Project title:	Desk study looking at the relationship between Dry Matter Content of apples and fruit quality
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DISCLAIMER

The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.

CONTENTS

Background and introduction

Recent studies (particularly by Palmer & Tustin in New Zealand) have shown that there is a good correlation between the dry matter content (DMC) of apples and both the ex-store sugar levels and eating quality.

This desk study investigates this correlation and the factors that determine fruit DMC under the following headings:-

Relationship between DMC and fruit quality

Plant physiology and DMC

Effect of tree shape and fruit position on DMC

Effect of light on DMC

Effect of nutrition on DMC

Effect of water on DMC

The report also includes recommendations for work to investigate the effect of orchard management practices on DMC.

Relationship between fruit DMC and quality

As fruit grows, complex physiological and metabolic processes interact and contribute to the in-flow of carbon, nitrogen and minerals. The accumulation of DMC is a simple way of measuring the outcome of these complicated processes. Fruit DMC includes compounds that may directly contribute to the flavour of the fruit and compounds that will be incorporated into the structural elements of the cell and influence the textural properties of the fruit. DMC specifically represents the biological processes responsible for setting up the textural characteristics, carbohydrate status and flavour potential of the fruit (Palmer et al, 2010).

Perring (1984) found good correlations between fruit firmness and dry matter. The alcohol insoluble dry matter (AIM) (mainly cellulose, pectin and starch) was higher in orchards grown under an overall grass sward than those with overall cultivation. It was also found that nitrogen fertiliser significantly reduced AIM as did irrigation when it led to larger fruit. However larger fruit caused by early thinning had higher AIM. Firmness of Cox both at harvest and after six months of storage, correlated with fruit dry matter in a series of fruit samples collected from thinning and irrigation treatments, which were designed to give a wide range of fruit firmness (Perring, 1985 & 1986).

In what they believe is the first extensive study of its kind in apples, Palmer et al (2010) set out to quantify the variation in apple fruit DMC across several cultivars and to examine possible links between fruit DMC and other key quality attributes such as flesh firmness, to see if DMC can be used to predict consumer preference.

Fruit from Gala and Scifresh from 29 orchards were sampled from two different growing regions in New Zealand. Mean DMC ranged from 13.8% to 14.7% for Gala and 15.9% to 16.4% for Scifresh. The range for individual orchards was 13.0% to 15.6% for Gala and 15.2% to 17.6% for Scifresh, while individual fruits ranged from 10.8% to 18.9% for Gala and 20.1% to 23.5% for Scifresh.

A close relationship was found between DMC at harvest and total soluble solids (TSS) after 12 weeks of storage. Differences between the two cultivars were noted: the relationship between DMC at harvest and TSS was stronger after six weeks storage in Scifresh than after 12 weeks. However in a study of 22 individual fruits from eight cultivars (Cox, Royal Gala, Pink Lady, Pacific Rose, Pacific Beauty, Scifresh, Granny Smith & Fuji) there was a close correlation (r^2=0.77) again between harvest DMC and TSS after 12 weeks storage.

McGlone et al (2002) found a strong correlation between the DMC of Royal Gala and the soluble solid content, once all the starch had been converted to sugar. This was confirmed in the reviewers' own studies in apples during storage assessments after the 2013 harvest (unpublished).

In contrast to Perring's findings, the New Zealand workers found no significant relationship between fruit DMC at harvest and fruit firmness in Royal Gala at harvest, after six or 12 weeks storage. The primary relationship was with fruit firmness at harvest and ex-store firmness. In Scifresh the best correlation of ex-store firmness was with harvest firmness but there was also a good correlation with harvest DMC.

Flesh firmness is strongly influenced by fruit maturity so this must be taken into account. In a separate study supported by the New Zealand team, Saei et al (2011) working in Iran with Royal Gala, found that when harvested at the same stage of maturity, harvest firmness and ex-store firmness could be correlated with fruit DMC. Thinning treatments to achieve different sized fruit, showed that fruit size had little influence on fruit firmness at harvest except on un-thinned trees which produced small fruit of <120g which were softer. Softening rates in store were largely consistent regardless of DMC, except for fruit with very low (13%) DMC, which softened more rapidly. Therefore fruit with higher DMC had higher fruit firmness and remained relatively firmer during storage. The authors conclude that their study raises the possibility of using fruit DMC as an important tool to aid decisions on the order of orchard marketing, to ensure consumers receive a reliable supply of fruit with optimum texture.

