydrates is a fundamental determinant of yield and quality of the harvested portion of all crops.

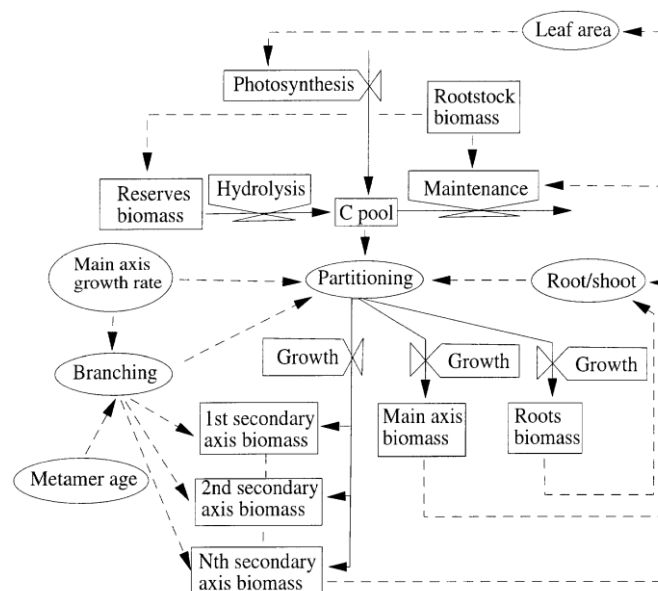


Figure 1. Diagram of carbohydrate partitioning model. Rectangles represent state variables, valve symbols represent flows and circles represent auxiliary variables. Solid lines represent flow of matter and dashed lines represent flow of information (Génard et al., 1998)

Source/sink relationships have been well studied in many fruit tree species, particularly apples (*Malus domestica*). However, the spatial and temporal relationships among carbohydrate sources

(e.g., leaves and stored reserves) are not well understood in cherries, especially when grafted on precocious and productive new rootstocks such as Gisela 5 (Whiting and Lang, 2004). In cherries the period between full bloom and harvest is shorter than other crops such as apples (less than 90 days in cherries as opposed to 150 days on average in apples), and the leaf canopy develops mainly after anthesis occurring throughout fruit development (Loescher et al., 1985; Keller and Loescher, 1989; Lang, 2001a; Lauri and Claverie, 2008). This suggests that carbohydrate reserves play a critical role towards sustaining early vegetative growth and fruiting (Ayala, 2004).

Storage carbohydrates are necessary to sustain growth under periods of stress, during dormancy, and are important during initiation of growth in spring (Flore and Layne, 1999). At bud break, carbohydrate reserves provide the carbon needed for growth until the leaf area of the tree provides enough assimilation to meet sink demand (Flore and Layne, 1999). Keller and Loescher (1989) found that non-structural carbohydrates in sweet cherry fruit change quantitatively and qualitatively during the season and consist mainly of starch, sorbitol, sucrose, fructose, glucose and raffinose. They also reported that total non-structural carbohydrates (TNC) were highest at leaf abscission, and shortly after bud break TNC decreased in all perennial tissues except the spurs where they increased. TNC then increased gradually once provided with current year's assimilate until fruit harvest, after which they accumulated at a higher rate. Understanding these carbohydrate partitioning and source/sink relationships may lead to better management strategies for sweet cherry fruit quality.

2.1 Effects of source availability on fruit quality

Sweet cherry fruit quality – particularly size and sweetness – are highly dependent on carbohydrate availability and translocation. Within a branch, the major sinks that might be considered to be competitors of fruit development include vegetative growth (current season shoot growth), other fruits and young leaves (Ayala and Lang, 2004). As sweet cherries are typically a vigorous, non-precocious, upright growing tree they require relatively aggressive management to moderate canopy volume and stature by annual pruning. This alters the light distribution, fruit populations, and leaf area, often resulting in larger and sweeter fruit due to favourable enhancement of carbohydrate source/sink relationships (Lang et al., 2004). New precocious and sometimes dwarfing rootstocks are also being used to make trees begin bearing at a much earlier age and also have the effect of reducing canopy leaf area and trunk/root storage reserve volume (Keller and Loescher, 1989; Lang et al., 2004). Fruit size in sweet cherry is dependent mainly on cell number, which is defined by cell divisions occurring before and after anthesis (Ayala and Lang, 2004). Ho (1988) states that this cell division is an important activity that attracts assimilates to sink organs in early stages of development. In apples the translocations out of the leaves situated near fruits is accelerated in comparison to leaves on trees without fruits (Hansen, 1967). Toldam-Andersen (1998) showed similar activity in sour cherries where early stage fruits act as sinks by removing photoassimilates from the translocation system. In this species, dry matter partitioning is dependent on the fruit growth stage, with a higher accumulation of carbon in the fruits during flesh development (Fig. 2).

