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Variation in ‘Hayward’ Kiwifruit Quality Characteristics.

A thesis submitted in partial fulfilment of
the requirements for the degree of

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THE UNIVERSITY OF
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Abstract

Quantify the magnitude, sources and distribution of variation in fruit quality traits within kiwifruit populations and identify opportunities for the management of this variation.

Near-infrared (NIR) grading was used as a tool for monitoring fruit quality, and measurements combined with orchard/vine information to investigate opportunities for the management of the variation in fruit quality traits with a particular focus on fruit DM. NIR enabled non-destructive assessment of the quality characteristics of individual fruit from 96 commercial orchards, comprising 550 fruit-lines, across four consecutive seasons, resulting in a dataset of measurements made on 146.7 million individual fruit. The distribution of quality traits within fruit populations and the relationships between quality traits were examined. The spatial component of variation in fruit quality was investigated to assess the potential for zonal management practices. Finally, the effects of growth temperatures on fruit quality were studied.

Significant variation in fruit quality was observed between-seasons, between-orchards, and between-vines within an orchard. From comparison of CVs between quality traits, cropload was more variable than fruit weight which varied more than fruit DM, independent of the production scale considered (between-orchard or between-vine). Across a hierarchy of fruit populations (individual vine, fruit-line and orchard), the majority of fruit quality distributions demonstrated significant deviations from normality. However, departures from normality can be tolerated for estimation of the proportion of fruit with specific quality criteria. The sources of variation in fruit weight and DM populations were investigated at both a between-orchard scale and a within-orchard scale. Between-orchard variation was significant, however, the majority of variation occurred within-fruitlines, within-orchards and within seasons. The within-fruitline component of variation was investigated separately. Both between-vine and within-vine variation were significant, but within-vine variation was dominant. The focus of management should be on reducing variation occurring within-fruitlines within-orchards, which is largely attributable to variation occurring within the individual vine.

Higher croploads per vine have negative consequences for fruit weight but variable effects on DM. Increasing croploads reduce both FW and DW allocations for each fruit, therefore the effect of cropload on DM is dependent on the relative reductions in FW and DW. The DW allocations to fruit are not limited by DW production, at least up to the croploads observed in this study (≤ 65 fruit m^{-2}).

The potential for zonal management was investigated. Variation in fruit quality characteristics between-orchards across the Te Puke growing region, and between-vines within an individual orchard area were investigated using geostatistics. A spatial component to variation was identified both between-orchard and between-vine. However, the effect of spatial variation was diluted by that of non-spatial variation and therefore, zonation between orchards or between areas within-orchards should not be where the effort in managing variation is concentrated.

Orchard altitude correlated with some aspects of fruit quality. Mean fruit weight declined 0.5g and within-orchard variation in fruit weight declined 0.25 units with a 25m increase in orchard altitude. Mean fruit DM was independent of orchard altitude and within-orchard variability in DM declined 0.023 units per 25m increase in orchard altitude. Differences in orchard altitude equated with differences in growth temperatures. Warm spring and cool summer temperatures favour the growth of high DM fruit. The effects of spring temperatures on canopy development and maturation were investigated to elucidate potential physiological mechanisms for temperatures effects on fruit growth. Higher spring growth temperatures increased the rate of total leaf area development and promoted development of leaf photosynthesis. Higher spring growth temperatures favoured a more positive carbon balance, which has beneficial effects on the development of fruit quality characteristics.

Post-harvest, the traditional practice of grading fruit into count sizes generally also segregates for DM, and large count size fruit will often have higher DM than small sized fruit. Between fruit populations, a positive correlation was identified between fruit DM and acidity; therefore, segregation of the inventory by DM will also segregate for acidity. High DM fruit are also more acidic with a higher, more favourable brix/acid ratio when ripe. It is recommended that fruit DM status be managed in the inventory, not by maturity area as is the current practice, but by groups of similar count sizes within maturity areas.

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Abbreviations

°C	Degrees Celsius
A	Net photosynthetic assimilation rate
A_{\max}	Maximum light saturated rate of photosynthesis
ANOVA	Analysis of variance
C	Carbon
CA	Controlled atmosphere cool-storage
c_i	internal leaf CO ₂ concentration
CO ₂	Carbon dioxide
CV	Coefficient of variation
DAA	Days after anthesis
DM	Fruit dry matter content expressed as a percentage
DW	Dry weight
FOBS	Free on board stowage
FW	Fresh weight
G	Gini coefficient
g_s	Stomatal conductance
ha	Hectare
hDM	Fruit dry matter content at harvest
HSD	Highest significant difference
hSSC	Soluble solids content at harvest
J_{\max}	Rate of photosynthetic electron flow at saturating irradiance
KgF	Kilograms force
LAI	Leaf area index
LED	Light emitting diode
LSD	Least significant difference
N	Newton's
NaOH	Sodium hydroxide
NIR	Near Infra-red
nm	Nano metres
NZ	New Zealand
O ₂	Oxygen
P	Statistical level of significance
PA	Precision agriculture
PAR _i	Photosynthetically active radiation
PFD	Photon flux density
PLS	Partial least squares
Q-Q	Quantile-Quantile
R ²	Square of the Pearson product moment correlation coefficient
rSSC	Soluble solids content when ripe
rTA	Titrateable acidity when ripe
RuBP	Ribulose biphosphate
SEM	Standard error of the mean
SLA	Specific leaf area
SSC	Soluble solids content
TA	Titrateable acidity
V_{\max}	Maximum rate of carboxylation
VpdL	Vapour pressure deficit (Leaf)

Chapter 1: Introduction, Review of Literature and Study Rationale.

1.1 Overview

Kiwifruit is currently New Zealand's largest horticultural export crop, earning approximately \$720 million (FOBS) in the year ending March 2005, with fruit being exported to over 60 countries (www.stats.govt.nz). Production volumes for the 2006 season were predicted to be ~89.5 million trays of export fruit across all production categories (conventional and organic) and varieties (Hayward and Hort16A) (www.nzkgi.org.nz).

The increase in world kiwifruit production in the previous decades has seen New Zealand move from a dominant position in the international market to become just one of many producers in an oversupplied market. Consequently competition in the international markets for kiwifruit sales is increasing. In order for the New Zealand kiwifruit industry to expand or maintain market share it must achieve a competitive advantage through the supply of a product differentiated by quality. Apart from product differentiation achieved by service, grade standards and presentation, the industry needs to further differentiate by more subjective quality attributes including firmness, taste and freedom from disease.

Variation in fruit quality is a natural phenomenon which is influenced by a range of orchard and post-harvest factors. A better understanding of how fruit quality traits vary within and between fruit populations is required to enable industry to manage this variation. Knowledge of the nature of variation in fruit quality is potentially valuable as a research, production and ultimately marketing tool.

1.2 Kiwifruit Varieties of Commercial Importance

The genus *Actinidia* consists of a group of perennial deciduous plants originating from eastern or southern Asia (Ferguson, 1984). There are more than 50 species and 100 taxa in the genus *Actinidia*, all of which have a climbing habit and are commonly found growing wild as part of the forest under-storey in temperate forests of mountains and hills in south western China (Ferguson, 1990).

The two main economically important species of *Actinidia* are *A. deliciosa* and *A. chinensis*. *A. deliciosa* is the species best known around the world as kiwifruit and is commercially grown in many countries for domestic consumption and export. There are a large number of named cultivars of *A. deliciosa* including ‘Allison’, ‘Bruno’, ‘Constricted’, ‘Elmwood’, ‘Gracie’, Hayward, ‘Monty’ and ‘Skelton’ (Thorp et al., 1990). Commercially it is the variety *Actinidia deliciosa* (A. Chev.) C. F. Liang et A. R. Ferguson var. *deliciosa* ‘Hayward’ which is the most important internationally. The cultivar Hayward was a selection made from seedlings by the nurseryman Hayward Wright in the 1920s (Ferguson & Bollard, 1990). However, Hayward did not become predominant until New Zealand export markets showed a preference for this cultivar in the 1970s (Sale & Lyford, 1990). By 1980, 98.5% of kiwifruit planted in the Bay of Plenty (the main kiwifruit growing region of New Zealand) was Hayward (Ferguson & Bollard, 1990). Hayward has become the industry standard due to a number of characteristics of the fruit such as large size, good flavour, long storage potential and its comparatively lower vigour (Ferguson & Bollard, 1990), although it tends to produce less fruit than other cultivars (Sale & Lyford, 1990).

A. chinensis is the second species of commercial importance. Currently, *Actinidia chinensis* (Planch.) var. *chinensis* ‘Hort16A’, a proprietary yellow-fleshed kiwifruit is the only other major kiwifruit cultivar to be traded internationally. The origins of Hort16A date to a cross made in New Zealand in 1987 between a female and male derived from two seed introductions of *A. chinensis* obtained from China (Muggleston et al., 1998). The female parent was identified at harvest in 1987 as having small ovate fruit with good flavour and pale yellow flesh. The

male was selected because of its female sibling's superior fruit size. The objective of the crossing was to combine fruit size, good flavour and yellow flesh. The resulting seedlings were cultivated and evaluated, and small scale grower trials started in 1995. The selection Hort16A was licensed in 1995 and is now marketed under the name ZESPRI™ GOLD.

1.3 Horticultural Characteristics

1.3.1 General

Most members of the *Actinidia* genus are functionally dioecious (Schmid, 1978; Ferguson, 1984). Although pistillate flowers on female vines produce pollen, it is nonviable, while ovaries present in flowers on male vines do not contain viable ovules (Schmid, 1978). Thus there is a requirement for both male and female vines in order for cross-pollination to occur. Pollination is important as very high numbers of seeds (700+) are required to attain export sized Hayward kiwifruit (Hopping, 1976), whereas in Hort16A seed numbers in the range of 400-600 are sufficient (Patterson et al., 2003).

The specific growing requirements of kiwifruit are free draining soils, an adequate supply of moisture (particularly when young), relatively high atmospheric humidity and a period of winter chilling (Sale & Lyford, 1990). *A. deliciosa* and *A. chinensis* are frost tender when in leaf, although other species, particularly *A. kolomikta* and *A. arguta*, are frost hardy and can survive winter temperatures of as low as – 40°C (Sale & Lyford, 1990).

Most commercial plantings are based on rows of plants trained on either a T-bar or a pergola structure (Sale, 1985). These structures have been found to promote high yields of export grade fruit, while minimising pruning time (Hopping et al., 1993). The structures support the weight of the crop, as well as allowing accurate

canopy management to restrict vegetative growth which if unchecked may become excessively vigorous at the expense of fruit growth. Vines are grown as a single straight trunk, and upon reaching the top of the structure, a single permanent leader or ‘cordon’ is allowed to grow in each direction along a central wire. One-year-old canes are selected each year on the basis of length, thickness and closeness to the main leader and are tied down onto the support wires. In spring, bud-break occurs followed by leaf expansion and the development of flower buds on these shoots (Brundell, 1975). As flowers arise only from the current season’s growth (Sale & Lyford, 1990), bud-break is of critical importance for overall yield. Although a lack of winter chilling often limits bud-break (Lionakis & Schwabe, 1984; McPherson et al., 1995), the requirement for winter chilling can be overcome to some extent by the application of the dormancy breaking chemical, hydrogen cyanamide (Lionakis & Schwabe, 1984). Kiwifruit vines display vigorous vegetative growth and intensive summer pruning is required in order to control it and to maintain vines in a manageable state (Sale & Lyford, 1990). Summer pruning involves the removal of actively growing shoot tips from fruiting lateral shoots, removal of re-growth from lateral buds and removal of tangled growth from around fruits, canes and lateral shoots. Summer pruning may be required several times during the season, particularly during mid-summer when vegetative growth is extremely rapid (Sale & Lyford, 1990). In winter, when vines are in a dormant state, tied down canes which have provided fruit and lateral shoots in the previous season are pruned off as close to the leader as possible. These are replaced with new ‘replacement canes’ that have arisen as vigorous new growth close to the leader during the previous season.

1.3.2 Hayward

Commercial kiwifruit orchards have traditionally used Hayward scion grafted onto seedling ‘Bruno’ rootstock. Seedling rootstocks are used because of the low cost of propagation and high success of grafting, rather than any productive advantage conferred by the rootstock (Cruz-Castillo et al., 1997). Cruz-Castillo et

al. (1997) reported that the initial growth of Hayward clones on their own roots was as good as or better than grafted plants. Several authors have demonstrated that kiwifruit rootstock selections have the potential to affect fruit growth and vine productivity. Hayward scion grafted to a Te Puke (New Zealand) selection of *A. hemsleyana* (TR2, Kaimai) was reported to allow production of around twice as many flowers as seedling rootstocks and produced a similar average fruit size despite carrying a 20% higher crop load (Lowe & White, 1991). Rootstock selections of *A. eriantha* and *A. rufa* also gave increased flowering, whereas *A. chinensis* gave decreased flowering (Lowe & White, 1991; Wang et al., 1994). The increase in flowering was found to be due to decreased abortion of floral primordia in spring (Wang et al., 1994), possibly due to an increased mobilisation of carbohydrates to shoots at this time (Lowe & White, 1991).

1.3.3 Hort16A

Vines of Hort16A have been rapidly established in New Zealand kiwifruit orchards since 1995 by grafting over mature Hayward vines using cleft and step grafting techniques. Resultant canopy growth on mature rootstocks has been rapid with full canopy development achieved in 2-3 seasons, thus enabling a rapid return to production following removal of the Hayward canopy (Patterson et al., 2003). New plantings have also been made with Hort16A grafted to *A. deliciosa* 'Bruno' seedling rootstocks and to a lesser extent grafted to 'Kaimai' (possibly *A. eriantha* Benth. x *A. hemsleyana* Dunn) clonal stock. Clearwater et al. (2004) investigated the effect of 4 different clonal rootstocks on canopy development of Hort16A kiwifruit from which rootstocks were classified as high or low-vigour. They subsequently demonstrated that vigour controlling rootstocks affected shoot growth and leaf area development of Hort16A during the initial period of shoot growth immediately after budburst (Clearwater et al., 2004; Clearwater et al., 2006).

A key difference in phenology between Hayward and Hort16A vine growth is the earlier budbreak, shoot growth and flowering of Hort16A during spring. Budbreak and flowering are both 3-4 weeks earlier than Hayward. These differences in timing have implications for orchard management operations for Hort16A, including winter pruning, application of budbreak enhancers and the introduction of beehives for pollination (Patterson et al., 2003).

Hort16A vine growth under New Zealand conditions is typically more vegetatively vigorous than that of Hayward. As a consequence of this, there is a greater need for management of summer growth of Hort16A. In addition, the vegetative growth and extension of long canes of Hort16A continues for a longer period into late summer than is characteristic for Hayward (Patterson et al., 2003).

1.4 The New Zealand kiwifruit industry

Commercial plantings of kiwifruit in New Zealand were made in the early 1930s and the popularity of the fruit increased gradually until the early 1970s when kiwifruit plantings increased exponentially in response to a lucrative export market. Kiwifruit is currently New Zealand's largest horticultural export crop, earning approximately \$720 million in 2005 (Figure 1.1). Following this commercial success, kiwifruit production began in earnest in several other countries most notably Italy, France, Chile, Japan and the USA (Warrington, 1990).

Global kiwifruit production has stabilised after the expansion in the 1980's to around 104,000 hectares, clustered between latitudes 38° and 42° North and South. Italy produces the largest volume, followed by New Zealand; China, Chile, France, Greece, Japan and USA are also substantial producers. Plantings and production yields of Hayward kiwifruit in New Zealand have increased from 10,161 ha yielding an average of 5,492 trays/ha in 1995 to 10,934 ha in 2005 producing an average yield of 7,847 trays/ha (Zespri Group Ltd, Annual report

2004-05). The volume of Hayward fruit produced by the New Zealand industry during the 2006 season was ~68 million trays (www.nzkgi.org.nz). Since the commercial release of Hort16A in 1995, approximately 2000 ha have been planted in New Zealand and licensed plantings have been established in Italy, the USA and Japan (Patterson et al., 2003). The first significant commercial export of the fruit was from New Zealand to Japan in 1998; this has subsequently increased to current production levels of ~18.5 million trays in the 2006 season (www.nzkgi.org.nz).

The basic structure of the New Zealand kiwifruit industry is that of a single-desk export marketing operation run by Zespri Group Ltd, an organisation owned primarily by grower shareholders. Production of kiwifruit remains in the hands of many individual growers; in 2003-04, Zespri reported 3,153 supplying orchards with an average size of approx 3.4 hectares. Zespri has made substantial efforts to differentiate its products in the international market on the basis of cultivars, grading standards, time of year and cultivation practices such as organic growing methods. By and large, that effort has been successful and New Zealand has generally been able to earn a premium for its fruit in most major markets (Belrose Incorporated, 2005). New Zealand Hayward fruit, marketed as ZESPRI™ GREEN, has earned a premium over Hayward fruit from other countries and over second class New Zealand Hayward, marketed as K1W1, not meeting the strict standards required for ZESPRI™ GREEN. The Hort16A cultivar, marketed as ZESPRI™ GOLD, has continued to maintain a substantial premium over ZESPRI™ GREEN even as its share of the New Zealand kiwifruit export has reached 18.5 percent. Organically produced fruit, both Hayward and Hort16A, has consistently earned a premium over conventionally-grown product (Belrose Incorporated, 2005).

The average net return of New Zealand kiwifruit exports was the highest of the three main kiwifruit producers (Italy, NZ and Chile) in 10 out of the last 14 years (1990-2004), despite the fact that New Zealand exporters face much higher transportation costs to get their product to international markets (Belrose Incorporated, 2005). During the 1990-2004 period the average net return for New

Zealand Hayward fruit was \$1,090.49 (\$US per metric ton), for Italy \$955.32, and for Chile \$635.47 (Belrose Incorporated, 2005). Average returns to New Zealand kiwifruit growers are presented in Table 1.1. Despite earning a premium per unit produced, returns to organic growers are less than those for their conventional counterparts due to the low yields produced under organic systems.

Table 1.1. New Zealand Orchard Gate Returns for Kiwifruit (NZ\$ per hectare).

Product	1999-00	2000-01	2001-02	2002-03	2003-04
Zespri™ Green	30,008	27,510	29,748	32,455	37,593
Zespri™ Green Organic	32,528	29,945	25,842	32,293	37,033
Zespri™ Gold	5,081	26,985	27,415	42,857	44,425
Average All Kiwifruit	27,896	27,587	29,297	33,685	38,488

Source: World Kiwifruit Review 2005, Belrose Inc

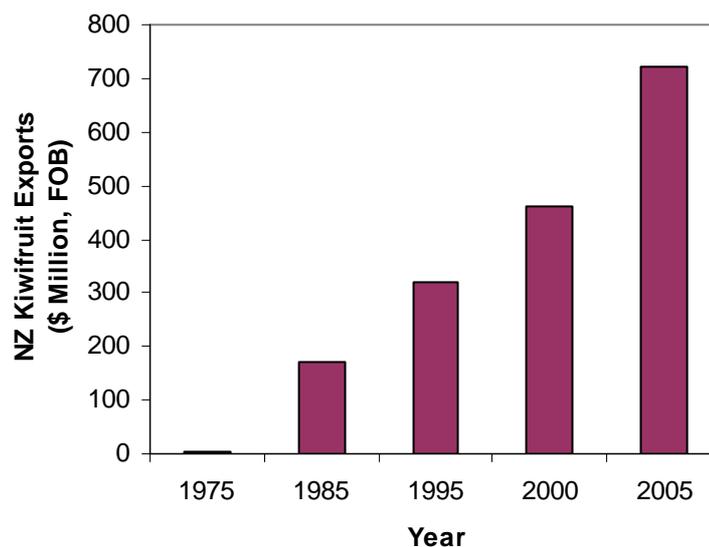


Figure 1.1. The Value of NZ Kiwifruit Exports (1975-2005).

Source: Statistics New Zealand (www.stats.govt.nz).

1.5 Current trends in international kiwifruit trade and marketing

Both of New Zealand's main fresh fruit industries, kiwifruit and pipfruit, have a high export dependency at approximately 95% and 55% respectively (Rabobank, 2001). The sustainability of the New Zealand kiwifruit industry is dependent on the ability to sell fruit in the international markets. The implications are that the New Zealand industries are vulnerable to fluctuations in the international markets and, second, producers and exporters must be familiar with and, able to respond to changing market conditions and trends. Below are reviewed some of the major trends in the global fruit trade, and the opportunities and threats facing the New Zealand kiwifruit industry.