Studies by other workers have shown consistent differences in fruit DMC between cultivars, with Pink Lady ® notable for its high DMC and Royal Gala for its low DMC (Palmer et al, 2010). Perring's survey of Cox's Orange Pippin over nine years, showed that fruit DMC from the same trees varied from 15.9% to 20.6%. In consumer panel tests, consumers' scores for overall liking of fruit, acceptability and intention to purchase, were all significantly increased as harvest DMC increased.

Palmer proposed that fruit DMC be used as a new quality metric for apples. As it does not change significantly during the ripening process, it is not a replacement for maturity testing, but can be used to predict the eating quality potential after storage. Traditional maturity tests (starch, firmness, sugars and background colour) are more dynamic, changing appreciably during ripening and storage, which makes it difficult to predict ex-store quality from their measurement at harvest. DMC should be viewed as a complementary quality index. As fruit from different cultivars varies in DMC, it will primarily be used to differentiate between consignments of the same cultivar rather than between cultivars. The traditional maturity tests will still be necessary to monitor the ripening and to determine if eating quality potential is actually realised in the market place. Fruit with a high DMC will only achieve its increased eating quality if it is harvested at the correct stage of maturity and stored in a way that best conserves firmness, sugar and acidity (Palmer et al, 2010).

Plant physiology and DMC

Dry matter is made up largely of structural and non-structural carbohydrates. Carbohydrates produced by leaves (the source) during photosynthesis are accumulated in shoots, branches, trunk, roots and fruits (the sinks) and in a classic study, Monteith (1977) elucidated that dry matter productivity of crops including apple is essentially a linear function of total radiant energy interception over the season. This relationship has been further verified for apple by Palmer (1988, 1989). Researchers refer to the Harvest Index (HI) which is the proportion of the total, or above ground dry matter, that is in the fruit. In young or poorly managed orchards the HI can be low or even zero but in well managed dwarf trees, can range from 0.5 - 0.8 (Lakso et al, 1999). The carbohydrate demand by the fruit varies during the season. During the period from around two to four weeks after full bloom, the demand of the crop increases rapidly because of the presence of many fruits and their exponential growth rate, and the competition between the fruit and shoot development reduces the fraction of carbohydrate available to the fruit, especially if the incident light is low. The second period when carbohydrate can be limiting is in the period just before harvest when temperatures and light levels are declining. Observations by Lakso (1999) found that fruit growth rates remained linear on lightly cropping trees but declined on heavily cropping trees. Lakso also found that the demand appears to increase rapidly after bloom, peaking about four to six weeks after bloom then remains quite stable until harvest.

Measurements of DMC in fruits of Idared from full bloom to harvest showed that the DMC was very high (20%) at full bloom, decreased to about 10% over the next five weeks then increased to about 14% before decreasing very slowly at 0.01% per day until the end of the season (Schechter, 1993). Differences in dry weight assimilation and partitioning have been shown between cultivars (Ng et al. 2013).

The relative strength of the sources of carbohydrates affects the volume of carbohydrates partitioned to the various sinks. The flow of carbohydrates via the phloem can also influence the relative volumes that go to the sinks and this can be affected by the distance between the source and the sink. Marcelis (1995), and Hansen (1967) found that the greater part of carbon absorbed by spur leaves was transferred to fruits on the same spur, while translocation from leaves of extension shoots was also largely to nearby fruits.

Effect of crop load

Wunsche (2000 & 2005), Sharples (1968), Palmer (1977) and Kelner et al., (2000) have all shown that crop load influences fruit DMC with general agreement that decreasing crop loads result in an increase in size, soluble solids, flesh firmness, dry matter and advanced maturity at harvest. An increase in fruit firmness at low crop loads is likely to be related to increases in soluble solids and dry matter (Wunsche, 2000) and possibly to increased cell number in the cortex plus increased cell turgor.

Wunsche (2000) and Palmer (1996) applied crop load treatments at blossom time. In Palmer’s experiment, yields were reduced from 38 kg/tree (two flowers per cluster) to 6.9 kg/tree (two flowers on one cluster in every 16 with all other flowers removed). All flowers on one year old wood were removed. Dry matter ranged from 13.5% in the lightly thinned trees to 15.6% in the heavily thinned trees. In Wunsche’s experiment, crop load was related to trunk cross sectional area (TCA). Yields ranged from 0 to 57 kg/tree (0 to 8.7 fruits/cm^2 TCA) and DMC ranged from 14.3% on heavy cropping trees to 17.8% on low cropping trees.