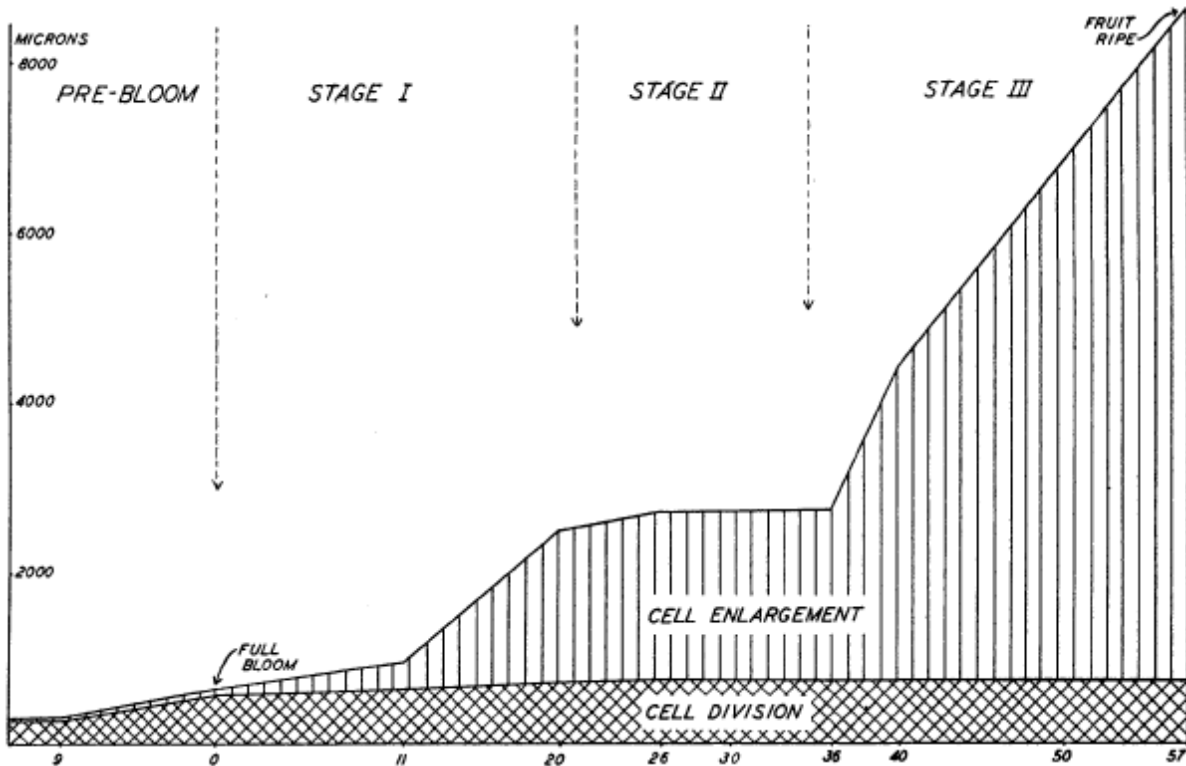


Figure 2: Diagram of cherry fruit development pattern (Tukey & Young, 1939). The first (I) and third (III) are phases of rapid fruit growth, and the second (II) is a relatively quiet stage and correlates with pit hardening. Stage I is the period of cell division and the following growth (II & III) are the result of cell enlargement (Kupferman, 1986).