1.5.1 Trade volumes

Not only has world fruit production increased significantly in the past two decades but the proportion of fresh fruit produced that is exported has risen from 6.9% in 1980 to approximately 9% by the close of the 1990's (Rabobank, 1997). For example, China as an emerging fruit production giant (particularly in apples and potentially in kiwifruit) could increase the volumes of global export fruit to about 20% if it decided to export 10% of its total production. As a consequence, fruit is available year round from multiple international suppliers and, in selected markets there is saturated supply (Rabobank, 2001). The danger is that kiwifruit will be relegated to a commodity product, with the associated emphasis on volume and reduced margins. The New Zealand kiwifruit industry needs to differentiate itself from competing international suppliers by offering value added products that provide sustainable competitive advantage.

1.5.2 Market trends

The modern retail markets are characterised by concentrated retail buying power, demands for product traceability and increasing pressure on the margins at all stages in the commodity chain (Rabobank, 2001). Consumers also now have a greater range of choice in fresh fruits than was historically available, and such fruits are available year round. This, in combination with saturated world fruit markets, means gains for kiwifruit will have to come at the expense of other fruit types already on market shelves (Belrose Incorporated, 2001). To choose kiwifruit over competing fruits, consumers need to be constantly reminded of kiwifruit product advantages. In essence, the kiwifruit system must deliver product to the consumer with added assurances and improved quality (Belrose Incorporated, 2005)

The highest value markets to the New Zealand industry are the Asian markets, particularly Japan. In the 2004/05 season, across both Hayward and Hort16A, the Japanese market took 20% of fruit produced but yielded 90% of the industries net returns (Zespri International Ltd, 2005c). The key criteria for growth in Asian markets are fruit quality and consistency (Zespri International Ltd, 2001). The continued profitability of the New Zealand kiwifruit industry is dependent on maintaining market share in the key Japanese market and the critical criterion for Japanese consumers is fruit quality.

1.6 The importance of fruit quality

Increased competition within the global market place has demanded an increased emphasis on fruit quality as a means to develop competitive advantage. For example, in Europe, the new market organisation enjoins farmers to form producer groups whose goal is to improve fruit quality (Lescourret & Genard, 2005). Fruit quality, even when reduced to organoleptic qualities (such as sweetness or acidity) that meet consumer demand, is a multi criterion concept.

Each quality trait is the result of a complex chain of biological processes that depend on environmental conditions and orchard management practices (Lescourret and Genard, 2005).

Appearance quality factors include size, shape, colour and freedom from defects and decay. Defects can originate before harvest as a result of damage by insects, diseases, birds and/or hail, chemical injuries, and various blemishes (such as scars, scabs, abrasions and staining). Postharvest defects may be physical, physiological or pathological (Lancaster & MacRae, 2000). Textural quality factors include firmness, juiciness and mealiness. Flavour or eating quality depends upon sweetness (types and concentrations of sugars), sourness or acidity (types and concentrations of acids, buffering capacity), astringency (phenolic compounds) and aroma (concentrations of odour-active volatile compounds). Off-flavours may result from the accumulation of fermentative metabolites (acetaldehyde, ethanol, ethyl acetate). Nutritional quality is related to contents of vitamins, minerals, dietary fibre and phytochemicals (Collins et al., 2001; Rush et al., 2002).

Consumers of fruit expect consistency and quality. The presence of individual fruits with attributes outside the expected or accepted range of quality may affect consumer perception of the entire fruit category (Jaeger et al., 2003). It is in the interests of fruit producers and marketers to produce reliable supplies of high quality fruit, consistent with respect to the attributes perceived as important by the consumer. Perceptions of important quality criteria may vary between producers, retailers and consumers (Lockshin & Rhodus, 1991).

It must be acknowledged that variability in quality is inherent in the nature of fruit. A component of this variation arises from within the plant. Additional variability is introduced between individual plants, within an orchard, and between geographically separated orchards by differences in management, site, plant material, environment and climate. Within an orchard and within crop plants, management techniques may influence the variation in a fruit population by differentially affecting individuals within that population.

Variability within fruit populations represents both marketing opportunities and difficulties (Werner, 1983; Höhn, 1990; Koostra et al., 1994). Opportunity arises from the ability to manipulate variation and supply fruit able to satisfy the specific requirements of different consumer groups. Difficulties come from variable fruit quality with the production of fruit that may not be acceptable to any consumer group.

1.7 Fruit quality and consumer satisfaction

Most market research indicates that sensory characteristics (appearance, texture, taste, odour and flavour) are the primary reason consumers purchase a particular type of fruit (Wismer et al., 2005). A survey undertaken in the UK indicated that 80% of consumers considered fruit quality more important than price (Market Review, 1996). A survey of U.S apple consumers revealed that ~70% purchase apples for their eating quality (flavour, texture, and taste) (Harker, 2002b). In their review of the literature, Harker et al (2003) noted that many studies have demonstrated that quality is more important to consumers than price when prices are varied within the expected commercial range (Harker et al., 2003). Satisfying the quality expectations of consumers has direct consequences on the likelihood of repeat purchasing (Deliza & Macfie, 1996).

There is a lack of reports in the literature on consumer preference of kiwifruit; the majority of work done to date is proprietary and not publicly available. Extensive work has been done with consumer preference of apples, from which we can draw parallels with kiwifruit. However, such comparisons must be made with caution because consumers have different quality preconceptions and expectations for each fruit type. Consumer expectations vary with consumer age and ethnicity. Japanese consumers generally prefer sweeter fruit and European consumers more acidic fruit (Stec et al., 1989). However, variability in preferences among individuals of the same ethnicity is often greater than the average difference between ethnicities (Jaeger et al., 1998; Harker et al., 2003). Different age groups

can also have markedly different preferences. Children tend to respond more positively to attributes of sweetness and flavour of apples than adults who tend to respond to texture and sourness (Kuhn & Thybo, 2001). The focus on sweetness by very young and old consumers was confirmed by research on orange beverages (Zandstra & de Graaf, 1998). Therefore, fruit quality should not be considered as an absolute, unchanging variable but, rather, a concept that can change with time as individual consumers expectations change.

Failure to meet consumer expectations of quality may be detrimental to an entire industry as well as to a particular cultivar. Following a bad apple eating experience, 58% of Australian consumers indicated they change cultivars, 31% purchase fewer fruit, 24% switch to other types of fruit, 17% stop buying for a while, 10% change to higher priced apples, 5% switch brands, and <1% change to lower priced apples (Batt & Sadler, 1998). The converse is also true, meeting or exceeding consumer expectations has a positive impact on fruit sales. Marketing of fruit-lines with particular attributes that appeal to consumers, such as guaranteed sweetness, has been shown to stimulate repeat buying and/or to command higher prices (Anon, 2000; Armstrong, 2000; Anon, 2002). Studies of consumer preferences for apple have characterised the relative importance of price compared to other factors (consumer perceptions and behaviour, as well as eating quality) that influence consumer's choice of apples (Harker, 2002a; Harker, 2002b; Harker, 2002c). The results suggest these other factors are far more important than price. Demand (sales) for apples can be stimulated by decreasing the retail price or by increasing consumer choice. A 1% decrease in price only resulted in a ~1% increase in sales. However, an improvement in fruit quality and consumer attitudes towards apples by just 1% could increase consumer demand for apples by 12 to 59% depending on cultivar (Harker, 2002a; Harker, 2002b; Harker, 2002c).

Improving the quality of New Zealand kiwifruit supplied to export markets has the potential to maintain/improve market share and premium returns. The following sections review individual fruit quality traits and, orchard and post-harvest factors known to affect them.

1.8 Kiwifruit Quality Characteristics

1.8.1 Size

Within the *Actinidia* genotype, average fruit weight at harvest has been reported to range from 2g to 134g (White et al., 2005). Kiwifruit is marketed internationally in quality classes primarily based on fruit size and to a lesser extent on cosmetic appearance and internal quality. In the early 1990's the New Zealand industry placed considerable emphasis on marketing larger fruit sizes and avoided marketing the smallest size grades altogether. This was a response to an over-supply of fruit, both in the world market and from New Zealand kiwifruit growers, as well as to a demand for larger fruit (Currie et al., 1999). Financial encouragement by means of a premium price for large size fruit was provided to growers. For example, returns to growers per fruit from the larger fruit sizes were approximately double that of small fruit sizes in 1993. In addition a large market potential was identified for jumbo-sized fruit in certain markets (Currie et al., 1999).

1.8.2 Taste

Preferred tasting kiwifruit have an ideal combination of sugars, organic acids and aroma volatiles in the ripe fruit (Lancaster, 2002). These constituents in addition to starch, cell walls, minerals and seeds make up the kiwifruit dry matter (DM) content. Fruit accumulate all these components or their precursors as part of their DM during development on the vine.

1.8.2.1 Sugars

In Hayward kiwifruit the main soluble sugars in eating ripe fruit are, from higher to lower concentration, glucose, fructose, sucrose and inositol (Heatherbell, 1975; Okuse & Ryugo, 1981; Patterson et al., 1991). Though each sugar has a different

relative sweetness score, trial work has confirmed that it is fructose which has the greatest effect on sweetness perception in kiwifruit (McMath et al., 1991; McMath & Gilbert, 1992).

1.8.2.2 Organic acids

The organic acids provide the tangy, zesty taste perception characteristic of kiwifruit. The main types of organic acids in kiwifruit are citric, quinic, malic and ascorbic acid (Heatherbell, 1975). Titratable acidity of New Zealand Hayward at harvest is often in the 1.3 – 1.4% range (MacRae et al., 1989b; Marsh et al., 2004); higher acidity (2.0 - 2.5%) at harvest has been reported for fruit grown in Israel, California and Italy (Benarie et al., 1982; Tombessi et al., 1993; Crisosto & Crisosto, 2001). *A.chinensis* lines had similar levels of quinic acid, but slightly higher levels of citric and malic acids (McMath & Gilbert, 1992). In Hort16A malic acid is slightly higher than in Hayward and citric acid slightly lower, with both varieties having similar quinic acid levels (Young et al., 1999). Although total titratable acidity levels in Hayward kiwifruit remain stable during storage at 0°C, it is known that citric acid levels decline but malic acid levels are maintained (Marsh et al., 2004).

1.8.2.3 Aroma volatiles

In addition to the sweet and sour/tangy flavour balance in kiwifruit, the contribution of volatile organic compounds ('volatiles') is important for kiwifruit flavour, consumer acceptance and the perception of both sweetness and acid levels (McMath et al., 1991; Jaeger et al., 2003). The volatile compounds give the aroma and flavour of kiwifruit. Between 80 and 90 volatile compounds have been identified in Hayward kiwifruit and about 15 of these compounds have been shown to be of significance in kiwifruit flavour. The significance of the others has yet to be established (Young & Patterson, 1990; Perera et al., 1998).

Methyl butanoate is the major ester in ripe kiwifruit (Young & Patterson, 1985). Increased amounts of E-hex-2-enal and hexenal increased the perceived intensity of kiwifruit aroma (Gilbert et al., 1996). Increased levels of ethyl butanoate in a model system resulted in increased perception of kiwifruit flavour (Gilbert et al., 1996). The volatile composition of kiwifruit varies considerably with ripeness (as

measured by firmness), maturity and storage conditions (Young & Patterson, 1985; Bartley & Schwede, 1989; Patterson et al., 1991). There was an increase in ester levels, in particular when fruit were 0.6KgF (Kilograms force) or softer (Patterson et al., 1991). Over ripe fruit has an excess of the esters, particularly ethyl butanoate, which was disliked by consumers (Young & Patterson, 1995).

1.8.3 Firmness

Firmness is the key criterion in the assessment of suitability of kiwifruit for export and consumption. The firmness of Hayward kiwifruit at harvest is generally in the range of 6 – 11 KgF, the Hort16A variety has a firmness range of 4 -5 KgF at harvest, both varieties are considered to be eating-ripe when the firmness is in the range of ~1.0 - 0.5 KgF (MacRae et al., 1990; Patterson et al., 2003). Hence a large decrease in fruit firmness must take place after harvest before the fruit is ready to eat.

The relationship between firmness and time is critical to the industry's ability to deliver fruit of appropriate firmness to its customers. New Zealand industry standards are such that lines of fruit will not be exported if the mean firmness (measured by penetrometer) falls below the export threshold level of 11.8 N (Newtons) or 1.2 KgF; individual fruit must all be firmer than 9.81 N or 1.0 KgF (Hopkirk et al., 1989; Lallu, 1997; Lallu et al., 1999).

Many physiological processes in kiwifruit purportedly contribute to fruit softening including cell wall swelling and breakdown, the hydrolysis of starch, and a decrease in water and osmotic potential (Arpaia et al., 1987; Redgewell & Percey, 1992; Redgewell & Fry, 1993). Of these, probably the most important physiological change leading to the softening of kiwifruit, and for that matter many other fruits, is the loss of cell wall integrity, particularly the dissolution of pectin structures (Brummell, 2006). Softening of kiwifruit typically consists of two phases. The first phase involves the largest changes in firmness and is accompanied by considerable breakdown of cell walls due predominantly to the

solubilisation of pectin and degradation of hemicelluloses. The second, slower phase of softening can be attributed mostly to the depolymerisation of solubilised pectin and the loss of sugars from the cell wall (MacRae et al., 1992).

A major problem for the kiwifruit industry is the unpredictability of fruit softening. It is currently not possible to predict at harvest what the softening rate of fruit will be from different orchards, regions or between vines. This unpredictability means that the industry does not know when fruit will reach 1.2 KgF, the minimum firmness acceptable for export (Hopkirk et al., 1989; Lallu, 1997; Lallu et al., 1999). Variable fruit softening imposes major costs on the industry. These involve large direct costs associated with condition checking, fruit rejection and repacking prior to export or marketing. Approximately 70% of all losses in packed kiwifruit in 1991 were the result of premature softening (Banks, 1992).

1.8.4 The interaction between fruit quality characteristics and consumer acceptance

Scott et al. (1986) identified a significant relationship between flavour and soluble solids concentration (SSC) of ripe fruit (Scott et al., 1986). Fruit with SSC > 13% were more acceptable to a sensory panel than fruit with SSC < 13% (MacRae et al., 1989a). McMath and Gilbert (1991) used a panel of Japanese consumers to investigate the relationship between kiwifruit SSC and consumer satisfaction. They found that fruit of SSC 13-16% and SSC > 18% were equally preferred, although acceptability scores for SSC > 18% were slightly higher; fruit with SSC < 13% were not liked, and 48% of consumers tested would buy fruit of SSC 13-16% and 100% would buy fruit SSC > 18% (McMath & Gilbert, 1992). Mitchell and co-workers (1992) identified a similar relationship with consumers preferring sweeter (SSC > 13%) fruit rather than less sweet fruit (SSC < 13%) (Mitchell et al., 1992). Using sensory evaluation, flavour acceptability of kiwifruit was found to increase with increasing SSC (Rossiter, 2000). As expected, perceived "sweetness intensity" increased with increasing SSC. Acidity did not influence

flavour acceptability. At high SSC, sugars were able to suppress the effects of variations in acidity. Changes in SSC did not influence "flavour intensity", confirming that aroma volatiles may be important contributors to kiwifruit flavour intensity (Rossiter et al., 2000). Crisosto and Crisosto (2001) conducted consumer acceptance tests to determine the relationship between ripe soluble solids concentration (rSSC) and ripe titratable acidity (rTA) on consumer acceptance of Hayward kiwifruit. Kiwifruit with rSSC that ranged from 11.6 to >13.5% were acceptable to consumers but with different degrees of liking. rTA played a significant role in consumer acceptance only in kiwifruit with low rSSC (< 11.6%) and high rTA (> 1.17%) (Crisosto & Crisosto, 2001).

Consumer preferences within a single fruit-type and/or cultivar are often defined by the stage of ripeness (Harker et al., 2003). Firmness will create an expectation for particular flavour and texture attributes when fruit are eating ripe (Lancaster & MacRae, 2000). Firmer fruit tend to be less ripe, and thus taste more acidic and have a volatile profile based on the presence of aldehydes that give a grassy/stalky aroma and flavour. Softer fruit will be much more mature, lower in acidity, and tend to have a volatile profile based on the presence of esters that give a fruity aroma and flavour (Harker et al., 2003). Consumers tend to separate into groups that like more-ripe or less-ripe versions of the same fruit. These preferences for different levels of ripeness are apparent in studies of Hayward kiwifruit (Stec et al., 1989).

However, at any other stage between harvest and eating ripeness, firmness is not predictive of taste and aroma. Thus although firmness is easy to measure, it can be misleading as an indicator of taste and aroma. Firmness is considered the primary indicator of kiwifruit eating ripeness, but it is not well related to other attributes of good eating quality; DM and SSC are not well related to firmness (McGlone & Kawano, 1998).

Hayward kiwifruit may have DM in the range of approximately 12-20% of the fresh weight at harvest (Beever & Hopkirk, 1990), with most fruit having an at-harvest DM content in the range of 14-17% (Burdon et al., 2004). The rSSC can

be reliably predicted from fruit DM content at the time of harvest (Jordan et al., 2000; Burdon et al., 2004), consequently, there is a direct link between fruit DM content at harvest and consumer preference of ripe fruit (Lancaster, 2002; Burdon et al., 2004). Burdon et al. (1999) found Japanese consumers to dislike fruit with DM <15% and to prefer fruit with a DM >19% (Burdon et al., 1999). Harker et al. (2001) worked with a range of consumer groups of differing ethnicities and found that all ethnic groups could distinguish between high and low DM Hayward fruit. All consumer groups showed a distinct preference for fruit of >18% DM, fruit with a DM <14% was universally disliked, while consumer liking of fruit with DM 16-18% was conditional on fruit firmness (Harker et al., 2001). Thus all studies showed that consumers prefer higher DM fruit. Fruit DM content at harvest can be used as an indicator of ripe SSC and, therefore, subsequent consumer preference. Consequently fruit DM is used as a measure of commercial acceptability within the NZ kiwifruit industry. In New Zealand, growers receive premium payments for the production of high DM kiwifruit, which is marketed under the TASTE ZESPRI™ programme.

1.9 Factors Influencing Fruit Quality

Many preharvest and postharvest factors influence the composition and quality of fruit. These include: preharvest climatic conditions, edaphic factors and cultural practises, maturity at harvest and harvesting method, and postharvest handling procedures. Despite variability between fruit, kiwifruit vines in New Zealand are uniformly managed at an orchard block level. Vines are strip-picked at harvest, resulting in wide variation in fruit quality traits within each fruitline.

1.9.1 On-orchard

1.9.1.1 Temperature

Climate is the primary determinant of crop yield and quality, with temperature being the key driver of all crop development. Relationships between temperatures

experienced during the growth period and fruit quality have been widely reported (Hopkirk et al., 1989; Minchin et al., 2003; Richardson et al., 2004; Snelgar, 2004; Snelgar et al., 2005a; Snelgar et al., 2005b; Snelgar et al., 2006). The analysis of Snelgar et al. (2006) suggests that average air temperature is the major climatic variable affecting Hayward kiwifruit DM content, but the effect of temperature changes dramatically during the season (Snelgar et al., 2006). During spring high temperatures increase DM while during summer high temperatures reduce DM. Two recent studies have clearly demonstrated that high temperatures during summer increase vegetative vigour and lead to low DM in Hayward fruit. Richardson et al. (2004) showed that heating potted vines 7°C above ambient temperature in a controlled climate room during summer and early autumn reduced DM from 22.6% to 14.2% (Richardson et al., 2004). Heated vines produced nine times more summer prunings than control vines. Snelgar et al. (2005a) heated mature kiwifruit vines by 4.6°C during January to March and reduced DM by 0.6%. The rate of shoot elongation was increased by over 50% (Snelgar et al., 2005a). It seems likely that the reduction in DM due to high summer temperatures is an indirect effect, because studies in which only the fruit of Hayward and Hort16A vines were heated showed that high summer temperatures increased fruit DM (Snelgar, 2004; Snelgar et al., 2005b). The authors subsequently hypothesised that high temperatures during summer stimulate both fruit growth and vegetative growth, but the stimulation of vegetative growth is so excessive that fruit are not able to compete effectively for limited carbohydrate resources (Snelgar et al., 2006). From work with Hort16A, Snelgar et al. (2005b) observed that high temperatures early in the season increased both fresh weight and DM accumulation in a balanced manner, so that the DM concentration was not altered significantly. In contrast, high temperatures near the end of the season, when fruit growth rates are lower, have the potential to increase the DM concentration of Hort16A fruit. One possibility is that this late-season increase in DM resulted from increased rates of water loss when fruits were heated (Snelgar et al., 2005b).