Beruter (1989) showed that by adjusting fruit numbers per cluster at the start of fruit development, carbohydrate partitioning between starch and sugars can be altered and the larger fruit from clusters thinned to singles contained higher levels of fructose, sucrose and starch than the smaller fruit.

Trials in the mid 1980's at East Malling Research Station showed that thinning Cox on MM106 increased fruit size, fruit firmness and dry matter (Horscroft, 1987).

Effect of light and fruit position

Workers in Sweden (Nilsson, 2006) showed that fruit grown on the outside of the tree canopy of apple (cv Aroma) on M9 planted at 4m x 2m, had significantly higher DMC and soluble solids than fruit inside the canopy. There was a significant linear correlation between DMC and soluble solids concentration (r=0.64 to 0.79). The differences in DMC between outside fruit and inside fruit were 13% (1998) and 7% (1999). The researchers concluded that the significantly higher DMC and soluble solid content in outside apples in both years indicate a close relationship between the light level within the tree canopy and the concentrations of stored carbohydrates at harvest. This is in agreement with earlier investigations by Jackson et al (1977), Seeley et al (1980), Robinson et al (1983) and Tustin et al (1988).

Fruits grown on Golden Delicious and Granny Smith trees trained in the Hawkes Bay method were tested for DMC and it was found that with decreasing crown position (i.e. more shade) there was a decrease in fruit size, DMC and soluble carbohydrate concentration (Haynes & Goh, 1980).

The accumulation of dry matter can be affected by relatively short periods of shade. McArtney et al (1988) showed that the rate of increase in dry matter in Gala grown on M 26 was reduced and then subsequently increased following shading for just six days between 34 and 39 days after full bloom.

Studies by Li et al (1992) from 1982 - 1985 showed significant differences (ranging from 19 - 51%) in yield and fruit dry matter content respectively, between apple trees grown with two different crown shapes. The shapes were a two layer crown and a round head crown. The two layer crown gave the higher yield and DMC, adding further weight to the argument that light interception by and distribution in the canopy influences the DMC in fruit.

In experiments to assess the effect of reflective mulches and Particle Film (PF) sprays (e.g. Kaolin) to alter light levels in fruit tree canopies, it was generally found that increases in fruit weight and greater partitioning of dry matter to the fruit could be achieved. Interactions with irrigation treatments affecting the vapour pressure deficit in hotter climates were also observed. The greatest increase in overall photosynthetically active radiation (PAR) did not lead to the highest level of dry matter and this was explained by the particular wave lengths of light being reflected into the canopy. Where an aluminized film (APF) was used, PAR was the greatest but dry matter was not as high as with the PF sprays and the response not as great as found by other workers using woven reflective cloth which altered the light quality compared to the APF, especially in the red to far red part of the spectrum (Glenn, 2007, 2009).

Effect of irrigation

The effects of irrigation as reported in the literature reviewed were inconsistent, probably due to the varying objectives of the experimental work and the climatic conditions under which the trials were carried out. Partial root drying experimental work in a semi-arid region resulted in increases in DMC (Zegbe, 2011).

Early studies in the mid 1980's at East Malling Research Station showed that trickle irrigated Cox grown on MM106 had lower mineral content (other than Boron) and lower dry matter concentrations than Cox without irrigation (EMRS Annual Report, 1984).

Girona et al found that in young peach trees, fruit dry matter accumulation was relatively insensitive to water stress regardless of fruit load and developmental stage. Girona (2004) and Cohen (1988) also found that dry matter accumulation on grapefruit trees under water stressed treatments was only slightly impaired. Steinberg (1990) working with young potted peach trees found that although total dry matter production reduced progressively with each reduction in watering, most of the reduction occurred in the vegetative parts of the tree in a halting of later branching and new leaf production.

In a trial (Kilili et al, 1996) on seven year old Braeburn trees on MM106 conducted in New Zealand, water was withheld during the first half of the season (from full bloom plus 104 days), or from the second half (full bloom plus 104 days to 194 days - harvest), or throughout the whole season, and compared to a fully watered control. The control treatment had the largest fruit but the lowest dry matter; late withholding of water did not significantly reduce fruit size and significantly increased dry matter. Gross yield per tree was similar in all four treatments (Table 1).

Irrigation Treatment	Mean fruit weight (g)	Yield (kg/tree)	Dry matter content
Control	206.3	51	13.4%
Early withholding	184.8	56	14.0%
Late withholding	200.4	53	15.2%
Full season withholding	182.6	50	15.4%

Table 1. Gross yield per tree of 7 year old Braeburn trees on MM 106 (Kilili et al, 1996)

A further experiment also in New Zealand on ten year old Braeburn showed that dry matter could be increased by deficit irrigation treatments compared to a commercially irrigated control. The deficit irrigated trees were irrigated with the same amount of water but at half the frequency of commercially irrigated trees. As in the previous work, deficit irrigation was applied early in the season, late in the season, or through the whole season. Improvements in fruit firmness and sugar content were also recorded (Mpelasoka et al, 2001).