DeJong and Goudriaan (1989) plotted the rate of dry matter accumulation during fruit development and determined that there are two distinct phases of active sink activity regardless of variety in peaches, and Kappes (1985) has shown similar results in sour cherries. This indicates that sink demand is greatest during the initial phase of activity and that there are only two phases of fruit growth. Ryugo (1986) found that young shoots are usually exposed to more light than the fruiting spurs on older wood, therefore providing more photoassimilates for fruit growth and higher total soluble solids. Therefore it is desirable to increase the proportion of fruit on 1- and 2- year shoots relative to spurs because these fruit are usually of higher quality (Faust, 1989; Roper and Loescher, 1987) or that the tree is structured in such a way to ensure good light interception of fruiting spurs on older wood.

2.1.1 Crop load

Crop load regulation is key to the production of export quality cherries (Link, 2000). Over-cropped trees produce small, soft fruit due to a limited carbohydrate and nutrient supply (Proebsting and Mills, 1981; Whiting and Lang, 2004) and studies in sweet cherry have shown that leaf photosynthesis decreased significantly for lighter cropping trees (Wibbe and Blanke, 1995) or where root sink strength was decreased via girdling (Quentin et al 2013). Achieving the optimum balance can be difficult as the variation in crop load and individual fruit size on a single tree is immense, and thus is one of the industry's greatest problems (Menzies, 2005). Within a specific spur or branch, the leaf-to-fruit ratio determines how much photosynthate goes into a particular fruit, thus increased

leaf:fruit will increase the size of fruits, although the absolute ratio varies between varieties and rootstocks (Menzies, 2005). Spayd et al. (1986) hypothesised that higher crop loads can increase the competition between fruit for carbohydrates and lower crop loads result in higher assimilate supplies for the individual fruit. This can result in an increase in fruit size and concentration of sugars (Spayd et al. 1986; Proebsting and Mills, 1981). Larger fruit can be less prone to pitting, bruising and other injuries during handling as the larger surface area indicates well developed epidermal cells which are directly related to optimal nutrient uptake and a greater accumulation of photosynthates (Looney et al. 1996; Patten et al. 1983). However lower crop loads can also increase vegetative growth with the current season's vegetative growth being a strong carbohydrate sink (Kappel, 1991). The sensitivity of sweet cherry to the leaf area:fruit (LA:F) ratio becomes evident in highly productive and/ or low-vigour combinations. In these cases, the contribution of photoassimilates by leaves becomes especially relevant because smaller and precocious trees produce a higher crop load that competes with vegetative growth during the growing season (Ayala and Andrade, 2009). This necessarily involves the adjustment of the LA:F ratio to avoid an imbalance between vegetative and reproductive sinks, which compete for carbohydrates during the period of fruit development (Ayala, 2004). Generally speaking, fruit have priority over leaves when in competition for resources and trees with large crops have less foliage development and smaller increases in trunk girth (Flore and Layne, 1999). Crop load regulation can be achieved by several methods including thinning (hand, chemical or mechanical), artificial spur extinction or bud thinning. However, hand thinning is expensive and time consuming (Childers, 1983) and although chemical blossom thinning is becoming more widespread there is the potential risk of over-thinning. There is also conflicting evidence on the impact of spur extinction and bud thinning on fruit quality and yield (Bound et al., 2013). These range from a reduction in yield and increase in fruit size, firmness and sugar content (Whiting and Lang, 2004; Bound et al 2013), or a positive effect on fruit size distribution without a reduction in yield (von Bennewitz et al., 2010), through to no distinct responses (Ayala and Andrade, 2009; Einhorn et al., 2011; Measham et al., 2012) and permanent yield reductions with fruit firmness only improving in lower cropping trees in one season (Neilsen et al., 2007). It appears that the potential for crop load manipulation to positively influence fruit quality is dependent on rootstock, variety, climate, training system effects, fruit sink limitations or competition from vegetative sinks and the level of crop load set. Measham et al. (2012) found that lower crop loads resulted in a greater incidence of fruit cracking in sweet cherry and that cracking is more likely attributed to cell expansion during the later stages of fruit growth. As most initial shoot and leaf growth in spring is supported by stored carbohydrates and nitrogen (McCamant, 1988; Keller and Loescher, 1989; Weinbaum, 1978), the effects of over cropping may last well beyond the initial problematic crop. Reductions in subsequent year vigour, manifested as both reduced shoot elongation and reduced leaf expansion can lead to a lower carbon assimilation potential even as crop demand continues to increase as sweet cherry spurs form more readily on low-vigour shoots (Gutzwiler and Lang, 2001).