Temperature has been reported to have significant effects on kiwifruit maturation (Snelgar et al., 2005a). Minimum temperatures during the growing season

strongly influence fruit maturation as cool nights tend to favour the accumulation of SSC in fruit (Seager et al., 1996). For Hayward kiwifruit, high temperatures immediately prior to harvest can delay the conversion of starch into sugars, and thus commercial maturity clearance, as measured by SSC (Snelgar et al., 1993). The timing of the maturation process in Hort16A (change in flesh colour) varies slightly with harvest site and season and this led Minchin et al. (2003) to propose that elevated temperatures 100–150 d after flowering tend to delay the change in colour (Minchin et al., 2003). Heating Hort16A fruit early in the season increased the SSC at harvest, as well as inducing more yellow (lower hue angle) and softer fruit at harvest (Snelgar et al., 2005b).

The influence of growth temperatures on Hayward fruit quality is the subject of chapter 6.

1.9.1.2 Production system

Anecdotal reports claim that the management practices of organic and conventional production systems contribute both to differences in quality of crops and to their subsequent storage behaviour. Comparisons of organic and conventional production systems for other crops have revealed little or no differences in the quality and/or composition of crops (Ruger, 1984; Reinken, 1987). For example, differences were observed in the concentrations of some minerals (e.g Nitrogen and Calcium) in the foliage of organically and conventionally grown peach trees but the quality of the fruit from those trees did not differ significantly (Rader et al., 1985). In comparative studies on yield, researchers have generally found reduced yields from organic systems (Ruger, 1984; Rader et al., 1985; Gliessman et al., 1986; Reinken, 1987). Differences in yield have been attributed to differences in the quantity and quality of fertilizers being applied to each system, with more readily available nitrogen being typical of conventional systems. Poorer yields from organic systems have also been associated with insect and disease problems (Vossen et al., 1994).

There have been few comparisons of the quality of kiwifruit from organic and conventional systems. Organically grown kiwifruit fruit were found to be as firm

or firmer than conventionally grown fruit at harvest and after four months storage (Hasey et al., 1996). Woodward (2001) reported that organic orchards produced higher DM fruit than that of conventional production systems in the 2001 season (Woodward, 2001). Despite a paucity of evidence in the literature, it is popularly believed that kiwifruit from organic orchards are smaller sized with higher DM and subsequently store better than fruit from their conventional counterparts.

1.9.1.3 Water

Plant water stress has a number of effects on the quality of fruits. For example, the colour and SSC of apple have been improved by water stress albeit at the expense of fruit size (Lotter et al., 1985). The reported effects of plant water stress on kiwifruit storage behaviour are inconsistent, with beneficial effects in some cases (Swain, 1984), no effect (Smittle et al., 1992), or even negative effects (Proebsting et al., 1984) reported. These inconsistencies may have arisen because water stress advanced fruit maturity at the time of harvest, and experimental procedures did not correct for potential effects on fruit storage behaviour (Reid et al., 1996). The availability of water for vine growth is one of the main determinants for production of export fruit (Prendergast et al., 1987; Judd et al., 1989; Salinger & Kenny, 1995). The minimum annual rainfall requirement has been defined as 1250mm (Judd et al., 1989) with the need for irrigation in drier areas and in drier than average years. Ultimately the minimum rainfall required to match the evaporative demand is determined by the soil water storage and critical deficit for the soil type (Salinger & Kenny, 1995). It is known that in some kiwifruit growing regions of the world a significant reduction in harvest weight will occur if the supply of irrigation water is limited over summer (Judd et al., 1989). Relieving the vine of drought stress restores the growth rate of the fruit to that of fruit on non-stressed vines, but dry weight and fresh weight accumulation lost during the period of drought stress is never recovered (Judd & McAneney, 1987; Prendergast et al., 1987).

For kiwifruit, mild water stress has been reported to improve fruit quality. Reid et al. (1996) found a general trend of reduced irrigation resulting in decreased fruit fresh weight and increased SSC at harvest (Reid et al., 1996). Withholding

irrigation early in the season had no effect on mean fruit weight at harvest but the fruit had a slower decline of firmness in store. Unfortunately there were no records of fruit DM. Miller et al. (1998), using potted vines, found that early water stress (14-35 days after bloom) reduced fruit fresh weight by 30g whereas later water stress (95-116 days after bloom) resulted in a smaller reduction in fruit fresh weight (13g), compared with fruit from the well irrigated control treatment. Fruit DM was 28% on the late stressed fruit compared with 25% on the control and early stressed fruit (Miller et al., 1998); these DM values are very high but are typical of potted vines (Richardson et al., 2004).

The response of kiwifruit to a lack of water is similar to the effects of transient waterlogging on fruit quality (Smith & Miller, 1991a). In this study the authors reported that flooding of the root system during the early stages of fruit growth increased the concentration of soluble solids in the fruit at harvest and also fruit firmness. In contrast, a similar waterlogging stress imposed late in the season advanced fruit maturity and hastened ripening. The similarity in responses suggests that similar regulatory or physical processes are operating during both water logging and drought stress. In other species water logging has been shown to cause root anoxia, which in turn leads to reductions in root hydraulic conductance and decreased water supply to the shoots (Tournaire-Roux et al., 2003).

1.9.1.4 Mineral nutrition

The effect of plant nutrition on fruit quality is a contentious issue supported by conflicting research findings. In the case of DM there is some indication that fruit grown under high nitrogen fertilisation have a lower DM content, and this may be an indirect effect through high nitrogen levels producing denser canopies (promoting vegetative growth) (Lancaster & MacRae, 2000). In the work of Benge (1999), calcium was strongly implicated in the storage behaviour of kiwifruit (Benge, 1999). In particular, fruit with higher calcium concentrations had lower incidences of localised softening ('soft patches') than fruit with lower calcium concentrations, which is consistent with other work in this area (Davie, 1997). Benge (1999) suggested there was also some indication that the

concentrations of magnesium and nitrogen in fruit are important in the development of soft patches. Buwalda and Meekings (1993) found that nitrogen supply did not significantly affect any of the measured variables during the first season of their experiment. In the second season, canopy leaf area was reduced significantly where nitrogen supply was limited (Buwalda & Meekings, 1993). The relatively slow expression of effects of varying nitrogen supply in experiments, typical of perennial plants, indicates that nitrogen reserves within the soil-plant system may have buffered the plant from changes in rates of application of nitrogen fertiliser (Marschner, 1986). It is also possible that root growth may have increased with decreasing nitrogen supply, facilitating nitrogen uptake in spite of reduced nitrogen availability and maintaining nitrogen supply to the canopy (Dasberg, 1987; Buwalda & Lenz, 1992).

1.9.1.5 Canopy Management and the fruit light environment

It is popularly believed that the way kiwifruit shoots are managed can affect fruit quality and fruit storage behaviour (Ombler, 1991; McLeod, 1992; Mulligan, 1993). In general the nature of the canopy has effects on: light levels to fruit underneath the canopy, temperature underneath the canopy, and the production of photosynthate by the vine and the supply of sugars, water and minerals to the fruit.

The purpose of canopy management is to control the vegetative growth of kiwifruit shoots. Vegetative growth has been proposed as a stronger sink for carbohydrate than fruit growth (Snelgar et al., 2005a; Snelgar et al., 2006); unchecked vegetative growth will out-compete fruit for resources to the detriment of fruit quality. Allocation of photosynthetic products within a vine, especially to the fruit, is strongly influenced by canopy architecture and therefore is largely controllable by management practises such as pruning and fruit thinning (Buwalda & Smith, 1990). Dense canopies produced fruit of lower DM and firmness (Tombessi et al., 1993; Hopkirk et al., 1994) and this may be a consequence of inadequate light exposure of leaves which is known to be essential for fruit development and quality (Biasi et al., 1995). Snelgar et al. (1998) altered pruning regimes between orchards to manipulate canopy density and reported many

differences in fruit between the canopy types. However, many of the differences observed between the two study orchards could not be attributed to variations in canopy density (Snelgar et al., 1998).

Canopy management also affects the light environment of fruit. A number of investigations have identified relationships between fruit quality traits and the fruit light environment. For example, stone fruit grown under a high-light environment (outside canopy) were found to have a longer shelf life, with a lower incidence of storage disorders, than fruit grown under a low light environment (inside canopy) (Crisosto et al., 1997). Similarly, kiwifruit shaded by canopy during growth have been found to soften more quickly (Snelgar & Hopkirk, 1988). Kiwifruit from shaded positions within the canopy have also been associated with lower mean fresh weight (Snelgar et al., 1991), SSC (Antognozzi et al., 1995) and chlorophyll content (Antognozzi et al., 1995).

1.9.1.6 Crop load

For a given canopy, increasing crop loads have consistently resulted in smaller fruit size (Burge et al., 1987; Cooper & Marshall, 1987; Snelgar & Thorp, 1988; Lahav et al., 1989; Richardson & McAneney, 1990; Antognozzi et al., 1991; Inglese & Gullo, 1991). This effect is generally interpreted as the available carbon, although being increased, being distributed between greater numbers of fruit. Richardson et al. (1997) found high crop loadings reduced fruit size by 18% but had little effect (<1%) on DM and SSC of fruit (Richardson et al., 1997a). A slightly negative response of Hayward DM (~0.5%) over a large range of croploads (5-60 fruit m⁻²) has been reported (Woodward, 2001), others have found a non-significant effect of crop load on kiwifruit DM (Snelgar et al., 1998). Earlier data from the same study showed that the relationship between mean fruit fresh weight and crop load could be changed by Leaf Area Index (LAI), with a more pronounced decline in mean fresh weight with crop load at high LAIs over a range from 2.5 to 6 (Snelgar & Martin, 1997).

The relationship between cropload and fruit quality is more extensively reviewed and investigated in chapter 3.

1.9.1.7 Fruit Maturity at Harvest

Maturity at harvest is the most important factor that determines storage life and final fruit quality. Immature fruits are more subject to shrivelling and mechanical damage and are of inferior quality when ripe. Overripe fruits are likely to become soft and mealy with insipid flavour soon after harvest. Fruit picked either too early or too late in its season are more susceptible to physiological disorders and have a shorter shelf life than when picked at the proper maturity (Kader, 1999).

Commercially, main crop Hayward kiwifruit in NZ is harvested with a minimum maturity index of 6.2 % SSC, while Hort16A kiwifruit meets commercial maturity standards when flesh colour has a Hue angle less than 103°. Fruit that are harvested with SSC less than 6% do not store as well as more mature fruit and do not develop good flavour (Beever & Hopkirk, 1990), for example Crisosto and Crisosto (2001) reported that Hayward kiwifruit picked with SSC<6.2% developed flesh breakdown. It is recommended that fruit intended for long-term storage be harvested with a maturity index between 7 and 10 (Hopkirk et al., 1986) although delaying harvesting increases the risk of damage from frosts and winter storms (Beever & Hopkirk, 1990).

The relationship between fruit maturity and other aspects of fruit quality is more extensively reviewed and investigated in chapter 3.

1.9.2 Post-harvest

In addition to preharvest factors, a number of factors are reported to affect the storage behaviour and subsequent internal quality of kiwifruit after their removal from the vine. Much research has investigated how post-harvest conditions influence the rate of fruit softening; in comparison the post-harvest influences on other quality traits has received scant attention. The current state of knowledge is briefly reviewed below.

1.9.2.1 Controlled Atmosphere storage

The atmospheric composition of coolstores can have a dramatic influence on the storage life of fruit. There has been considerable research on controlled atmosphere (CA) storage and its impact on the softening of kiwifruit whilst in comparison, few reports are available on how CA effects other fruit quality traits. Controlled atmospheres, particularly those high in CO₂, retard the rate of softening in many fruits and this is also true for kiwifruit (Basiourny, 1998). However, storage in atmospheres containing more than 10% CO₂, especially for long periods, has proven detrimental to fruit quality (Irving, 1992). CA storage in 0.5% O₂ resulted in off flavours due to anaerobic respiration (Thomai & Sfakiotakis, 1997).

1.9.2.2 Mechanical damage

Compression and impact forces on fruit associated with normal harvesting and handling have been found to have significant negative effects on their quality during storage (Davie, 1997). Localised softening is especially exacerbated by mechanical damage (Davie, 1997). Kiwifruit of all firmnesses can become damaged at harvest, however, softer fruit appear to be more susceptible to mechanical damage (Davie, 1997). The pronounced “beak” at the distal end of Hort16A fruit is a potential source of damage during any fruit-to-fruit contact that occurs during all facets of fruit handling. Hort16A fruit are also softer than Hayward at commercial maturity and, therefore, more vulnerable to damage (Patterson et al., 2003).

1.9.2.3 Storage temperature

Once kiwifruit have been harvested and packed they are placed in coolstorage for periods of up to one year at 0°C, in the case of Hayward (Cotter et al., 1991), and for up to 12-16 weeks at 1.5°C for Hort16A (Patterson et al., 2003). During storage starch is converted to soluble sugars and fruit lose their capacity to produce aroma volatiles, this can lead to fruit being perceived as ‘bland’ tasting (Lancaster & MacRae, 2000). As found for most fruits, temperature has a major effect on the rate of ripening. Respiration rates decrease as fruit temperature is reduced from ambient to 0°C (Heatherbell, 1975; Fukui et al., 1976). The rate of

softening in the first few weeks after harvest is also reduced at lower temperatures. At 0°C, packed fruit at first soften rapidly from a flesh firmness of approx 80 N to 30 N in 4-6 weeks (Beever & Hopkirk, 1990). Thereafter the rate of softening slows considerably. At 20°C, the initial rate of softening is only slightly greater than that at 0°C, but this rate is maintained, and fruit soon become fully ripe, then overripe (Beever & Hopkirk, 1990). Hence, kiwifruit are typically stored at 0°C to maximise their storage life.

In a study on the effect of storage temperature on fruit flavour, MacRae et al. (1990) reported that storage at 4°C resulted in greater malic acid concentrations than storage at 0°C. These fruit were perceived as less sweet and had more negative descriptions and lower acceptability to consumer panels (MacRae et al., 1990). Storage of Hort16A at higher temperatures results in more rapid softening and/or the development of more rots but does facilitate the postharvest development of the yellow flesh colour (Patterson et al., 2003).

1.9.2.4 Postharvest disorders

Fruit quality at harvest has been linked with fruit storage performance. In cucumber it has been reported that fruit more susceptible to postharvest chilling injury were characterised by lower DM than unaffected fruit (Cabrera et al., 1992). In kiwifruit, Hort16A fruit which developed postharvest chilling injury were less mature at harvest and had lower DM than unaffected fruit (Clark et al., 2003). The manifestation of postharvest disorders during storage, especially *Botrytis cinerea* (which causes stem-end rot), may also have considerable effects on the storage behaviour of neighbouring kiwifruit. Such diseases can stimulate ethylene production in infected fruit and this may accelerate fruit softening in neighbouring non-infected fruit (Brook, 1992; Manning & Pak, 1993; Niklis et al., 1993).

1.10 Non-destructive measurement of fruit attributes

A unique aspect of this study was the use of large datasets of fruit quality measurements obtained by near infra-red (NIR) estimation from orchards supplying the Eleos Ltd packhouse located in Te Puke, New Zealand. Fruit quality characteristics were recorded for individual export grade fruit pieces at the time of packing using a NIR grading system. The resulting datasets are unique in that individual fruit records were associated with the producing orchard area, and that this was done over four consecutive seasons (2001-2004). There are many non-destructive methods developed for measuring a range of attributes in intact fruit (Watada, 1989; Costa et al., 2003). However, because NIR has been a key technique in this research, this review focuses on NIR spectroscopy and its applications in non-destructive estimation of fruit quality traits.

1.10.1 Near-infrared Spectroscopy

Typical NIR spectroscopy studies the spectral properties of a wavelength region between 780-2500nm (Williams & Norris, 2001). NIR spectroscopy has long been used in chemistry to study the characteristics of chemical compounds and recently has been extended to measure various attributes of intact fruit (Richard & Ozanich, 1999). NIR is the most developed method for non-destructive assessment of internal composition and texture of intact fruit available. A wide range of NIR instrumentation, accessories and software packages are currently available for both laboratory and commercial applications (Guthrie & Walsh, 1997).

1.10.1.1 Principle of NIR

The principle of NIR spectroscopy is that different chemicals have different absorption spectra in the NIR region. NIR spectra of fruit can be affected by both the chemical composition of the fruit and the physical properties of the fruit (McGlone & Kawano, 1998). Fruit tissue consists of water, carbohydrates and

proteins which have large numbers of NIR active chemical groups such as CH, OH, NH and C=O, all of which contribute to the overall NIR spectra of a fruit piece (Williams & Norris, 2001).

1.10.1.2 Data analysis

Raw spectra contain background noise and are subject to instrument drift and baseline changes. Many pre-treatments have been developed to reduce background noise and remove linear baseline changes between spectra (Williams & Norris, 2001). Log transformation of raw spectra against a baseline to generate absorbance spectra is an essential pre-treatment for NIR data, while other statistical treatments have also been useful (Geladi et al., 1985; Barnes et al., 1989; Mowat & Poole, 1997; Schaare & Fraser, 2000; Williams & Norris, 2001). Relationships between targeted fruit attributes and derivative spectra can be established using the following procedures (Osbourne et al., 1993; Schaare & Fraser, 2000; Williams & Norris, 2001).

- Principal component analysis,
- Multiple Linear Regression,
- Multiplicative Scatter Correlation Technique,
- Partial Least Square Method (PLS) and modified PLS method,
- Canonical Discriminant Analysis.

The purpose of these statistical procedures is to model the fruit attribute of interest in terms of the NIR spectra thereby enabling estimation of fruit attributes from the fruit NIR spectra.



Figure 1.2. Multi-lane near infra-red (NIR) grading system (Taste Technologies Ltd, Auckland, New Zealand) fitted to a commercial kiwifruit grader (Compac™ grading equipment, Auckland, New Zealand).

1.10.2 Applications of NIR

1.10.2.1 Laboratory

NIR has been used successfully to measure several compositional attributes of intact horticultural produce including SSC (Richard & Ozanich, 1999; Guthrie et al., 2005), DM (McGlone & Kawano, 1998; Guthrie et al., 2005), starch content (Weber & Haase, 1996), chlorophyll content (Slaughter, 1995; Zude-Sasse et al., 2002) and pH (Lammertyn et al., 1998). NIR has also been used to detect internal disorders of intact fruit, such as surface bruising and bitter pit in apple, section drying in tangerine, surface defects in peach, spongy tissue in radish, and flesh firmness in plum (Miller & Delwiche, 1991; Onda et al., 1994; Geeola & Peiper, 1994; Marcelis et al., 1995; Peiris et al., 1998; Nicolai et al., 2006). Mineral content (e.g. calcium and phosphorus contents) of poultry and pig feeds have also been estimated using NIR (Atanassova & Ilchev, 1997).

In kiwifruit, NIR has been successfully used to estimate SSC (McGlone & Kawano, 1998; Schaare & Fraser, 2000) and DM (McGlone & Kawano, 1998) on intact kiwifruit with an overall R^2 above 0.90. The estimation of firmness has

been less accurate (the best $R^2 = 0.76$) possibly because there is insufficient pectin in kiwifruit (<1% by weight) for accurate detection by NIR (McGlone & Kawano, 1998). Whole fruit density and internal flesh hue angle of yellow-fleshed Hort16A kiwifruit have been estimated from interactance spectra with R^2 of 0.74 and 0.82 respectively (Schaare & Fraser, 2000). Mowat and colleagues demonstrated that NIR spectroscopy can be extended beyond simple sorting, to differentiating between groups of kiwifruit with properties altered by pre-harvest treatments (Mowat & Poole, 1997; Broom et al., 2000). NIR correctly classified 99% of the fruit by pre-harvest treatment at harvest and 87% after storage. Treatments applied were leaf removal or shading berries with aluminium foil through crop development, or dipping the berries in ethephon two weeks prior to harvest (Mowat & Poole, 1997). This result is superior to that achieved using combinations of fruit weight, skin colour, DM and SSC, indicating that NIR spectra contain more information than just sugar concentration and residual starch contents. This concept was further investigated by Clark et al. (2004) who tested NIR prediction of Hort16A storage performance at the time of postharvest grading. Hort16A kiwifruit were successfully categorised into sub-populations with differing probabilities of developing chilling injury in subsequent coolstorage (Clark et al., 2004).