Effect of nutrition

In trials using Gala on M26 in sand culture at Cornell University where the trees were adequately supplied with nutrients, the nutrient accumulation in the fruit largely followed its dry matter accumulation and a large proportion of the nutrient accumulation occurred from the end of shoot growth to harvest. Through successive destructive analyses of whole trees, the trial was able to determine nutrient levels and increases in dry matter in different parts of the tree throughout the season, but the effect of altering nutrient levels was not investigated (Cheng, 2009).

Studies into the accumulation of potassium in leaves and fruits of French prune showed close correlations between fruit potassium and dry matter accumulation (Niederholzer et al, 1991).

Trials to determine whether increased nitrogen (N) fertilisation could lead to improvements in Gala fruit size in pot grown trees, showed that fruit dry matter increased as N increased.

This increase was partly due to increased cell numbers. An increase in soluble solids in the fruit was also found (Xia et al, 2009).

Summary and conclusion

Fruit DMC has been shown to be related to ex-store firmness, sugar levels and eating quality, and has the potential to be developed as an additional quality measurement alongside traditional maturity and quality tests, to enable growers to provide a more consistent product to the market.

Fruit DMC is a measure of the photosynthetic efficiency of the leaves, the tree and the growing system and is therefore influenced by many factors in the orchard environment. The most important of these are:

- **Light** - The overall light levels during a season and the efficiency of light interception by the orchard and the distribution of light throughout the canopy affects the DMC.
- **Crop load** - Several studies have shown that crop load and the time of thinning can have significant effects on fruit DMC. Large fruit achieved by early thinning can have increased DMC, whereas heavy crop loads of small fruit can result in low fruit DMC, so making assumptions of DMC based on fruit size alone unreliable.
- **Irrigation and soil management** - Early work showed that soil management and irrigation could influence fruit DMC and more recent studies have elucidated the effects of irrigating during the early season and late season. Given the interactions between water availability, crop load and fruit size, the results are difficult to interpret but generally restricted watering regimes especially closer to harvest, improved fruit DMC.
- **Nutrition** - Varying applied rates of nitrogen affected fruit DMC and levels were inconsistent between published results, but the nitrogen also affected cropping level which may have influenced DMC. The positive effect of increased potassium levels on DMC in stone fruit was noted.
- **Tree management** - Most tree management practices that improved DMC were due to improvements in light interception and distribution. One paper reported an increase in DMC when paclobutrazol (Cultar) was applied.

Recommendations for future work

1. Confirm the relationship between harvest DMC and ex-store quality for fruit grown under UK conditions. Work should be done on a range of cultivars and over a longer storage period than the 6 or 12 weeks used in the New Zealand studies. It is suggested that fruit DMC is measured from a range of cultivars (apples and pears) and orchards, with varying crop loads and growing practices, to provide a benchmark of fruit DMC within the UK crop. The fruit samples should be stored and assessed for quality attributes (e.g. firmness and TSS) after 6, 12 and 18 weeks storage, in standard industry conditions.
2. Determine the harvest DMC in current apple and pear experiments investigating crop load, soil moisture status and tree management. Fruit wall, deficit irrigation and rootstock/variety evaluations etc. should be assessed for their influence on fruit DMC at harvest, and the maturity determined at the time of sampling.
3. Demonstrate that good management practices such as early thinning, growth control, increasing potassium and restricted irrigation can improve fruit DMC. A systems trial should be established in Gala orchard(s) to assess the impact of the various treatments listed on both fruit DMC at harvest and ex-store eating quality. If possible some taste panel assessments should be included.
4. Assess the effect of reflective mulches on fruit DMC under UK conditions. Work should compare the use of reflective mulches for different periods (e.g. 3 months from early fruitlet to harvest, 2 months and 1 month up to harvest) on fruit DMC and also their effect on harvest levels of sugar, starch and fruit firmness with assessments also made after 6, 12 & 18 weeks storage.
5. Determine consumer preference between fruit from low, medium and high DMC orchards. This is a critical element of any experimental programme so that the relationship between eating quality, intention to purchase and harvest DMC is determined for UK varieties and growing conditions. Standards that the industry can adopt and work to should be developed.

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