2.1.2 Climate Effects on fruit quality

As cherries are temperate fruit, they require both a warm growing season and a winter dormant period, with winter chilling necessary in order to break winter dormancy to allow growth to resume in spring (Howell and Perry, 1990). Trees rely heavily on stored nutrient reserves from the previous year for bud burst and initial growth, with warm temperatures and good light levels needed to support cell division and photosynthesis. These conditions promote bud burst, with cherry shoot and flower/fruit growth occurring simultaneously afterwards. Conditions after harvest are also important as these will affect the ability of the tree to accumulate reserves for next year's growth (Looney et al. 1996). As the fruit itself spends a relatively short period of time on the tree from flowering to maturity, fruit quality is very susceptible to the climatic conditions during this time (James, 2011). Cool temperatures and cloudy or rainy weather are thought to be particularly detrimental to fruit quality although the relative importance of these environmental factors and their effects on carbohydrate acquisition isn't well known (Atkinson et al., 2001).

The two periods of most concern are when the trees are in blossom and when fruit is ripening, although varieties vary in their sensitivity. Reduced fruit set can occur if rain persists during the blossoming periods, and more direct damage to fruit and increased disease pressure can occur if rain persists during the fruit ripening period (James, 2011). Sams (1999) found evidence suggesting that pre-harvest weather conditions influence fruit firmness. Sekse et al. (2009) also found pronounced differences in firmness at harvest and more importantly firmness development during ripening between two seasons in sweet cherries, suggesting that this was most likely due to weather conditions. Sekse (1995) and Hovland and Sekse (2004) also reported that water accumulation in the sweet cherry fruit was influenced by environmental factors, with turgor pressure believed to be an important component of fruit firmness. Thus it is believed that a lack of carbohydrate availability may result in poor fruit structure. Furthermore, yield loss from rain-induced fruit cracking is a perpetual risk associated with the production of sweet cherries, and is difficult to manage due to the unpredictability of fruit responses to late season rainfall (Measham et al, 2012).

Environmental factors such as low light intensity and low temperatures may increase fruit abscission, presumably by decreasing photo-assimilation. Flore and Lakso (1989) observed that several days of cloudy weather lowered photosynthesis, and even 1-2 days after sunny conditions returned some trees were still carbohydrate depleted. Since current photoassimilates support new vegetative and fruit growth, any environmental stresses that limit growth may cause significant accumulation of carbon, which can feedback inhibit photosynthesis (Luxmoore, 1991; Flore and Lakso (1989). Tukey (1939) also found that the durations of stage I and II of fruit development were inversely related to night temperature, with the duration of stage III correlating positively with night temperature.

2.2 Carbohydrate Manipulation

Crop load regulation, girdling, and pruning are important techniques for manipulating the source/sink demands for carbohydrates and thus increase the yield of high quality fruit (Naschitz et al., 2010; Smith et al., 2007). Manipulation of the sources and sinks has differing effects as the tree's responses are not regulated by a centralised system but instead are a product of the relative strength of local meristems (Honkanen et al., 1999).