1.10.2.2 Commercial Applications of NIR technology

NIR spectroscopy has been commercially applied to the in-line sorting of fruit for SSC and, to a much lesser extent, DM, especially in Japan (Kawano, 1998). However, there is no formal material available on the performance of these units.

Woodward (2003a) reported on a NIR grading trial where Hort16A kiwifruit were segregated on the basis of internal flesh colour (Hue° angle), the industry measure of fruit maturity. NIR segregation successfully created a subpopulation that met commercial maturity standards from a fruit population not meeting industry maturity standards (Woodward, 2003a). Walsh et al. (2004) reported that NIR technology was well suited to sorting on SSC in apple, and useful (in decreasing order of accuracy), for sorting of stone fruit, mandarin, banana, melons, onions, tomato and papaya. In the case of sorting fruit on DM the authors found NIR was

best suited to kiwifruit, and useful, (in decreasing order of accuracy), for sorting of banana, mango, avocado, tomato and potato (Walsh et al., 2004). The success of the NIR technology for in-line sorting applications was a function of fruit physical properties, namely thickness of fruit skin, and the range in the quality characteristic within fruit populations (Walsh et al., 2004).

1.11 Research Topic and Significance

It has been argued that in an increasingly competitive international market the New Zealand kiwifruit industry needs to differentiate its product from that of competitors. It is proposed that this is achieved by supplying the highest quality fruit to export markets. Satisfying consumer quality expectations has direct consequences on the willingness to pay a premium price and on the likelihood of repeat purchasing. Of the kiwifruit quality traits, taste is of primary importance. A direct relationship between fruit DM at harvest and the subsequent consumer acceptance of fruit taste has been established. Therefore, DM at harvest is used as a predictor of consumer preference. Supplying markets with fruit of consistently high DM is a major industry goal.

Variation in fruit quality is a natural phenomenon which is influenced by a range of pre- and post-harvest factors. A greater understanding of how fruit quality traits vary within and between fruit populations is required to enable industry to manage variation in fruit quality attributes.

1.11.1 Thesis Aim

Quantify the magnitude, sources and distribution of variation in fruit quality traits within kiwifruit populations and identify opportunities for the management of this variation.

This thesis describes the variation in fruit quality traits (with a focus on DM) occurring within a hierarchy of fruit populations, the relationships between fruit quality traits, and some of the factors which affect the level of variation and the interrelationships between characteristics. Chapters are related, but each is written as an independent study focusing on a different aspect of variation in fruit quality.

1.11.2 Chapter 2 objective

The objective was to describe the distribution of individual fruit weights and DM within populations, investigate the sources of variation, and determine whether quality distributions could be modelled with a probability density function. The hypothesis was fruit weights and DM were normally distributed within fruit populations which would enable prediction of the proportion of fruit within a population meeting specific quality criteria.

1.11.3 Chapter 3 objective

The objective was to examine the relationships between fruit quality attributes. The hypothesis was that orchards, orchard areas, and individual vines that produce larger fruit also produce fruit of higher DM and lower acidity, which are firmer at harvest than smaller sized, low DM, high acid fruit.

1.11.4 Chapter 4 objective

The objective was to model the spatial component of between-orchard variation in fruit quality characteristics across a growing region, and identify whether any areas consistently produce fruit of distinct qualities. The hypothesis was that lower altitude orchards meet commercial maturity standards earlier and produce lower yields of larger sized, higher DM fruit compared to orchards located at higher altitudes.

1.11.5 Chapter 5 objective

The objective was to investigate between-vine variation within a single orchard area across consecutive seasons to quantify both the magnitude and spatial component of variation. First, the hypothesis was tested that it is possible to identify vines that consistently produce high or low yield or quality and that such vines are spatially aggregated within the orchard area. Secondly, the proposition was tested that the spatial aggregation of such vines will be temporally consistent and of sufficient magnitude to enable implementation of zonal management strategies.

1.11.6 Chapter 6 objective

Previously published agrometeorological models were used to investigate the effect of temperature on fruit DM content and test the hypothesis that higher temperatures during the spring growth period have a positive effect on subsequent fruit DM content. Canopy development and vine carbon balance were examined in a field-based whole-vine heating experiment to elucidate the underlying physiological effect of temperature on fruit development.

1.11.7 Chapter 7 objective

Summary and conclusions: How do fruit quality traits vary within fruit populations, what are the relationships between fruit qualities, and what factors influence the variation and the interrelationships? Do opportunities exist to successfully manage the variation in fruit quality?

Chapter 2: The distribution of quality characteristics within fruit populations.

2.1 Introduction

Fruit size and DM (dry matter content as a %) are important attributes for kiwifruit which in part determine grower returns. In the supply chain, they are important characteristics in inventory management. In the market, fruit DM has been linked with consumer satisfaction and the likelihood of repeat purchasing (Lancaster, 2002; Burdon et al., 2004; Harker et al., 2004). The ability to predict fruit size and DM distributions helps guide decisions on crop management and postharvest planning. Though the eating experience is at the individual fruit level, commercial decisions on orchard management, maturity clearance, supply chain management and market suitability are made on populations of fruit. Fruit sampling is used to provide estimates of population parameters (like mean and variance), to which a theoretical distribution could be fitted to estimate the distribution of fruit quality traits within the population. Adequate description of fruit quality distributions at any point in time enables industry to predict the proportion of fruit within a population meeting specific quality criteria.

2.1.1 Fruit growth

Although fruit DM may be a useful fruit quality parameter, in reality it is the ratio of fruit dry weight (DW) to fresh weight (FW), two parameters that can change independently during fruit growth. The accumulation of fruit FW in Hayward kiwifruit normally shows an initial rapid increase over the first 60 DAA (days after anthesis) followed by a more gradual increase towards harvest, frequently

tending to a plateau just before harvest at about 160 DAA (Walton & De Jong, 1990; Davison, 1990; Antognozzi et al., 1996; Richardson et al., 1997a; Hall et al., 2002). The growth curve has been described variously as a double sigmoid or two straight lines (Hall et al., 1996). By 60 DAA the fruit FW has reached over 50% of its final weight and the majority of the growth in fruit length and diameter has been completed (Davison, 1990). The accumulation of DW by Hayward fruit is approximately linear from about 20 DAA to harvest (Walton & De Jong, 1990; Davison, 1990; Sawanobori & Shimura, 1990; Smith et al., 1995; Antognozzi et al., 1996; Richardson et al., 1997a; Ferrandino & Guidoni, 1998; Han & Kawabata, 2002). The changes in DM depend on the FW and DW accumulation curves. Fruit DM shows a distinctive dip at 50 DAA, followed by a rapid, curvilinear increase until about 140 DAA, then a more gradual increase towards a harvest maximum (Walton & De Jong, 1990; Davison, 1990; Sawanobori & Shimura, 1990; Smith et al., 1995; Antognozzi et al., 1996; Richardson et al., 1997a; Ferrandino & Guidoni, 1998; Han & Kawabata, 2002).

It is currently not known how fruit weight and DM are distributed within fruit populations during the growth period. Early season quality distributions are of interest as these can form the basis for developing predictive models that project forward initial fruit quality distributions to harvest. In studies of apple it has been found that lognormal distributions are well able to describe fruit size distributions during the fruit growth period through to harvest (De Silva et al., 1997). This enabled accurate prediction of fruit size distributions at harvest from early season fruit measurements (De Silva et al., 1997).

2.1.2 Fruit weight and DM distributions at harvest

In Hayward kiwifruit the distribution of fruit weights frequently approximates a normal distribution (Snelgar & Hopkirk, 1988; Judd et al., 1989; McAneney et al., 1989; Snelgar et al., 1992) though at times it is significantly skewed (Judd et al., 1989; Manson et al., 1991; Manson et al., 1994). In some cases orchard management has been demonstrated to alter average fruit weights without

changing the shape of the fruit weight distribution. For example, the Hayward fruit weight distribution could be adequately approximated by a normal distribution both prior and post application of a water stress (Judd & McAneney, 1987). In contrast, work investigating the effect of fruit thinning on kiwifruit size distributions found all distributions to be skewed after thinning (Burge et al., 1987).

Little has been published on the distribution of DM within kiwifruit populations. Anecdotally it has been argued that DM distributions are positively skewed towards higher DM values within fruit-lines and, therefore, orchard sampling systems that assume normality are fundamentally flawed. To test this claim Mowat and Amos (2002) fitted normal distributions to 75 Hayward kiwifruit DM datasets and the fit was assessed by the skewness of the data. An average skewness of -0.05 was reported across all fruit-lines which led the authors to conclude that DM distributions in Hayward kiwifruit followed a normal distribution (Mowat & Amos, 2002).

2.1.3 Components of variation

There is a need to quantify the relative magnitudes of the sources of variation in fruit weight and DM within a maturity block, between blocks within an orchard, between orchards within a district, between districts and between years (Zespri International Ltd, 2001). Knowledge of the relative magnitude of the different sources of variation in quality parameters will help focus management practices on minimising the most significant sources of variation. Both within-vine (Smith et al., 1994) and between-vine variation (McPherson et al., 1994) have been reported to be dominant in kiwifruit, while yet others have reported that the magnitude of the various sources of variation are specific for the quality characteristic considered (Miles et al., 1996).

2.1.4 Chapter goals

Published models of fruit growth assume that harvest fruit weights are normally distributed around their mean value and that fruit weight distributions have a constant standard deviation independent of their mean weight (Judd & McAneney, 1987; Judd et al., 1989). These assumptions were tested across a hierarchy of fruit populations (individual vine, fruit-line and orchard) to discover if they are applicable to fruit DM distributions.

The kiwifruit industry is interested in the ability to accurately predict the proportion of high- or low-quality fruit within a population. It was hypothesised that fruit size and DM are normally distributed within fruit populations and that this assumption could be used to accurately predict the proportion of small or low-DM fruit within the tails of the distribution.

Two datasets were analysed to quantify the sources of variation in fruit weight and DM distributions: A macro dataset encompassing many orchards across time and a micro-dataset containing measurements made on individual vines in a single orchard area across time. From this analysis the magnitude of between-orchard variation and the contributions of between-vine and within-vine variation to the total observed variance in fruit quality characteristics were quantified.

Finally, it may be important to know how and when during the fruit growth period populations distinguish themselves as having the potential to be high- or low-quality fruit at harvest. It was hypothesised that the potential for large fruit size and high DM are established early during the fruit growth period (≤ 50 DAA).

2.2 Methods

2.2.1 Fruit Monitoring

2.2.1.1 Macro study

The macro study was conducted from May 2001 to June 2004 with *Actinidia deliciosa* (A. Chev.) C. F. Liang et A. R. Ferguson var. *deliciosa* ‘Hayward’ kiwifruit harvested at commercial maturity ($^{\circ}\text{Brix} \geq 6.2\%$) from 96 commercial orchards in the Te Puke region ($37^{\circ}49'S$, $176^{\circ}19'E$), New Zealand. Fruit quality characteristics were determined for each individual export fruit piece on a commercial kiwifruit grader (Compac™ grading equipment, Auckland, New Zealand) fitted with an Near infra-red (NIR) grading system (Taste Technologies Ltd, Auckland, New Zealand) for logging of fruit weights and counts, and non-destructive estimation of fruit DM.

At weekly intervals a calibration fruit set was used to determine a correction factor for NIR estimation of fruit DM, based on values derived from standard laboratory methods (McGlone & Kawano, 1998). During the course of the study period, results from linear regression between NIR estimation of fruit DM and laboratory determination of fruit DM using traditional oven drying techniques ranged between R^2 of 0.69 – 0.83 (data not presented). Raw NIR measurements were filtered to exclude measurements considered to be errors. The NIR system reported a dimensionless value of how measurements varied across the individual fruit piece, termed the ACC value. The effect of the ACC value on the relationship between NIR estimation and laboratory estimation of fruit properties was determined (data not presented). A critical ACC value was identified and raw NIR records with an $\text{ACC} \geq 4$ were excluded.

The resulting dataset contained fruit weight and DM measurements for 146.73 million class I export fruit pieces from 96 different orchards comprising 550 fruit-lines across four consecutive harvests (2001-2004). A fruit-line represents a management unit within the individual orchard and may comprise a single orchard block or group of blocks. Not every orchard/fruit-line is present in every year as

fruit entering into CA coolstorage was excluded and some orchards did not supply the packhouse for the entire study period.

2.2.1.2 Micro study

The micro study was conducted using individual Hayward vines within a single orchard area over three consecutive harvests (2003-2005). The orchard area was selected because historical records indicated that the block produced a highly variable crop. The vines were mature (>10-year-old) *Actinidia deliciosa* (A. Chev.) C. F. Liang et A. R. Ferguson var. *deliciosa* 'Hayward' kiwifruit plants trained on a pergola trellis. The rootstock was unknown but assumed to be seedlings of open-pollinated *A. deliciosa* var. *deliciosa* 'Bruno', the most common rootstock used in the New Zealand kiwifruit industry. The orchard area was a 0.17 ha block (30 x 65 m) with rows 4.6 m apart and vines spaced at 4.5 m within rows (84 vines in total). Vines were uniformly managed under standard commercial practices (Sale & Lyford, 1990). Each season, when the block attained commercial harvest maturity (6.2 °Brix), vines were harvested individually. Fruit numbers and quality characteristics were determined as described previously (section 2.2.1.1).

2.2.2 Statistical analysis

The assumption of normality for fruit weight and DM distributions was assessed using the Kolmogorov-Smirnov test in SPSS software. This test compares the actual observed distribution against a theoretical normal distribution with the same mean and standard deviation as the test distribution.

To visually assess the fit of fruit distributions to a theoretical normal distribution, quantile-quantile (Q-Q) plots were constructed in SPSS software. Q-Q plots presented the quantiles of fruit weight and DM distributions against the quantiles of a theoretical normal distribution. The fruit weight and DM distributions are deemed to approximate a theoretical normal distribution when the plot clusters around a straight line.

The relationships between population distribution parameters were modelled by regression using the REG procedure in SAS (SAS Institute Inc., 2003).

A components of variance analysis was performed using a mixed model in the SAS system (SAS Institute Inc., 2003). In the macro study season was set as a fixed effect and, orchard and maturity areas within orchards fully nested within season. In the micro study season was set as a fixed effect with individual vines nested within season.

2.2.3 Fruit development

Fruit growth was monitored for two individual vines within the micro study area (section 2.2.1.2) identified as consistently producing fruit of large sized high DM fruit and vines consistently producing small sized low DM fruit across seasons (vines identified using the methodology described in section 5.2.3.3). Over the course of the fruit growth period of season 2004/05, random 30 fruit samples were collected from individual vines at regular intervals from flowering through till harvest (20, 25, 49, 56, 70, 84, 105, 126, 147, 168, 185 DAA). Fruitlet weights and DM were determined using standard laboratory techniques (Snelgar & Hopkirk, 1988; Jordan et al., 2000; Burdon et al., 2004).

2.3 Results

2.3.1 Normality of fruit weight and DM distributions

When vines were harvested individually the majority of fruit weight and DM distributions could be approximated by a normal distribution (Table 2.1), however, the proportion of vines producing fruit populations that were normally distributed varied with season and quality characteristic considered (Table 2.1). A greater proportion of DM distributions were normal compared to weight distributions. Season 2003 produced the highest proportion of normal distributions for fruit quality characteristics and season 2004 the least.

Table 2.1. The normality of fruit weight and DM distributions of individual Hayward kiwifruit vines harvested and assessed individually at commercial maturity across consecutive seasons. The distributions of 84 vines were tested for normality using the Kolmogorov-Smirnov test at the 95% significance level.

Characteristic	Distribution	Season		
		2003	2004	2005
Fruit Weight	Normal	83.3%	65.5%	79.8%
	Non-normal	16.7%	34.5%	20.2%
Fruit DM	Normal	96.4%	84.5%	90.5%
	Non-normal	3.6%	15.5%	9.5%

The majority of larger scale fruit populations exhibited significant deviations from a theoretical normal distribution (Table 2.2). Examples of individual non-normal fruit weight and DM populations of differing scale (vine, fruit-line or orchard) were plotted against a theoretical normal distribution to enable visualisation of how the distributions were deviating from normality (Figure 2.1). The ‘centre’ (around the mean value) of fruit weight and DM distributions matched a normal distribution, deviations from normality occurred in the tails of the distributions. A theoretical normal distribution underestimated the frequency of fruit weights in

the tails of the weight distributions, suggesting fruit weight distributions were more kurtotic (Figure 2.1.A,C,E). A theoretical normal distribution overestimated the frequency of fruit DM in the tails of the DM distributions, suggesting fruit DM distributions were less kurtotic than a normal distribution (Figure 2.1.B,D,F).

Table 2.2. The normality of fruit weight and DM distributions of class I export Hayward kiwifruit populations assessed at the time of packing across consecutive seasons. The distributions of 1011 fruit-lines and 223 orchards across four consecutive harvests (2001-2004) were tested for normality using the Kolmogorov-Smirnov test at the 95% significance level.

Population Grouping	Characteristic	Distribution	Season			
			2001	2002	2003	2004
Fruit-line	Fruit Weight	Normal	14.1%	13.9%	5.8%	16.3%
		Non-normal	85.9%	86.1%	94.2%	83.7%
	Fruit DM	Normal	23.2%	6.3%	4.1%	0.7%
		Non-normal	76.8%	93.8%	95.9%	99.3%
Orchard	Fruit Weight	Normal	12.2%	6.3%	3.0%	5.8%
		Non-normal	87.8%	93.8%	97.0%	94.2%
	Fruit DM	Normal	9.8%	0.0%	6.1%	0.0%
		Non-normal	90.2%	100.0%	93.9%	100.0%

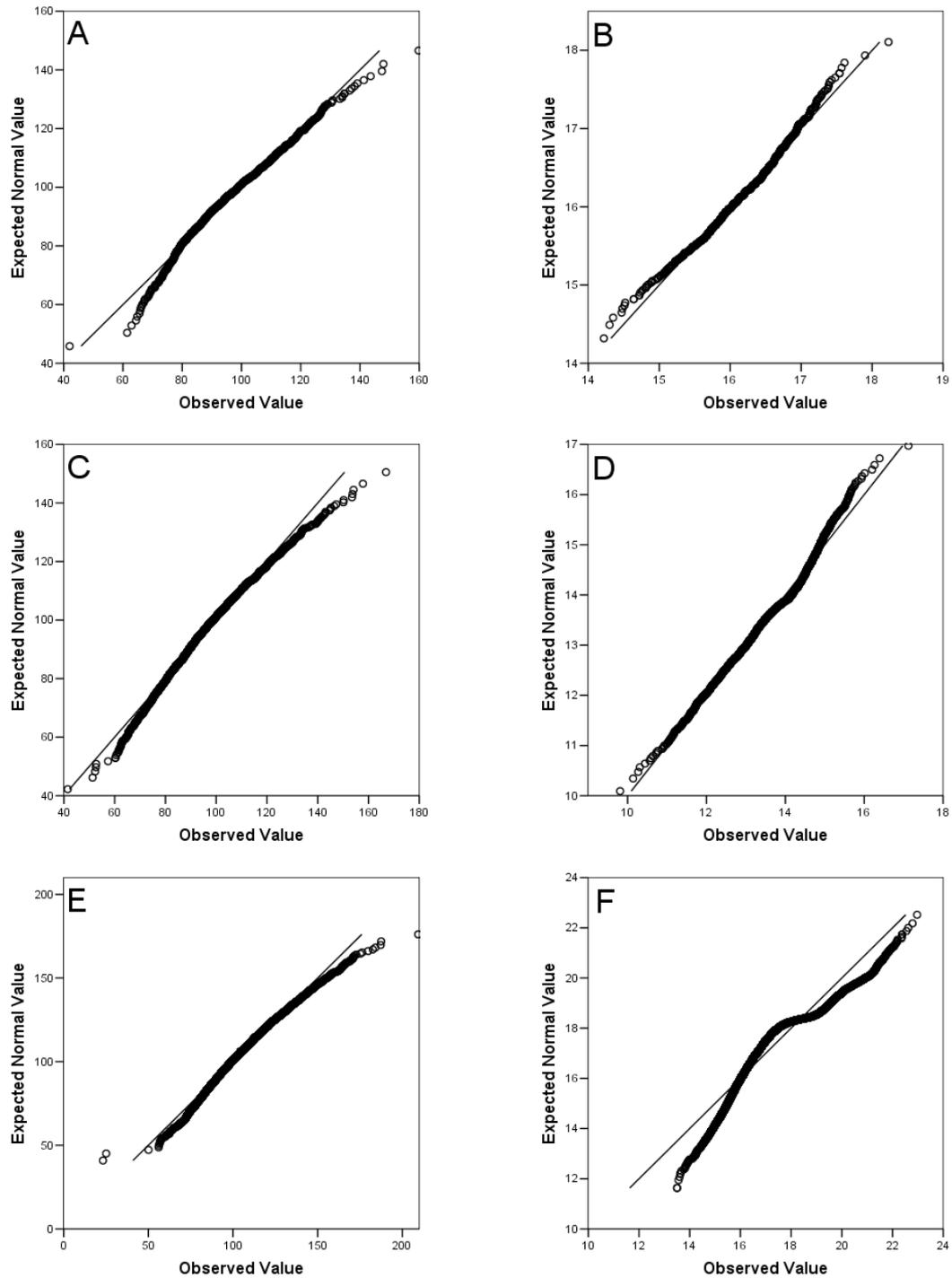


Figure 2.1. Examples of individual non-normal fruit populations of differing size (vine, fruit-line, or orchard) plotted against a theoretical standard normal distribution. Q-Q plots of fruit weight (A,C,E) and fruit DM distributions (B,D,F) at differing population groupings: individual vine (A,B); fruit-line (C,D) and orchard (E,F).