2.2.1 Source Manipulation

Manipulating source organs by defoliation, pruning or shading has been shown to stimulate photosynthesis and affect carbohydrate allocation due to the increased sink demand (Iglesias et al., 2002; Zhou and Quebedeaux, 2003; Génard et al. 1998). Roper and Loescher (1987) found that fruit quality and leaf area per fruit was positively correlated, with soluble sugar content most sensitive to increase in leaf area, followed by fruit weight and colour. Patten and Proebsting (1986) found that redness and sweetness of 'Bing' cherries increased logarithmically with light intensity at various canopy locations while Southwick et al. (1990) reported that fresh weight, dry weight, and sugar content of prunes developing at various canopy locations were linearly related to light interception. Ayala and Lang (2004) also determined that leaf populations on both fruiting and non-fruiting spur branch segments were required for full fruit development in sweet cherry with no sufficient compensatory effect when one of the main leaf populations was eliminated. Also, 90% leaf removal in apple trees was found to cause up-regulation in photosynthesis and reductions in foliar starch and soluble carbohydrate in remaining leaves, which is consistent with the increase in translocation of photoassimilates to zones of active or new sinks (Zhou and Quebedeaux, 2003). This shows that the various leaf populations are important for full fruit development (Lang, 2001b; Ayala and Lang, 2004; Corelli-Grappadelli and Lakso, 2004) and leaf removal experiments suggest that translocation of carbohydrates may exist over long distances i.e., between limbs and also from reserves, to support vegetative fruit growth (Whiting and Lang, 2004). Furthermore, source limitation of stored and soluble carbohydrates can have a negative impact on flowering and yield (Garcia Luis et al. 1995; George et al. 1996).

2.2.2 Sink Manipulation

In contrast, manipulation of sink organs through girdling or fruit thinning can reduce photosynthesis due to an accumulation of carbohydrates in the leaves due to decreased sink demand (if fruit are over-thinned) and a negative feedback regulatory mechanism on photosynthesis (Iglesias et al., 2002; Syvertsen et al., 2003; Nebauer et al., 2011; Quentin et al., 2013). Claverie and Lauri (2005) also showed that fruit spur thinning (FST) resulted in better photoassimilate distribution among a lower number of fruits, allowing for a balance between vegetative and reproductive growth. FST has produced mixed results though, with Claverie and Lauri (2005) reporting that FST increased fruit size improved fruit colour and moved the date of the harvest forward with effects being greater in the second year. Conversely Whiting and Ophardt (2005) did not find any effects of FST on fruit size and yield over a two-year study period, possibly due to removal of leaf area by FST. However, Ayala and Andrade (2009) found FST had no beneficial effects on fruit size, total soluble solids or fruit weight but did result in significant differences in the foliar development of current season growth and fruiting and on fruiting spurs.

Girdling has also been used to limit the flow of assimilates by reducing the phloem connections (Fig. 3). This involves removing a portion of the bark and thus impeding carbohydrate transport, which also creates a partially closed environment for carbon metabolism and transport above the girdle (Urban et al., 2004; Taiz & Zeiger, 2010).



Figure 3: Tree trunk girdling in sweet cherries (photo: Eric Mertes, 2013). This method involves a partial double girdle, where the top girdle ends, the bottom girdle overlaps, creating a temporary interruption of the phloem.

Girdling is a common horticultural practice used to manipulate tree growth and development, and fruit growth, in a variety of fruit species. It has been shown to advance fruit maturity and increase crop yield, increase fruit size, increase skin colour, and can be applied at the trunk, branch, or shoot level (Urban et al., 2004; Bound et al., 2013). The most immediate effect is to stop the basipetal movement of assimilates through the phloem, which results in an accumulation of carbohydrates above the girdle (Roper and Williams, 1989; Urban et al., 2004). Girdling has been shown to decrease net photosynthesis in several fruit tree species, although in the presence of a strong sink activity, such as the one provided by the presence of growing fruits, net photosynthesis may remain high (Proietti and Tombesi, 1990; Urban et al., 2004). Girdling experiments have indicated that sweet cherry spur leaves alone are not capable of supporting fruit growth and that fruit depend on photosynthate translocated from other parts of the tree (Roper et al., 1987). Also, the timing and long term use of girdling should be applied with caution as split-pit fruits can occur when fruits grow too quickly as pits are hardening, and the long term interruption of assimilate movement can result in tree death.

3.0 Nitrogen

For normal growth and optimum production, stone fruit require thirteen essential nutrients in varying amounts. Those needed in relatively large amounts are termed macronutrients (N, P, K, Ca, Mg, S), and those needed in smaller concentrations are termed micronutrients (Cl, Fe, Mn, Zn, B, Cu, Mo). These nutrients must be managed for optimum growth and production, and to minimise adverse environmental effects. Nutrition levels which produce an optimum balance between vegetative and reproductive growth are important for sustained, annual high fruit production, and thus through fertiliser management the aim is to produce healthy trees which produce moderate tree vigour and high quality fruit (Looney et al. 1996). Nitrogen (N) is one of the key macronutrients and is required for several different plant metabolic processes supporting tree growth, flower induction and quality, ovule fertilization, and fruit set and development (Sánchez et al., 1995; Sanzol and Herrero, 2001; Tagliavini and Millard, 2005). It is a highly mobile nutrient and is needed most where plant growth is actively occurring, especially in those processes involving cell division. Here it is mainly used for the production of amino acids and proteins and most active N is found in the protoplasm and the nucleus of plant cells. These proteins are important for structural functions and the activation of other proteins or acids within the plant. As N is so critical for the production of proteins, if N is deficient it will be transported from the oldest to the youngest parts of the plant resulting in a decrease in yield.

3.1 Nitrogen Management

The main goals of N management within orchard systems are to manage vigour, manage N concentrations with the tree components, manage orchard diseases and disorders, minimize pruning time, fertiliser and labour costs, optimise fruit quality and enhance profitability, minimize impacts on groundwater and surface water quality (Azarenko et al., 2008). An increasing body of research is revealing the complex dynamics of internal tree N-use and N-use-efficiency in deciduous tree crops (Millard and Grelet, 2010; Millard et al., 2006; San-Martino et al., 2010). Grassi et al. (2002) found that post-harvest applied N was partitioned to perennial storage tissues without contributing to current season growth. They observed very little root uptake of N in the spring, with trees relying primarily on N from remobilisation (root and trunk storage), 60% of which occurred during the first three weeks after bud break. This remobilisation of stored nitrogen is used by many trees to augment the supply of nutrients from the soil and can provide the majority of the nitrogen used for fruit growth each year. These results emphasize the importance of remobilization in supporting early-season growth (Millard, 1996; Millard and Proe 1991; Neilsen et al. 1997; Weinbaum and Van Kessel 1998; Dyckmans and Flessa 2001). In spring this remobilisation of stored N from tree roots, trunk and branches is utilised for flowering and growth, although the simultaneous flush of vegetative growth with bud differentiation and fruit development creates competition between organs for available resources (Loescher, 1990). Good nitrogen reserves can also help increase early fruit sizing by ensuring high early cell numbers per fruitlet (James, 2011). This is then supplemented by root uptake of external sources such as ammonium, nitrate and organic nitrogen (Fallahi et al., 1993). In contrast to other tree crops, sweet cherry is known for bearing primarily on second year and older fruiting spurs with a very short fruit development period. This has a significant effect on

the timeframe and availability of nutrient supply to meet demands of the developing fruit and leaf populations (Swarts et al., unpublished). Also, nitrogen applications before bud burst in early spring won't be available for fruit cell division, which influences final fruit size (San-Martino et al., 2010). Further research is needed though to determine the impacts of nitrogen applications on the development of floral tissues as excessive applications can induce plant vigour at the expense of flower bud initiation and development (James, 2011). The stage of rapid shoot growth takes place at the same time as the induction of flower buds for the next year's crop during spring through to early summer, with nitrogen uptake and photosynthetic production of carbohydrates helping to drive this growth. Fruit growth slows as nutrients are taken up from the soil, used primarily for shoot growth. 3-4 weeks prior to harvest fruit rapidly increase in size. Nitrogen applications during this period can reduce fruit colour, delay fruit maturity, lower soluble sugar concentrations and can either increase or decrease (Swarts et al 2013) fruit firmness indirectly due to either increasing cherry size or delayed maturity (Fallahi et al., 1993; Romano et al., 2006). Postharvest nitrogen applications are allocated preferentially to storage in roots and perennial tissues while contributing minimally to current season canopy growth (Dong et al., 2005). Thus these postharvest nitrogen applications may help in the accumulation of reserves for the next season growth, with research suggesting that these applications have the greatest effects on tree and cropping performance (Millard, 1996; San-Martino et al., 2010). It has also been suggested that this dependence on nitrogen reserves may be more critical in dwarfing combinations due to the presence of smaller permanent structures to accumulate reserves (Lang, 2002; Lang, 2005). There has been limited research into the effects of nitrogen fertilisation in high density cherry orchards (Grassi et al., 2002; Grassi et al., 2003; Guak et al., 2005) and the differences in effects between on young and adult trees (Dencker and Hansen, 1994; Neilsen et al., 2004; Azarenko et al., 2008; San-Martino et al., 2010).