2.3.2 Relationships between distribution parameters

At the individual vine, fruit-line, orchard, and seasonal level there was a positive correlation between mean fruit weight and variability in fruit weight (data not presented), and a positive correlation between the skewness and kurtosis of fruit weight distributions (Figure 2.2). A standard normal distribution is characterised by a skewness of 0 and kurtosis of 3; a graph of skewness versus kurtosis is commonly used to indicate which distributions might fit a given dataset (Judd et al., 1989; De Silva et al., 1997). Fruit populations skewed towards higher weight values were more kurtotic ('peaky') indicating variation within the population was due to frequent small deviations from the mean, rather than large infrequent deviations from the mean.

The lack of any consistent relationships between fruit DM distribution parameters suggests high DM fruit-lines can be adequately identified by their mean value.

Published growth curves for Hayward kiwifruit suggest that average weight and DM values increase as long as the fruit remains on the vine. The above analysis was repeated incorporating fruit age as a covariate; fruit age being defined as the time in days between flowering and harvest. No population parameters were consistently or significantly correlated with fruit age at harvest.

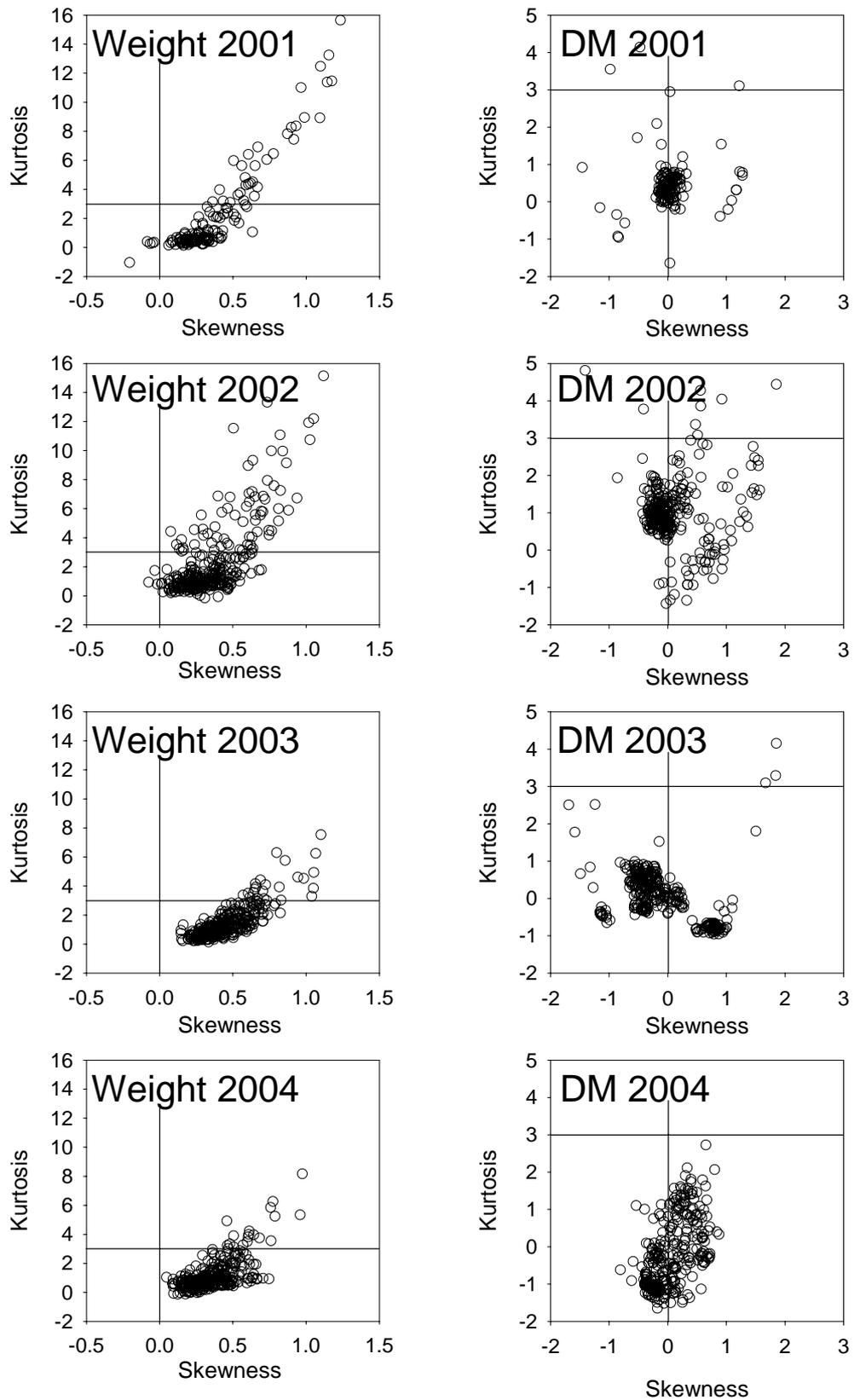


Figure 2.2. Skewness and kurtosis of all Hayward fruit-lines weight and DM distributions at harvest across consecutive seasons. A standard normal distribution is characterised by a skewness of 0 and kurtosis of 3.

2.3.3 The consequence of assuming normality on predicting the proportion of low-DM fruit within populations

The evidence showed that fruit weight and DM distributions were non-normal at population levels greater than the individual vine. We therefore examined the consequences of assuming normality for the prediction of fruit volumes in the distribution tails. A low DM fruit piece was defined as having a DM < 14.5% and, the actual measured proportion of low DM fruit was compared to that predicted by assuming fruit DM to be normally distributed in a hierarchy of fruit populations (Figure 2.3).

The orchard area harvested by vine (micro study) yielded very high mean DM values in season 2003 (mean DM = 18.3%) compared to the subsequent seasons of 2004 and 2005 (mean DM = 16.1 and 15.7%, respectively). There were no, or only a very low proportion of low DM fruit produced by individual vines in season 2003, thus the correlation between actual and predicted volumes of low DM fruit was poor ($R^2 = 0.04$). In the subsequent seasons and for larger fruit populations the actual distribution of fruit DM was well approximated by a normal distribution (Figure 2.3, Table 2.3).

In testing the consequences of assuming normality on the ability to predict fruit volumes in the tail of DM distributions an additional population grouping was included, fruit populations grouped by count sizes for each individual orchard. At packing, the New Zealand industry segregates fruit first by the orchard which produced the fruit and secondly by individual count size (fruit weight groupings). Thus, fruit count size by orchard represents the smallest discrete unit available in the postharvest inventory management system. Therefore it was of interest as to how well the assumption of normality would enable prediction of the proportion of low DM fruit within such fruit populations. The proportion of low DM fruit within fruit size groups was well predicted ($R^2 > 0.92$), the exception being season 2003 ($R^2 = 0.77$) when many orchards suffered from spring frosting (Figure 2.3, Table 2.3).

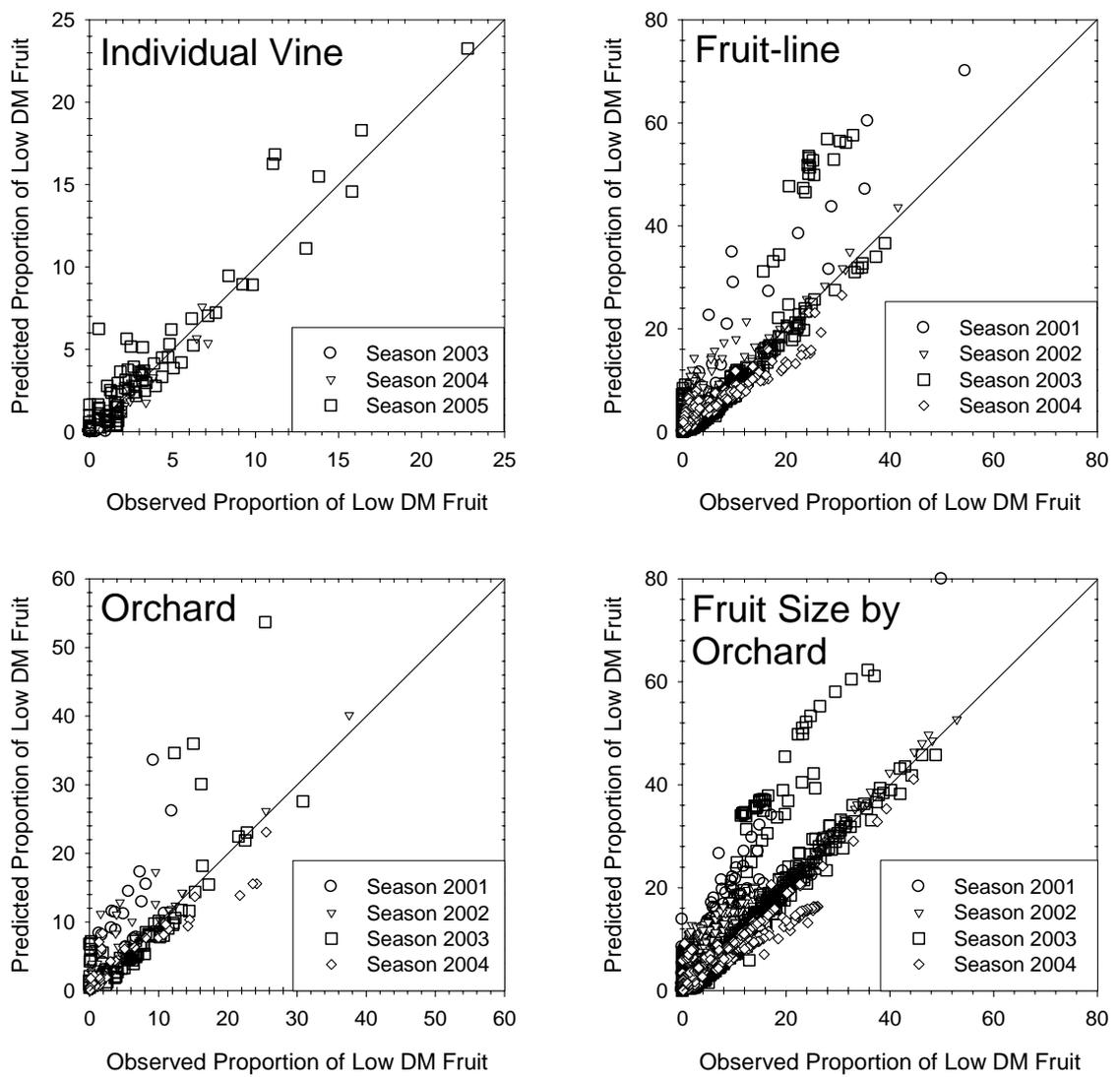


Figure 2.3. Relationships between the measured proportion of low DM fruit (DM < 14.5) and the predicted proportion. Predictions were based upon the assumption that fruit DM distributions are normally distributed in Hayward kiwifruit at different population levels across seasons. The results of linear regression analysis of these relationships are presented in Table 2.3.

Table 2.3. Consequences of assuming normality on the ability to predict the proportion of low DM fruit in the tail of DM distributions. Summary statistics of linear regressions of the predicted proportion of low DM fruit against the measured proportion, when DM is assumed to be normally distributed across a hierarchy of fruit populations over consecutive harvests (2003-2005).

Fruit Population Level	Season	n	R²	Standard Error of Estimate
Individual vine	2003	84	0.04	0.14%
	2004	84	0.92	0.44%
	2005	84	0.98	1.53%
Fruit-line	2001	142	0.89	5.04%
	2002	287	0.88	2.41%
	2003	292	0.75	6.54%
	2004	289	0.99	2.50%
Orchard	2001	41	0.69	5.80%
	2002	64	0.86	2.78%
	2003	66	0.64	5.89%
	2004	52	0.99	2.90%
Fruit Count Size by Orchard	2001	509	0.94	4.35%
	2002	767	0.92	2.69%
	2003	748	0.77	5.65%
	2004	623	0.99	3.05%

2.3.4 Sources of variation in fruit quality distributions

The initial approach taken was using ‘season’ as a fixed effect, with the various production units set as fully nested random effects. Using this approach it was not possible to determine a variance component estimate for season, the analysis focussed on the variation within seasons.

Differences between seasons in fruit weight and DM were significant over the study period (Table 2.4). Within seasons, variation within individual fruit-lines within orchards contributed most to total variation in both fruit weight and DM in the macro study (Table 2.4). Variation between-orchards within seasons were more important than variation between fruit-lines within orchards. The standard errors of the variance estimates for the random effects were high relative to the estimates themselves but the accuracy of the estimate of the variance components improved with movement down the fruit population hierarchy.

Table 2.4. Variance components of fruit weight and DM measured for 710,815 individual ‘Hayward fruit from 26 orchards consisting of 77 individual fruit-lines across three consecutive growing seasons (2002-2004). No variance component estimate was calculable for fixed effects; the presented value is an estimate of the mean seasonal value.

Variance Component		Weight			Dry Matter Content		
		Estimate	SE	P	Estimate	SE	P
Fixed Effects	Season 2002	103.77	1.22	< 0.01	16.55	0.20	< 0.01
	Season 2003	107.59	1.23	< 0.01	16.46	0.21	< 0.01
	Season 2004	103.36	1.23	< 0.01	16.52	0.21	< 0.01
Random Effects	Between-orchards within season	32.78	6.29	< 0.01	1.02	0.17	< 0.01
	Between fruit-lines within orchards	10.35	1.20	< 0.01	0.09	0.01	< 0.01
	Within fruit-lines	302.21	0.51	< 0.01	1.72	0.003	< 0.01

The macro study identified between-fruit variation within fruit-lines to be dominant; however this variance component estimate incorporated variation at finer scales such as variation within- and between-vines. Such small scale variation was investigated using the micro study. Within the test orchard area (~fruit-line) there was also a significant seasonal effect on fruit weight and DM (Table 2.5). However, within seasons, variation within-vines in fruit weight and DM was greater than variation between-vines.

Table 2.5. Variance components of vine fruit weight and DM measured for 86533 individual Hayward kiwifruit from 84 vines at commercial harvest across three consecutive growing seasons (2003-2005). No variance component estimate was calculable for fixed effects; the presented value is an estimate of the mean seasonal value.

Variance Component		Weight			Dry Matter Content		
		Estimate	SE	P	Estimate	SE	P
Fixed Effects	Season 2003	109.23	0.74	< 0.01	18.34	0.05	< 0.01
	Season 2004	98.00	0.71	< 0.01	16.14	0.04	< 0.01
	Season 2005	97.07	0.72	< 0.01	15.69	0.05	< 0.01
Random Effects	Between-vines within season	42.35	4.05	< 0.01	0.17	0.02	< 0.01
	Within-vine within season	251.99	1.21	< 0.01	0.45	0.002	< 0.01

To quantify the contribution of season to total observed variation in fruit quality traits relative to that of variation between orchards etc, the components of variance analysis was repeated with season set as a random effect. Inclusion of season as a random effect revealed that the contribution of season, relative to the other components of variance was slight – less than that attributable to between-orchard variation and comparable to that attributable to variation between fruit-lines within orchards (data not presented).

2.3.5 Fruit growth and the development of fruit quality characteristics

Individual vines identified as producing large sized high DM fruit and individual vines producing small sized low DM fruit were sampled at regular intervals throughout the fruit growth period of the 2005 season and the characteristics of their fruit distributions assessed (Figure 2.4). Kolmogorov-Smirnov tests were used to confirm that fruit weight and DM were normally distributed within vines throughout the growth period (data not shown), and as such the developmental distributions could be described using the population parameters of mean and standard deviation.

Differences between vines in mean FW and variability in FW only became evident post 100 DAA. Differences between vines in mean DW and DM were apparent from 50 DAA. Variability in fruit FW plateaued ~100 DAA, whilst for DW it increased in a linear fashion and, for DM it peaked ~150 DAA and declined through till harvest at 175 DAA (Figure 2.4). No consistent differences in the magnitude of variation in DM between vines were apparent throughout the fruit growth period. This is consistent with the previous observation that mean DM values were independent of the level of variation (standard deviation) in DM (section 2.3.2).

No obvious developmental trend was apparent in the skewness and kurtosis of fruit weight and fruit DM distributions (data not shown). If anything, fruit DM distributions became skewed towards lower DM as fruit developed on the vine.