3.2 Effects of nitrogen nutrition on Fruit Quality

Fruit nitrogen content has been implicated as a major factor in sweet cherry fruit quality. In particular excessive or insufficient amounts of nitrogen have the greatest effect on fruit size, firmness, colour, maturity, flavour and sugar content. The impact on these quality factors is further exacerbated during postharvest storage and can drastically reduce the shelf life of the fruit. Under normal circumstances fruit nitrogen content isn't particularly high in fruit tissues approaching harvest maturity, with fruit expansion at this stage of development being mostly a function of cell expansion from water uptake (Jiménez et al., 2006). Flore and Lane (1999) found that nitrogen deficiencies in cherries led to fewer flower buds being produced resulting in smaller fruit which are more highly coloured and mature earlier. In contrast Johnson and Uriu (1989) found that excessive nitrogen levels result in a delay in fruit maturity and decreased red colouration on the fruit, and either increase or decrease of cherry firmness indirectly due to either increasing cherry size or delayed maturity. High rates of nitrogen have previously been observed to either increase or decrease cherry firmness (Hanson and Proebsting, 1996), whereas research in apples showed that high rates of nitrogen tend to decrease fruit firmness (Fallahi et al., 1997). However, the increase in cherry firmness appears to be directly related to a decrease in cherry fruit size due to high nitrogen applications (Neilsen et al., 2004). Hansen (1980) determined that crop load has an important effect on leaf and fruit nitrogen concentrations, where trees with low crop loads being more sensitive to accumulating higher fruit nitrogen concentrations for a given nitrogen fertilisation regime (Neilsen et

al., 2009). Increasing nitrogen concentrations also resulted in delayed colouring, lower soluble sugars content and lower titratable acidity measurements implying maturity was delayed. Romano et al. (2006) determined that high nitrogen levels in cherry fruit can lead to a reduction in soluble sugar content, and Hansen (1997) and Stanberry and Clore (1950) reported that increased levels of nitrogen fertilisation led to delayed maturity. Neilson et al., (2007) also found that high nitrogen applications resulted in reduced fruit size and titratable acidity, but fruit total soluble solids and firmness were unaffected. Furthermore, excessive potassium levels have been linked to supplying more nitrogen than is required leading to poor fruit quality and can prevent the absorption of sufficient quantities of magnesium and calcium resulting in deficiencies of these elements (Looney et al. 1996).

4.0 Conclusion

From this review it can be concluded that although the effects of carbohydrate and nitrogen management on cherry tree growth have been investigated to an extent, the direct effects on fruit quality postharvest have not been studied in depth. The effects of carbohydrate and nitrogen management on fruit quality are not well understood and very few studies have attempted to link post-harvest fruit quality back to the orchards or management. This is particularly important when linking fruit firmness measurements back to carbohydrate availability and nitrogen applications. Additionally, if climate conditions correlate with fruit quality and in particular fruit firmness this could lead to a better understanding of the effects that underpin fruit firmness. As fruit firmness is a key quality factor and indicator of shelf-life, making these links could help to determine what underpins firmness at harvest and possibly lead to postharvest firmness predictions. Varietal and rootstock differences are also not well understood especially under differing nutrient and carbohydrate regimes, with little information regarding the influence of the nitrogen application date and carbohydrate manipulation.

The bulk of the information that is available relates primarily to the tree physiology and management, with little information available on the specific effects in sweet cherry fruit. Understanding these effects on fruit quality parameters is key to the production of high quality export fruit and hence further investigation is warranted. The PhD project, that this review is linked to, will address both an important knowledge gap in the scientific literature and provide applied outcomes that may assist producers in managing and understanding the impact of nitrogen applications and carbohydrate manipulation on fruit chemistry and quality postharvest.

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