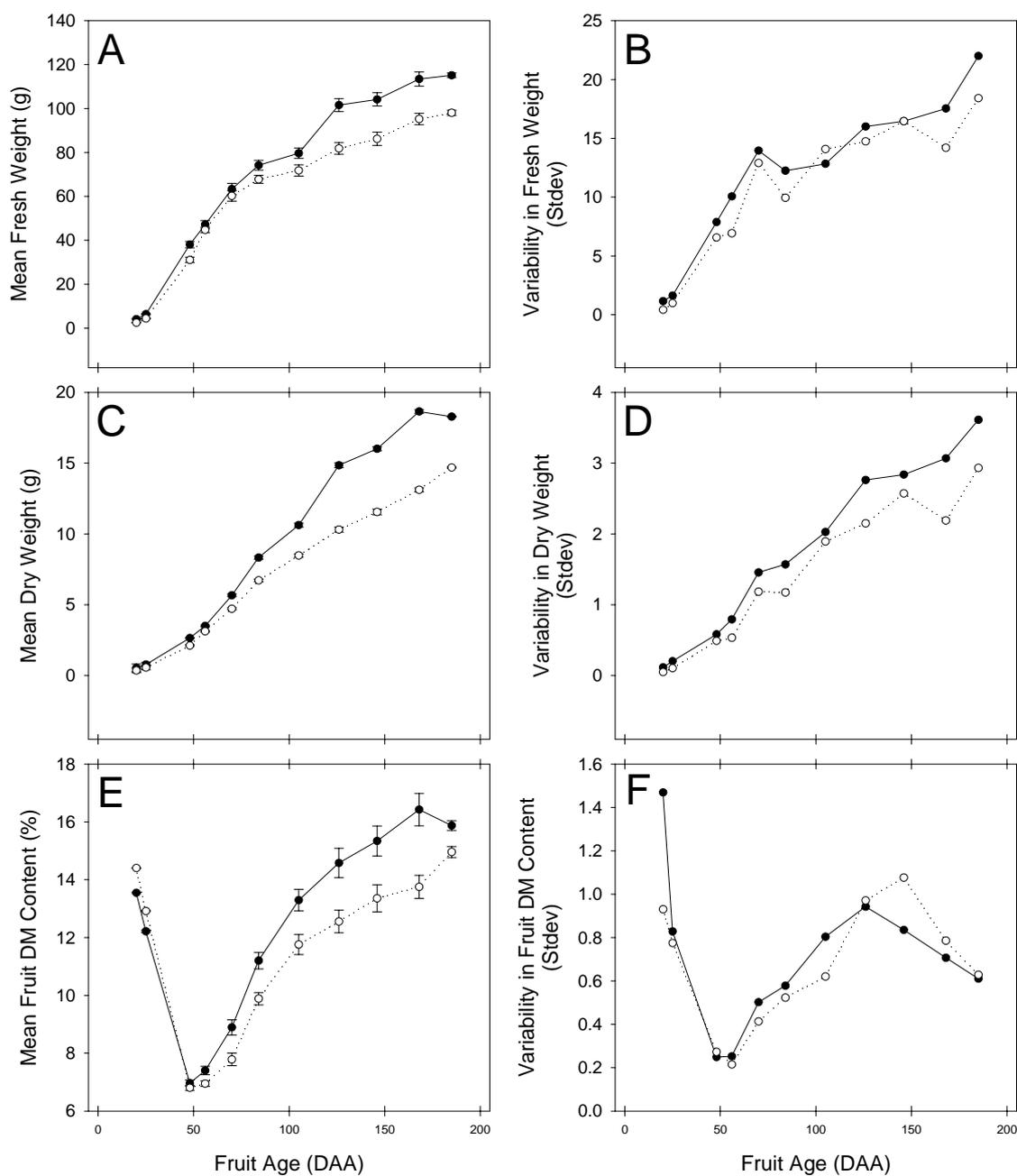


Figure 2.4. Comparison of average (A,C,E) and variability (B,D,F) in growth curves for Hayward fruit fresh weight (A,B), dry weight (C,D), and dry matter content (E,F) between vines producing large sized high DM fruit (●) and vines producing small sized low DM fruit (○). Mean values are presented \pm 1 SEM. Fruit age was quantified as days after anthesis (DAA).

2.4 Discussion

2.4.1 The normality of kiwifruit weight and DM distributions

From reviewing the literature it was hypothesised that fruit weight and DM were normally distributed within fruit populations. This hypothesis is rejected. Results presented in this study demonstrated significant deviations from normality for the majority of fruit quality distributions. However, for estimation of the proportion of fruit in the tails of distributions it appears that departures from normality can be tolerated. The New Zealand industry uses indexes that assume DM to be normally distributed within fruit populations to calculate grower ‘taste payments’ and to identify high- and low-DM fruit-lines within the inventory. The results of the current work suggest that the assumption of normality enables adequate prediction of the proportion of high- and low-DM fruit within populations.

Fruit characteristics are usually normally distributed within populations. Most apple fruit weight distributions conform to a normal distribution (Webb et al., 1980; Clarke, 1990; Zhang et al., 1995; Lotze & Bergh, 2004). Plum has been reported to have normally distributed fruit weight distributions (Wells & Bukovac, 1978). Maturation time, fruit weight and fruit SSC of persimmon cultivars also followed a normal distribution (Yamada et al., 1995). Do-Amaral et al. (1997) reviewed Brazilian studies of citrus and reported that all fruit variables studied conformed to a normal distribution (Do Amaral et al., 1997). Frequency distributions of strawberry seedlings for firmness and skin toughness of fruit exhibited a normal distribution curve (Mori, 2000). The assumption of normality has been an acceptable one to date in kiwifruit (Judd & McAneney, 1987; Snelgar & Hopkirk, 1988; Judd et al., 1989; McAneney et al., 1989; Snelgar et al., 1992; Mowat & Amos, 2002) and it would seem to remain so for prediction of the proportion of high- and low-DM fruit within populations.

Data presented here suggested that fruit weight and DM distributions were non-normal for fruit populations from units larger than the individual vine. The deviations were due to a positive skew in weight distributions and to DM distributions being flatter (kurtosis < 3) than that of a theoretical normal distribution. The positive skew observed in fruit-line and orchard fruit weight distributions was possibly an artefact of the dataset analysed, which only included export sized fruit as the grading process removed smaller sized (non-export grade) fruit. However, fruit weight distributions from vines individually strip picked, where all fruit weights were recorded, were still positively skewed but to a lesser extent than that seen in larger fruit populations (fruit-line and orchard) (data not presented). This is possibly a result of on-orchard thinning practices whereby small sized fruit are removed from vines prior to harvest (Burge et al., 1987). Within and across seasons the skewness of DM distributions approximated 0, consistent with the findings of Mowat and Amos (2002) who concluded DM was normally distributed within Hayward fruitlines. However, the kurtosis of DM distributions indicated the distributions were typically flatter than that of a standard normal distribution (kurtosis < 3) which indicated that much of the DM variance was due to infrequent large sized deviations from the mean value. The significant deviations from normality in fruit weight and DM distributions reported here may be an artefact of the mathematics of large datasets. Statistical tests involving large numbers of observations produce many degrees of freedom, so many that even slight differences are deemed to be statistically significant (Magurran, 1988; Bramley, 2005; Bramley & Janik, 2005).

2.4.2 Relationships between population parameters

It was hypothesised that mean fruit weight values would be either independent of the level of variability or that variability in fruit weight could be described with a constant standard deviation (Judd & McAneney, 1987; Judd et al., 1989; McAneney et al., 1989). Contrary to expectations, it was found that over a hierarchy of fruit populations (vine, fruit-line, orchard and season) mean fruit weight was positively correlated with variability in fruit weight, as were the

skewness and kurtosis of fruit weight distributions. The correlation between skewness and kurtosis suggests that as fruit populations become skewed towards larger sized fruit, deviations from the mean become more frequent but less extreme. No such relationships have been previously noted in kiwifruit but have been reported in other fruit crops. For instance, a positive correlation was found between average apple fruit weight and the standard deviation (Zhang et al., 1995), and the incidence and severity of fruit cracking in persimmon (Yamada et al., 2002).

No consistent relationships were identified between fruit DM population parameters. Similarly, no correlation was identified between mean and standard deviation of fruit dry mass in peach carried on the same shoots (Walcroft et al., 2004). This is consistent with the observations that there were no consistent differences in the levels of DM variability between high and low DM fruit-lines throughout the fruit growth period. This suggests high DM fruit-lines can be adequately identified by their mean value.

No relationships were identified between fruit age and the various population parameters describing fruit weight and DM distributions. Published growth models report a tight correlation between fruit age and the accumulation of weight and DM by kiwifruit (Walton & De Jong, 1990; Davison, 1990; Sawanobori & Shimura, 1990; Smith et al., 1995; Antognozzi et al., 1996; Richardson et al., 1997a; Ferrandino & Guidoni, 1998; Han & Kawabata, 2002). Fruit-lines produced over longer growth periods should have higher average values, and perhaps reduced variability as fruit get closer to their potential maximum size and DM - indeed many orchardists delay harvest in the hope of fruit achieving higher size and DM. It is suggested that site-to-site variation in fruit quality probably exceeds the variation arising from differences in the length of the fruit growth period.

2.4.3 Sources of variation in kiwifruit weight and DM distributions

It was found that within fruit-line variation was dominant across orchards. Within individual fruit-lines it was within-vine rather than between-vine variation that contributed the most to the total observed variation in fruit weight and DM.

Smith et al (1994) reported within-vine variation to be dominant in kiwifruit, but their measurements included only 3 vines and as such any calculation of between-vine variance should be treated with caution. In an investigation of the components of variation in kiwifruit firmness at harvest it was concluded that it was largely variation in firmness occurring within fruit-lines that contributed to the development of soft fruit in the market place (Feng et al., 2003a). In investigations into variability within other biological systems within-plant variation has been identified as being dominant. The largest contributor to total variance in cherry fruit size and seed mass was within-plant variation (~40%) (Jordano, 1995). Dunn and Martin (2000) investigated sources of variation in wine grape quality and concluded that bunch-to-bunch variability was dominant. Population-wide variance was mainly accounted for by variation among flowers of the same plant (56% of total) (Herrera et al., 2006). It is concluded that, within any given season, variation in fruit quality occurring within the individual vine is the largest contributor to the total observed variation.

In the present study season was treated as a fixed effect and it was not possible to quantify the contribution of seasonal variation relative to the contributions made by the other random sources of variation (between-orchard, within-fruitline etc). Repeating the analysis with season included as a random effect revealed that the contribution of season, relative to the other components of variance was slight – less than that attributable to between-orchard variation and comparable to that attributable to variation between fruit-lines within orchards. The inclusion of season as a random effect in the analysis must be treated with caution for two reasons. Three successive seasons can not really be considered to be a random sample of all possible seasons and agrometeorological studies suggest a minimum

of 30 seasons are required to adequately quantify seasonal effects (Chmielewski & Kohn, 1999a; Chmielewski & Kohn, 1999b; Chmielewski & Kohn, 2000). Seasonal variation has been reported to be dominant in studies of crop yield across a range of cropping systems (McBratney et al., 1997). In kiwifruit it has been reported that year-to-year variation accounted for the majority of variation in budbreak and flowering between growing regions (McPherson et al., 1994). Feng and co-workers (2003) found the seasonal effect to account for 23% of the total variance in kiwifruit harvest firmness. The finding of this study that the contribution of season to the total observed variation in fruit quality was small compared to the other factors investigated is in agreement with the small year effect found in peach modelling studies (Lescourret & Genard, 2005), and experimental studies on apple and peach fruit quality (Robinson et al., 1991; Genard et al., 2003).

2.4.4 Fruit development

It was proposed that the potential for large fruit size and high DM were established early during the fruit growth period (≤ 50 DAA). Consistent with this hypothesis, differences between vines in mean DM were apparent from 50 DAA onwards while differences in fruit weight parameters only became evident later in the growth period (100 DAA). The distribution of fruit weight and DM could be approximated by a normal distribution throughout the fruit growth period. Approximation to a theoretical distribution offers the potential for the development of predictive models that project forward initial fruit quality distributions to harvest (De Silva et al., 1997). The analysis of Hall et al. (1996) illustrated that the population parameters of kiwifruit weight distributions at harvest could be predicted from measurements made from 50 days after flowering onwards. Presumably there is the potential to make such predictions for fruit DM distributions at harvest; however, the necessary multi-season data is lacking in the present study and it was not possible to develop any such predictive tools.

Results presented here suggest that the potential for the development of high DM fruit is established early in the fruit growth period. Previous studies have identified the importance of early season growth temperatures on the development of kiwifruit quality characteristics (Hall et al., 1996; Richardson et al., 2004; Snelgar et al., 2005a; Snelgar et al., 2006), and this effect is explored further in chapter 6. Differences between vines in fruit weight characteristics were not apparent till later in the fruit growth period (~100 DAA), when previously it has been demonstrated that differences between kiwifruit weight distributions are identifiable from 50 DAA onwards (Hall et al., 1996). Any conclusions drawn from the current work must be tempered by the fact that the data came from individual vines from a single growing season.

2.5 Conclusion

The general trends of fruit weight distributions being positively skewed and fruit DM distributions being flatter than those of a theoretical normal distribution at harvest often resulted in non-normal distributions. However, despite these often significant deviations from normality, the distribution of fruit weight and DM within kiwifruit populations could be adequately approximated by assuming normality.

Over a hierarchy of fruit populations (vine, fruit-line, orchard and season) mean fruit weight was positively correlated with variability in fruit weight, as were the skewness and kurtosis of fruit weight distributions. Population parameters describing DM distributions were unrelated.

Differences in mean DM values between high- and low-DM vines were evident early in the fruit growth period, and these differences were maintained through till harvest. No differences in the magnitude of DM variation between vines were identified. This suggests that early season fruit sampling to determine mean DM values can identify low quality crops, forewarning growers and providing the opportunity for corrective action to be taken.

Within a given season, it is fruit-to-fruit variation occurring within fruit-lines that is the major source of variation in fruit weight and DM across the kiwifruit crop. The variation within fruit-lines is more a consequence of within-vine variation rather than between-vine variation. Orchard management practices intended to reduce variation in fruit quality need to target the variation occurring within a single vine.

Chapter 3: Relationships between fruit quality characteristics.

3.1 Introduction

An understanding of the relationships between fruit quality characteristics can indicate potential quality tradeoffs on-orchard arising from management decisions. In postharvest operations, relationships between quality traits could mean segregation of fruit populations on the basis of one quality trait will produce populations with distinctly different distributions of other qualities. This warrants investigation as the industry moves towards crop management based on fruit quality attributes.

3.1.1 Relationships between Hayward fruit weight, DM and cropload

3.1.1.1 Variation in fruit weight with cropload and season

Traditionally, kiwifruit growers in New Zealand (NZ) have been paid for the quantity of fruit meeting export standards with a premium being paid for large sized fruit as these are sold for higher prices in export markets (Currie et al., 1999). The size of individual fruit varies with cropload and season. Increasing crop loads of kiwifruit have consistently resulted in smaller average fruit size (Burge et al., 1987; Cooper & Marshall, 1987; Snelgar & Thorp, 1988; Lahav et al., 1989; Richardson & McAneney, 1990; Antognozzi et al., 1991; Inglese & Gullo, 1991). Hall and co-workers (1996) observed mean fruit volumes (~weights) at harvest for NZ Hayward kiwifruit to range from 85 – 130cm³; the magnitude of variation in harvest weights between fruit was not consistent across years or sites. The majority of variation in fruit size was established within 50 days of flowering (Hall et al., 1996). Orchard factors known to influence fruit

weight and its variability in fruit populations include insufficient pollination (Pan et al., 1994; Park & Park, 1997), flowering time (Smith et al., 1994), irrigation (Reid et al., 1996), application of fertilisers (Testoni et al., 1990; Tagliavini et al., 1995; Vasilakakis et al., 1997), plant growth regulators (Sive & Resnizky, 1987; Lotter, 1992; Fang et al., 1996; Costa et al., 1997; Ohara et al., 1997), and training and pruning (Manson et al., 1991; Smith et al., 1994; Miller et al., 2001).

Although the average fruit weight decreases as cropload on vines increases, for a given cropload, average fruit weight can vary as much as 20g between seasons (Cooper & Marshall, 1991). Between-vine differences in any of the seasonal, regional and/or orchard factors cited above would also contribute to variation in fruit weights within an orchard area.

3.1.1.2 Variation in fruit dry matter content with season, cropload and weight

Variation in fruit dry matter content (DM) has been reported between orchards and between seasons, the underlying causes for such variation has not yet been determined, although it is usually assumed that climactic variation is one of the key factors (Snelgar et al., 2005a). Praat et al. (2005) reported how average DM for the NZ Hayward crop varied between seasons with average DM being higher in 2002 (17.1%) compared with 2003 (16.6%) and 2004 (16.3%) (Praad et al., 2005). Average rSSC can also vary from season to season, suggesting average DM is also varying (Jordan et al., 2000; Burdon et al., 2004). The average rSSC for Hayward kiwifruit collected from several sites in Japan over nine seasons ranged from 11.8% in 2001 to 13.7% in 1995 (Suezawa et al., 2003).

In apple, the leaf:fruit ratio, or cropload, is probably the single factor with the strongest effect on fruit development (Toldam Andersen & Hansen, 1998). With increasing cropload accumulation of total and soluble DM as well as acid, colour, flavour and firmness decreases due to high internal assimilate competition (Hansen, 1989a; Hansen, 1989b; Toldam Andersen & Hansen, 1995; Poll et al., 1996). Therefore, a negative correlation between cropload and fruit DM could be expected in kiwifruit.

The literature suggests a positive correlation exists between fruit weight and DM. Lescourret and Genard (2003) proposed a link between fruit weight and sweetness in fruits and cited studies demonstrating such a positive correlation (Lescourret & Genard, 2003). Gomez-Del-Campo et al. (2005) reported that grape fruit size determined DM partitioning between fruit and the DM accumulation pattern, and used models of sink strength to explain how larger fruit attract more assimilates (Gomez-Del-Campo et al., 2005). Zhang et al. (2005) reported that the relative sink strength of pear fruit was greater in large fruit, and suggested that the movement of photosynthates into the fruit was determined by the sink strength of the fruit rather than the source strength (Zhang et al., 2005).

The hypothesis was that both fruit weight and DM of Hayward kiwifruit declines with increasing croploads.

3.1.2 Relationships between Hayward fruit firmness at harvest and measures of fruit maturity

Firmness is an important quality attribute of kiwifruit that has been linked with fruit storage performance and is considered the primary indicator of kiwifruit eating ripeness (McGlone & Kawano, 1998; Benge, 1999; Feng et al., 2003a; Feng et al., 2003b). Variation in fruit firmness at harvest has been related to variation in fruit firmness at out-turn (Benge, 1999). The firmness of fruit at harvest is related to the maturity of fruit (Feng et al., 2003a). Traditionally kiwifruit maturity has been estimated from the soluble solids content (SSC) of the fruit (Harman, 1981), however fruit DM has been proposed as an indicator of maturity (Burdon et al., 2004), and the properties of fruit size and cropload have also been reported to relate to fruit maturation (Seager et al., 1995; Crisosto et al., 1999).

3.1.2.1 Soluble solids content

Soluble solids content (SSC %), measured by a refractometer, increases with fruit maturity and has long been used as an index for harvest maturity of Hayward kiwifruit (Asami et al., 1988). In the NZ kiwifruit industry a fruitline requires an average SSC > 6.2% to meet harvest maturity standards (Richardson et al., 1997b; Watt, 1999). Fruit that are harvested with SSC less than 6% do not store as well as more mature fruit and do not develop good flavour (Beever & Hopkirk, 1990). Given that SSC varies considerably within fruit-lines (Hopkirk et al., 1986; Smith et al., 1994; Pyke et al., 1996), variation in SSC is suggestive of variation in individual fruit maturities which in turn is suggestive of variation in fruit firmness.

3.1.2.2 Dry Matter Content

Fruit DM increases with late harvest (Smith et al., 1995), thus DM has been proposed as important to fruit storage performance through its relationship with maturity. It has been reported that firmer fruit at the end of storage had higher SSC than softer fruit (Tagliavini et al., 1995) and this implies that fruit with a high DM at harvest would have greater storage potential than low DM fruit, as DM at harvest is predictive of ripe SSC (Burdon et al., 2004). Furthermore, Davie (1997) found fruit with storage disorders such as soft patches to have low DM (Davie, 1997). Clark et al. (2004) reported that the population of 'Hort16A' kiwifruit most susceptible to chilling injury and rot expression during storage were characterised by lower DM (Clark et al., 2004).

3.1.2.3 Indexes incorporating SSC and DM

Use of SSC alone as a maturity index may not always indicate the storage potential of fruit because conversion of starch to sugar occurs both on the vine and during storage (Crisosto et al., 1984). The ripening process of kiwifruit involves the solubilisation of the constituents of DM, thus DM at harvest (hDM) is predictive of soluble solids content when ripe (rSSC) and therefore the relationship between DM and SSC at harvest (hSSC) is indicative of fruit 'ripeness'. Burdon et al. (2004) reported the relationship between hDM and rSSC at sensory evaluation to be:

$$rSSC = -3.755 + 1.057 \text{ hDM} \quad (3.1)$$

By assuming that degradation of starch is linearly related to fruit maturity, equation 3.1 can be used to estimate the ‘percentage ripeness’ of a fruit piece:

$$\text{Ripeness (\%)} = \frac{\text{hSSC}}{1.057 \times \text{hDM} - 3.755} \times 100 \quad (3.2)$$

Where hSSC is the soluble solids content at harvest and hDM is the fruit dry matter content at harvest.

3.1.2.4 Cropload and Fruit Size

The literature suggests a link between cropload and fruit maturity; the larger the cropload the longer the time taken to attain maturity. Hayward kiwifruit maturation was markedly delayed in a high cropload treatment compared to fruit from a low cropload treatment (Seager et al., 1995). Palmer et al. (1997) reported that low croploads resulted in a significant advance in apple fruit maturity (Palmer et al., 1997). It was hypothesised that low cropload vines mature faster and their fruit are less firm when all vines were simultaneously harvested compared to fruit from high cropload vines. Therefore, variation in croploads between vines could contribute to variation in fruit firmness at harvest.

Previous studies have speculated on a relationship between fruit size at harvest and subsequent storage performance. Crisosto et al. (1999) reported that large Hayward kiwifruit softened at a slower rate compared to smaller sized fruit in coolstorage (Crisosto et al., 1999). Consequently, it was proposed that variation in fruit weight correlates with variation in fruit firmness at harvest.

3.1.3 Relationships between Hayward fruit acidity, weight and dry matter content

In crops other than kiwifruit, the Brix/acid ratio is commonly used as a measure of fruit maturity and palatability (Fellers, 1991) and is also an important factor in consumer acceptability of fruit (Harker et al., 2002). In kiwifruit, consumer preference is primarily determined by the sugar-acid balance (Jaeger et al., 2003). It has been demonstrated that consumers prefer kiwifruit with a higher brix/acid ratio (Crisosto & Crisosto, 2001).

At harvest, Hayward kiwifruit contain 0.9-2.5% total acidity, with 40-50% as citrate, 40-50% as quinate, and 10% as malate (Beever & Hopkirk, 1990; Marsh et al., 2004). In kiwifruit, the relationship between fruit acidity and other quality traits is unknown. A negative correlation has been reported to exist at harvest between brix and acid content of cherry (Yoon et al., 2006), apple (Yoon et al., 2005) and mandarin (Ishikawa et al., 1993). A negative correlation was observed between cucumber fruit size, DM and acid content (Lu et al., 2002). From such studies of other fruit systems it was hypothesized that kiwifruit acidity will decline with increasing fruit size and DM.

3.1.4 Chapter goals

As a consequence of industry's focus on fruit eating quality, this study was predominantly interested in how fruit DM related to other quality traits. It was hypothesised that orchards, orchard areas, or individual vines that produce larger fruit also produce fruit of higher DM and lower acidity. It was therefore expected that there would be a general correlation between fruit size, DM, and acidity across seasons, orchards, vines and individual fruit.

Secondly, cropload is a characteristic readily open to manipulation by orchardists (Byers, 1990; Richardson et al., 1994; Jindal et al., 2003). It was anticipated that croploading decisions have effects on subsequent fruit quality, with a negative correlation between cropload and fruit quality hypothesised.

Thirdly, variation in firmness of fruit at harvest has been linked with subsequent storage performance. Interrelationships between fruit harvest firmness and other fruit quality attributes were analysed on an individual vine basis to enhance understanding of the mechanisms of firmness variation and shed light on potential commercial harvest maturity criteria. The hypothesis was that larger sized, high DM fruit produced at high croploads would be firmer at harvest than smaller sized, low DM fruit produced at low croploads.

3.2 Methods

3.2.1 Fruit measurements

Relationships between fruit quality traits were investigated in the macro- and micro-datasets described previously in section 2.2.1

In the experiment where vines were harvested individually (seasons 2003-2005), and following NIR assessment of fruit properties, random 30 fruit samples per vine were destructively assessed for firmness with a motorised penetrometer fitted with a 7.9mm head (HortPlus Ltd, Cambridge, New Zealand).

A dataset of Hayward kiwifruit acidity measurements was made available by Sikig packhouse (Saint-Étienne-d'Orthe, France). Fruit-line titratable acidity was determined at harvest over four consecutive seasons (1999-2002). The relationships identified between quality traits using the French Hayward fruit dataset were validated against the properties of New Zealand grown fruit at harvest in season 2003. At commercial harvest a random 5 fruit sample was collected per fruitline and analysed for acidity in triplicate. Titratable acidity was measured on a 5g sample of frozen tissue, which had been macerated in 25ml of distilled water using a polytron (Kinematica™, Luzern, Switzerland) and by titration to pH 8.2 with 0.1 N NaOH using an automatic titrator (716 DMS Titrino, Metrohm, Herisau, Switzerland). Titratable acidity was reported as percentage citric acid.

3.2.2 Statistical Analysis

The relationships between fruit quality characteristics were modelled by regression using the REG procedure in SAS (SAS Institute Inc., 2003).

Correlations between individual fruit size and DM were quantified with Pearson's correlation coefficient. The correlation procedure was chosen for ease of presenting results as the correlation coefficient provided information on both the direction of the relationship and the strength of the relationship, compared to a regression approach which would have produced separate values for the slope and the significance of the relationship. The sign of the correlation coefficient indicates the direction of the relationship (positive or negative). The absolute value of the correlation coefficient indicates the strength, with larger absolute values indicating stronger relationships. Pearson's correlation coefficients were calculated using the bivariate correlation procedure in SPSS software.

Mean DM were compared between fruit size grades using posthoc comparisons (Tukey's LSD, $p < 0.05$) within the general linear model procedure of SPSS software.

A discriminant analysis was performed in SPSS software to quantify how predictive fruit size was of fruit DM. Individual fruit pieces were assigned to a quartile group (1 – 4; 1 being high DM and 4 being low DM) according to where they fell in the seasonal distribution of DM. Fruit count size and fruit age at harvest (~length of the fruit growth period) were used as prediction coefficients and DM quartile score as the grouping variable in a Fisher's linear discriminant function.

3.3 Results

3.3.1 Between- and within-vine relationships between Hayward cropload, fruit weight and dry matter content

Across seasons there was a consistent trend of declining average fruit fresh weight (FW) and fruit dry weight (DW) with increasing cropload per vine (Figure 3.1 and Table 3.1). The decrease in FW with increasing cropload was highest in the 2003 season following the spring frost (1 g per additional fruit m^{-2}) when vine croploads were unusually low. In the 'normal' seasons of 2004 and 2005, the decrease in FW with increasing cropload was more moderate (1g per 5 additional fruit m^{-2}).

Given that fruit DM is the ratio of DW to FW, the relationship between cropload and DM is dependent on the relative reductions in FW and DW per fruit. In 2003, fruit DM decreased with increasing croploads as fruit DW decreased to a greater extent than FW (Figure 3.1.B). In 2004 there was no change in DM with cropload, fruit DW and FW decreased in equal proportions. In 2005 DM increased with increasing croploads, as FW declined to a greater extent than DW as cropload increased.

There was a consistent positive linear correlation between vine cropload and total fruit DW across seasons (Figure 3.1.D). As a result of spring frosting, vines in the 2003 season had atypically low croploads (1 - 26 fruit m^{-2}) and as a consequence had reduced total fruit DW's (8 - 345 gDW m^{-2}). Vines in seasons 2004 and 2005 carried more typical croploads (20 - 60 fruit m^{-2}) and produced greater total fruit DW's (63 - 756 gDW m^{-2}).

Correlations between fruit fresh weight and DM within individual vines were similar to those observed when vine averages were compared. In the 2003 season the majority of vines had a positive correlation between individual fruit fresh weight and DM within-vines (Figure 3.2). In 2004, more vines had a negative correlation, while in 2005 approximately equal proportions of vines exhibited

negative and positive correlations within vines between individual fruit fresh weight and DM (Figure 3.2).

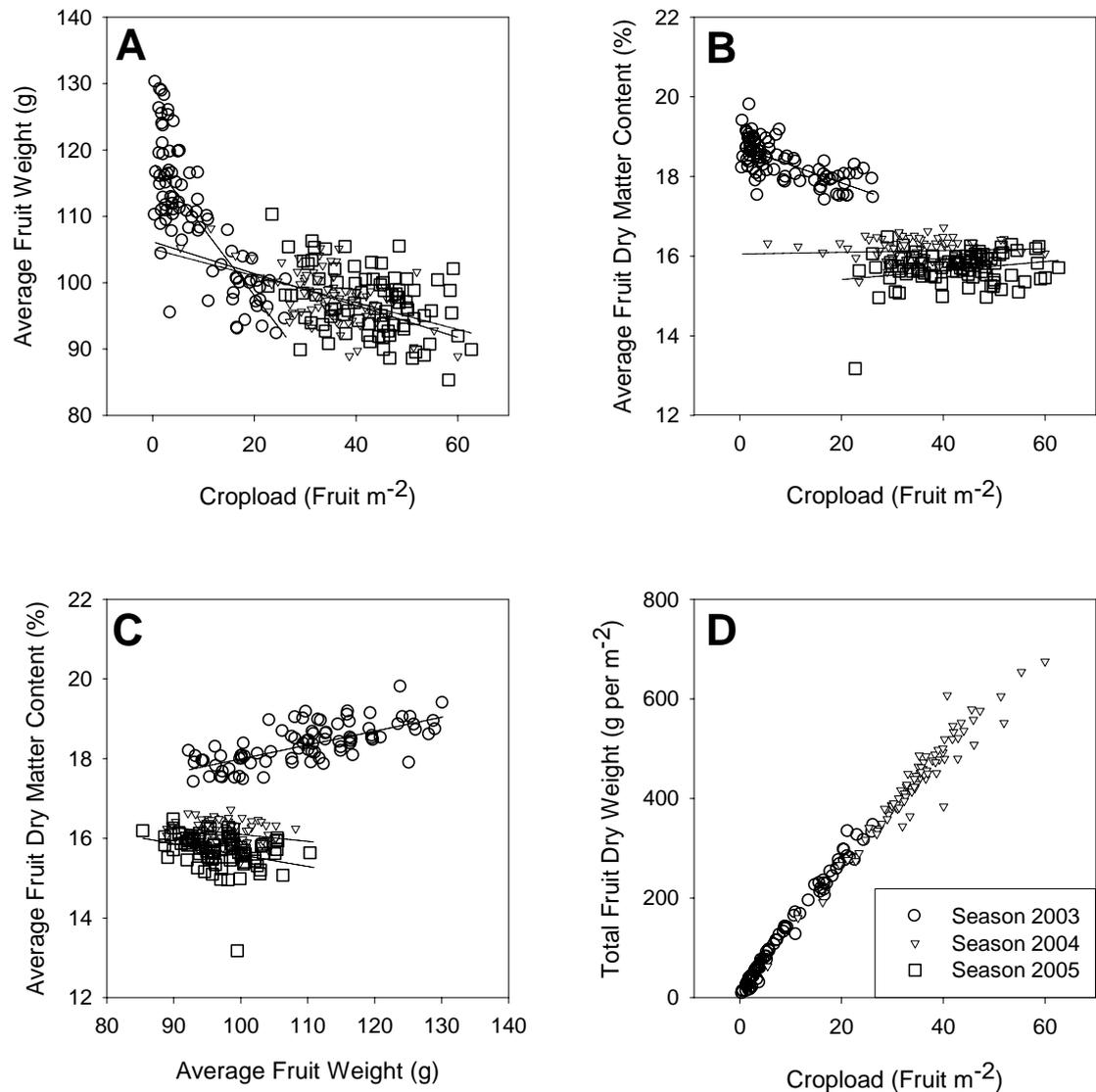


Figure 3.1. Linear relationships between average Hayward kiwifruit vine characteristics over three consecutive seasons (2003-2005): Cropload and average fruit weight per vine (A); Cropload and average fruit dry matter content per vine (B); Average fruit weight per vine and average fruit dry matter content per vine (C); and total dry weight of fruit per vine and cropload (D). The characteristics of the individual regressions are presented in Table 3.1.

Table 3.1. Summary of linear regression results of relationships between Hayward kiwifruit average quality characteristics per vine.

Fruit Characteristic		Period	Slope	R ²	P
Cropload	Fresh Weight	2003	-1.01	0.65	< 0.01
Cropload	Fresh Weight	2004	-0.24	0.28	< 0.01
Cropload	Fresh Weight	2005	-0.20	0.15	< 0.01
Cropload	Dry Weight	2003	-0.23	0.67	< 0.01
Cropload	Dry Weight	2004	-0.04	0.26	< 0.01
Cropload	Dry Weight	2005	-0.02	0.07	0.02
Cropload	DM%	2003	-0.04	0.47	< 0.01
Cropload	DM%	2004	0.00	0.00	0.54
Cropload	DM%	2005	0.01	0.05	0.04
Fresh Weight	DM%	2003	0.03	0.48	< 0.01
Fresh Weight	DM%	2004	-0.02	0.06	0.03
Fresh Weight	DM%	2005	-0.03	0.09	< 0.01
Cropload	Total Dry Weight	2003	13.49	0.91	< 0.01
Cropload	Total Dry Weight	2004	12.34	0.99	< 0.01
Cropload	Total Dry Weight	2005	11.50	0.91	< 0.01

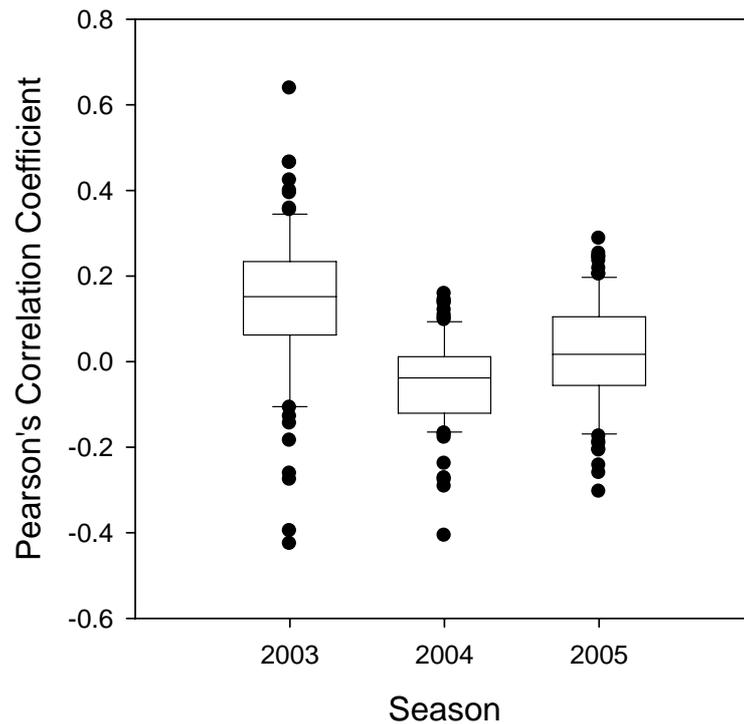


Figure 3.2. Within-vine relationships between individual fruit weights and DM. Pearson's correlation coefficients are presented by season for the relationships between individual fruit weights and DM within individual vines (n=84 vines).

3.3.2 Between- and within-fruitline relationships between Hayward fruit weight and dry matter content

In chapter 2 it was established that fruit-line weight and DM characteristics could be adequately approximated by population parameters associated with a standard normal distribution. To determine whether knowing population parameters for one quality trait enables estimation of other quality trait distributions, parameters were correlated between fruit-lines. Correlations between fruit weight and DM population parameters between-fruit-lines illustrated some significant relationships within seasons but no consistent significant correlations across seasons (Table 3.2.). No correlation between fruit weight and fruit DM population parameters was evident.

Between-fruit within fruit-lines there was a general trend of increasing fruit DM with increasing fruit weight (Figure 3.3). However, within any given season a proportion of fruit-lines displayed a negative correlation between fruit weight and DM, and the proportion of fruit-lines with such a negative correlation varied between seasons. The numbers of fruit-lines with a negative correlation between fruit weight and DM were 2 of 68 in season 2001, 43 of 112 in season 2002, 9 of 120 in season 2003, and 51 of 94 in season 2004.

Table 3.2. Correlations between fruit weight and DM population parameters between fruit-lines across seasons (2001-2004). Correlations were quantified with Pearson's correlation coefficient and deemed significant at the 5% level (*). The numbers of fruit-lines were 68, 112, 120 and 94 for seasons 2001-04 respectively.

		DM Mean	DM Variability	DM Skewness	DM Kurtosis
Season 2001	Weight Mean	0.054	-0.092	-0.166 *	0.144
	Weight Variability	-0.051	-0.098	-0.202 *	0.191 *
	Weight Skewness	-0.125	-0.192 *	-0.034	-0.004
	Weight Kurtosis	-0.108	-0.203 *	-0.014	-0.05
Season 2002	Weight Mean	-0.323 *	-0.115	-0.026	0.079
	Weight Variability	-0.154 *	0.036	0.146 *	0.046
	Weight Skewness	-0.058	-0.134 *	-0.233 *	0.016
	Weight Kurtosis	-0.112	-0.141 *	-0.267 *	-0.08
Season 2003	Weight Mean	-0.012	0.179 *	-0.084	0.005
	Weight Variability	-0.03	0.231 *	-0.072	-0.043
	Weight Skewness	-0.1	-0.048	0.008	0.031
	Weight Kurtosis	-0.138 *	-0.073	-0.116 *	0.181 *
Season 2004	Weight Mean	0.116 *	0.141 *	0.059	0.052
	Weight Variability	0.154 *	0.247 *	-0.093	-0.05
	Weight Skewness	-0.011	-0.149 *	0.113	0.071
	Weight Kurtosis	0.289 *	-0.072	0.225 *	0.121 *

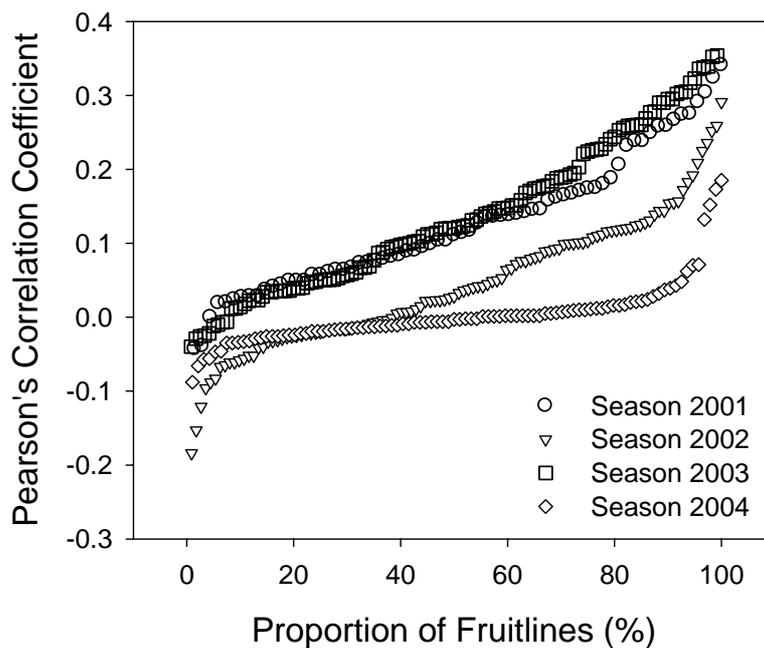


Figure 3.3. Within fruit-line relationships between individual fruit weights and DM. Pearson's correlation coefficients are presented by season for the relationships between individual fruit weights and DM within 68 fruit-lines from season 2001, 112 fruit-lines from season 2002, 120 fruit-lines from season 2003, and 94 fruit-lines from season 2004. The relationship was tested in 3.62 million export Hayward kiwifruit.

Kiwifruit packing traditionally grades fruit for size, this is done automatically whereby each fruit is weighed, assigned to a count size based upon its weight, and directed to a packing outlet with like sized fruit (McDonald, 1990). Given the generally positive correlation between fruit weight and DM within fruit-lines (Figure 3.3), the ability of fruit count size to predict a fruit's DM was tested. A discriminant function was able to correctly classify 33% of fruit to the correct DM quartile band based on fruit size and age at harvest. 66% of fruit were assigned to a DM quartile grouping ± 1 of their correct grouping. Fisher's linear discriminant functions demonstrated a positive correlation between both fruit age and DM quartile grouping, and fruit count size and DM quartile grouping. Fruit count size was given a greater weighting in the discriminant function than fruit age. As fruit size increased (lower count size) the probability of a fruit being high DM increased. As the length of the fruit growth period increased so did the likelihood of a fruit being low DM.

Examples of the average differences in fruit DM between count sizes within individual representative fruit-lines are presented in Tables 3.3 – 3.5. The examples presented are the fruit-lines with the most negative, most positive, and average degree of correlation between fruit weight and DM. Predictably, the fruitline with a negative correlation between fruit weight and DM shows average DM to be lower in larger sized fruit (lower count size) than in smaller sized fruit (higher count size), though the differences in DM is only significant in the smallest sized fruit (Table 3.3). The majority of fruit-lines illustrated a positive correlation between fruit weight and DM (Figure 3.3); examples of such fruitlines which differ in the strength of the positive correlation are presented in Tables 3.4 and 3.5. In fruit-lines with a positive correlation, larger sized fruit (lower count size) had higher mean DM than smaller sized (higher count size) fruit; the absolute difference in DM and the significance of the difference between count sizes increased with the strength of the correlation between fruit weight and DM.

Table 3.3. Mean difference in fruit DM between class I Hayward kiwifruit count sizes within a fruitline. Differences in DM between count sizes are presented by column then row, those marked * were significantly different (Tukey's LSD, $p < 0.05$). Presented is the comparison for the fruitline with the most negative correlation between fruit weight and DM (Season 2002, $n = 49712$ fruit, Pearson's $r = -0.184$).

	Size 22	Size 25	Size 27	Size 30	Size 33	Size 36	Size 39	Size 42
Size 22		0.056	-0.014	0.097	-0.007	-0.082	-0.300	-0.331
Size 25	-0.055		-0.069	0.042	-0.062	-0.138	-0.359 *	-0.387 *
Size 27	0.014	0.069		0.111	0.007	-0.068	-0.290 *	-0.317 *
Size 30	-0.097	-0.042	-0.111		-0.104	-0.180 *	-0.401 *	-0.428 *
Size 33	0.007	0.062	-0.007	0.104		-0.076	-0.297 *	-0.325 *
Size 36	0.082	0.138	0.068	0.180 *	0.076		-0.222 *	-0.249 *
Size 39	0.304	0.359 *	0.290 *	0.401 *	0.297 *	0.222 *		-0.027
Size 42	0.331	0.387 *	0.317 *	0.428 *	0.325 *	0.249 *	0.027	

Table 3.4. Mean difference in fruit DM between class I Hayward kiwifruit count sizes within a fruitline. Differences in DM between count sizes are presented by column then row, those marked * were significantly different (Tukey's LSD, $p < 0.05$). Presented is the comparison for the fruitline with an average correlation between fruit weight and DM (Season 2003, $n=283761$, Pearson's $r = 0.077$).

	Size 22	Size 25	Size 27	Size 30	Size 33	Size 36	Size 39	Size 42
Size 22		0.039	0.135	0.135	0.249 *	0.269 *	0.366 *	0.533 *
Size 25	-0.039		0.096	0.096	0.210 *	0.231 *	0.327 *	0.494 *
Size 27	-0.135	-0.096		0.001	0.114 *	0.135 *	0.232 *	0.399 *
Size 30	-0.135	-0.096	-0.001		0.113 *	0.134 *	0.231 *	0.398 *
Size 33	-0.249 *	-0.210 *	-0.114 *	-0.113 *		0.021	0.118 *	0.285 *
Size 36	-0.269 *	-0.231 *	-0.135 *	-0.134 *	-0.021		0.097 *	0.264 *
Size 39	-0.366 *	-0.327 *	-0.232 *	-0.231 *	-0.118 *	-0.097 *		0.167 *
Size 42	-0.533 *	-0.494 *	-0.399 *	-0.398 *	-0.285 *	-0.264 *	-0.167 *	

Table 3.5. Mean difference in fruit DM between class I Hayward kiwifruit count sizes within a fruitline. Differences in DM between count sizes are presented by column then row, those marked * were significantly different (Tukey's LSD, $p < 0.05$). Presented is the comparison for the fruitline with the most positive correlation between fruit weight and DM (Season 2003, $n=181507$, Pearson's $r = 0.371$).

	Size 22	Size 25	Size 27	Size 30	Size 33	Size 36	Size 39	Size 42
Size 22		0.261 *	.3323 *	0.534 *	0.735 *	0.917 *	1.247 *	1.584 *
Size 25	-0.261 *		0.072	0.274 *	0.474 *	0.656 *	0.986 *	1.323 *
Size 27	-0.332 *	-0.072		0.202 *	0.403 *	0.585 *	0.914 *	1.251 *
Size 30	-0.534 *	-0.274 *	-0.202 *		0.201 *	0.383 *	0.712 *	1.050 *
Size 33	-0.735 *	-0.474 *	-0.403 *	-0.201 *		0.182 *	0.512 *	0.849 *
Size 36	-0.917 *	-0.656 *	-0.585 *	-0.383 *	-0.182 *		0.330 *	0.667 *
Size 39	-1.247 *	-0.986 *	-0.914 *	-0.712 *	-0.512 *	-0.330 *		0.337 *
Size 42	-1.584 *	-1.323 *	-1.251 *	-1.050 *	-0.849 *	-0.667 *	-0.337 *	

3.3.3 Between-vine relationships between Hayward fruit firmness at harvest and measures of fruit maturity

Fruit firmness was independent of vine cropload, average fruit DM, and average fruit weight (Table 3.6.). A significant ($P < 0.05$) relationship between fruit weight and firmness was observed in 2005, yet it accounted for little of the variation in fruit firmness ($R^2=0.06$) (Table 3.6.).

Results from this study indicate that between-vine variation in fruit firmness is best correlated with between-vine differences in fruit maturity. Of the measures of fruit maturity investigated, the Ripeness index had the best correlation with fruit firmness at harvest (Table 3.6.). The traditional measure of kiwifruit maturity, Brix, had a relationship with fruit firmness that bordered on significance but explained less of the firmness variation ($R^2 < 0.50$) than that explained by Ripeness (Table 3.6.).

Table 3.6. Summary of linear relationships between Hayward kiwifruit average vine characteristics and average fruit firmness per vine at harvest across seasons (2003-2005). The relationships presented are comparisons of vine averages, not individual fruit.

Characteristic	Season	R²	P
Cropload (Fruit m ⁻²)	2003	0.35	0.09
	2004	0.09	0.39
	2005	0.02	0.69
DM (%)	2003	0.06	0.48
	2004	< 0.01	0.99
	2005	0.11	0.34
Brix Content (%)	2003	0.17	0.24
	2004	0.54	0.03
	2005	0.43	0.06
Fruit Weight (g)	2003	< 0.01	0.75
	2004	0.01	0.43
	2005	0.06	0.03
Ripeness (%)	2003	0.24	0.16
	2004	0.92	0.01
	2005	0.60	0.03

3.3.4 Between-fruitline relationships between Hayward fruit acidity and fruit weight and dry matter content

Within- and between-seasons, fruit titratable acidity (TA) was positively correlated with fruit DM (Figure 3.4 and Table 3.7.). When using the ripeness index described in section 3.1.2.3 as a measure of fruit maturity, fruit TA was independent of fruit maturity. A significant positive correlation was noted between fruit weight and TA in some seasons but this relationship was not significant in all seasons.

A linear regression was used to describe the positive correlation between fruit DM and TA observed over the four consecutive seasons of 1999 – 2002 in French grown Hayward kiwifruit. The resulting linear model was validated using TA and DM measurements of New Zealand grown fruit-lines sampled at harvest in season 2003 (n=83). The measured DM was used to predict TA, and the model was assessed by comparison of the predicted TA with the measured TA. The TA of fruit-lines in the 2003 season could be reasonably approximated from mean DM measurements ($R^2 = 0.39$, $p < 0.01$).

The brix/acid ratio is an important aspect of the sensory quality of fruit (Harker et al., 2002). During storage and ripening the TA in Hayward kiwifruit changes little (Matsumoto et al., 1983; MacRae et al., 1989b; Marsh et al., 2004). Thus using the relationship described above, the relationship between fruit DM at harvest and sugar content when ripe (rSSC) (Section 3.1.2.3), and assuming fruit TA does not significantly change between harvest and consumption, then measurement of fruit DM at harvest allows prediction of the brix/acid ratio when ripe (Figure 3.5.). Both predicted rSSC and TA increase with increasing fruit DM. The slope of the rSSC model is steeper (1.06) than that of the TA model (0.45), this produces a curvilinear relationship between the predicted brix/acid ratio and fruit DM.

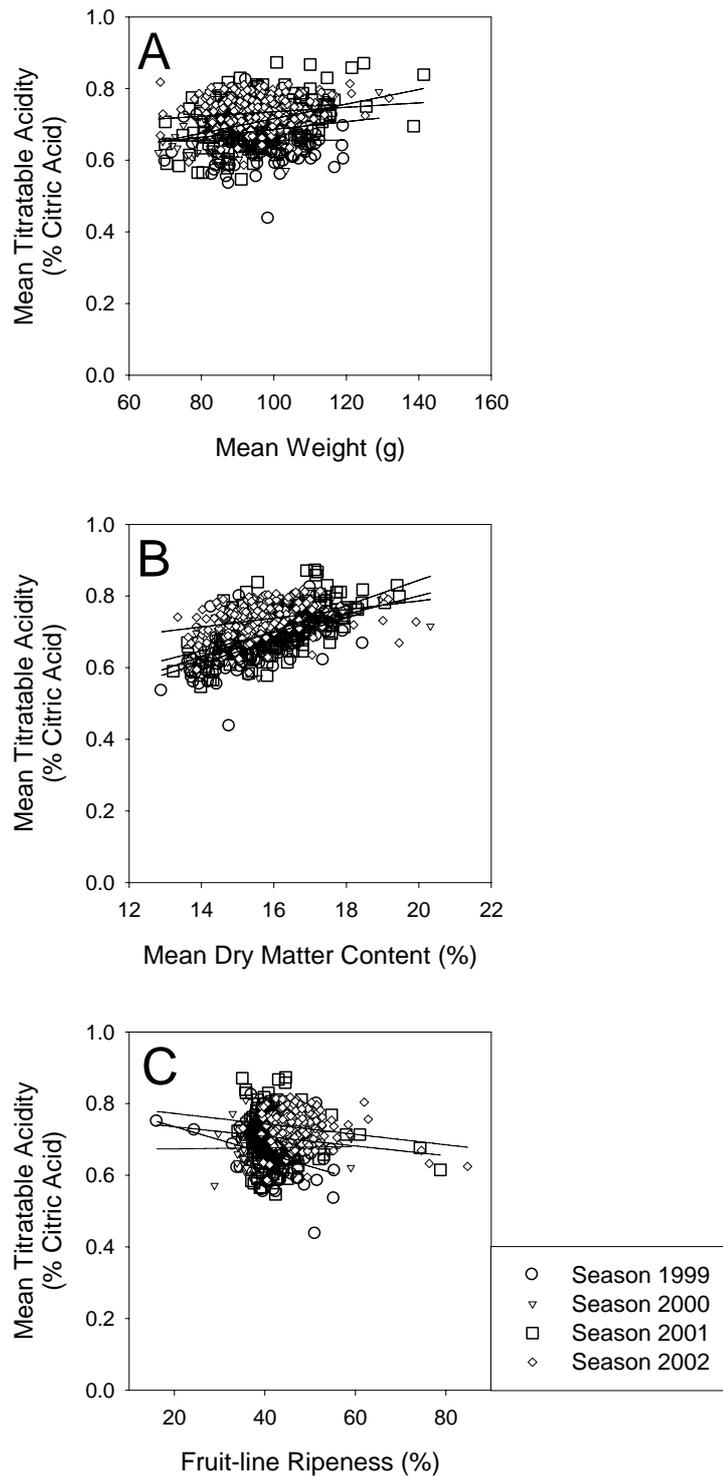


Figure 3.4. Linear relationships between French grown average Hayward fruitline titratable acidity (TA) and other fruit quality traits over four consecutive seasons (1999 – 2002): Average TA and average fruit weight (A); Average TA and average fruit DM (B); Average TA and average fruit ripeness (C). The number of fruitlines measured was 165, 178, 214 and 217 in seasons 1999, 2000, 2001 and 2002 respectively. The characteristics of the individual regressions are presented in Table 3.7.

Table 3.7. Summary of linear relationships between titratable acidity of French grown Hayward kiwifruit at harvest and other fruit quality traits across seasons (1999-2002). The number of fruitlines measured was 165, 178, 214 and 217 in seasons 1999, 2000, 2001 and 2002 respectively. The relationships presented are comparisons of fruitline averages, not individual fruit.

Characteristic	Season	Slope	R ²	P
Average Fruit Weight (g)	1999	0.38	0.00	0.64
	2000	3.30	0.05	< 0.01
	2001	3.98	0.12	< 0.01
	2002	1.37	0.01	0.21
Average DM (%)	1999	0.68	0.33	< 0.01
	2000	0.75	0.32	< 0.01
	2001	0.70	0.38	< 0.01
	2002	0.50	0.11	< 0.01
Ripeness (%)	1999	-3.07	0.16	< 0.01
	2000	0.19	0.00	0.60
	2001	-0.32	0.01	0.22
	2002	-0.51	0.00	0.30

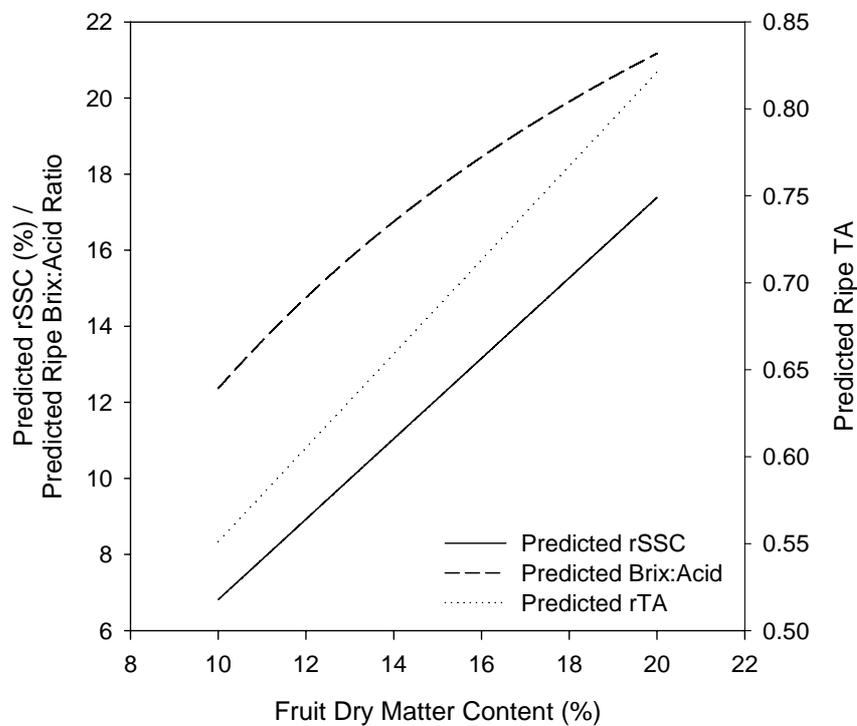


Figure 3.5. The modelled relationships between fruit acidity (TA) and soluble sugar content (rSSC) of ripe Hayward kiwifruit as affected by fruit DM at harvest.

3.4 Discussion

3.4.1 Between- and within-vine relationships between Hayward cropload, fruit weight and dry matter content

Fruit FW predictably decreased with increasing cropload, while the relationship between cropload and fruit DM appeared to depend on the year and the factors causing variation in crop load. Previous studies have shown that increasing crop loads have consistently resulted in smaller fruit (Cooper & Marshall, 1987; Richardson & McAneney, 1990; Antognozzi et al., 1991). The rate of reduction in fruit fresh weight with increasing cropload was comparable to that reported previously (Snelgar & Manson, 1990; Snelgar & Martin, 1997; Snelgar et al., 2005a). This relationship is generally interpreted as the same pool (amount) of available carbon being distributed among greater numbers of fruit. However, here it has been demonstrated that higher croploads result in a higher total amount of DW (carbon) allocated to the fruit (Figure 3.1.D). From studies of peach it has been noted that at a plant level, total fruit DM production is positively correlated with cropload, compared with a negative correlation between individual fruit dry weight and cropload (Pavel & Dejong, 1993a; Pavel & Dejong, 1993b). This is consistent with our observations that total fruit dry weight per vine was positively correlated with vine cropload (Figure 3.1.D) and that average individual fruit dry weights were negatively correlated with cropload (Table 3.1). Figure 3.1.D shows that with increasing croploads, vines allocate more DW to fruit. The relationship is linear and does not appear to flatten out at higher croploads, suggesting that DW allocations to fruit are not limited by DW production, at least up to the croploads observed in this study (≤ 65 fruit m^{-2}).

The relationship between cropload and fruit DM appeared to depend on the year and the factors causing variation in cropload. The lack of a consistent negative correlation between cropload and average fruit DM across seasons was contrary to

the initial hypothesis. From studies of apple and peach, the expectation was that for a limited pool of available carbon in kiwifruit, increases in cropload would result in less carbohydrate for individual fruit, and subsequently lower fruit DM. In peach, a positive linear correlation was identified between individual fruit DW and leaf area per fruit (Nicolas et al., 2006). A strong negative correlation between cropload and fruit DM in apple is well established (Atkinson et al., 1995; Palmer et al., 1997; Wünsche et al., 2000; Neilsen et al., 2001). While in the present study it is true that fruit DW decreases with cropload, FW also declines, as such the net affect on DM is dependent on the relative reductions in FW and DW per fruit. Bertin et al. (2000) reported that tomato fruit DM was unaffected by fruit load (Bertin et al., 2000). For kiwifruit, Richardson et al. (1997) found high crop loadings reduced fruit size by 18% but had little effect (<1%) on DM and SSC of fruit (Richardson et al., 1997a). Woodward (2001) reported a slight negative response of Hayward DM (~0.5%) across a large range of croploads (5-60 fruit m⁻²) (Woodward, 2001).

It must be noted that the present study is observational in nature; vine croploading was not manipulated and as such, the underlying factors driving the observed differences in vine cropload are largely unknown. The spring frost event of 2003 caused drastic floral thinning and shoot damage, this resulted in dramatic increases in fruit DM and led to a positive correlation between DM and FW. In the subsequent 'normal' seasons of 2004 and 2005, DM and FW were negatively correlated. The drivers of the variation in the later seasons of 2004 and 2005 were quite different.

3.4.2 Between- and within-fruitline relationships between Hayward fruit weight and dry matter content

The initial hypothesis was that there would be a general correlation between fruit size and DM across seasons, orchards, vines and individual fruit. This was not

always the case. Relationships varied between-fruit within individual vines, between vines, between-fruit within fruit-lines and between-fruit-lines.

Analysis of individual vine data showed that in the frost season of 2003, fruit weight and DM were positively correlated both within- and between-vines. In the subsequent seasons the relationship was negative between-vines and variable within-vines.

No correlation between fruit weight and fruit DM population parameters was evident between fruit-lines across seasons. Between-fruit within fruit-lines there was a general positive correlation between fruit weight and DM across seasons, however a proportion of fruit-lines exhibited a negative correlation and the proportion of such fruit-lines varied between-seasons. A positive correlation between fruit weight and DM suggests that large fruit have a greater capacity for accumulating both FW and DW but more so DW. Instances of fruit within-fruit-lines having a less positive (or negative) correlation between fruit size and DM demonstrates that differences in cultural practices can have major impacts on fruit development. The production of large sized fruit can be promoted in ways that do not necessarily guarantee high internal quality. It has been noted that kiwifruit FW is more responsive to cultural practises than DW (Palmer, 2006). Cultural practices known to promote FW weight accumulation to the detriment of fruit DM include the use of growth regulators (Patterson et al., 1993; Famiani et al., 1999; Cruz Castillo et al., 1999) and cane girdling, depending on the time of girdle application (Anon, 2005).

Despite the lack of a consistent relationship between fruit size and DM, the discriminant analysis demonstrated that fruit size at an individual fruit level could accurately predict the DM (quartile) category of 33% of fruit within any given year. It is concluded that, overall, grading fruit for size also segregates fruit for DM, and large count size fruit will often have higher DM than small sized fruit. For example Bramley (2005) commented that the grape berry weight can act as an index of both yield (large berries implies high yield) and quality (high quality tends to result from smaller berries). In apple a positive correlation between fruit size and internal quality exists under some circumstances but a positive

correlation as a general assumption is questionable as the correlation is dependent on cultural and climatic conditions (Toldam Andersen & Hansen, 1998). This appears to be the case with kiwifruit as well.

3.4.3 Between-vine relationships between Hayward fruit firmness at harvest and measures of fruit maturity

Fruit firmness at harvest was independent of vine cropload, average fruit DM, and average fruit weight. This was contrary to expectations; a negative correlation between cropload and fruit firmness, a positive correlation with fruit DM, and a positive correlation with fruit weight was hypothesised.

3.4.3.1 Cropload and fruit firmness

No consistently significant relationship was identified between vine cropload and fruit firmness at harvest. Fruit firmness is correlated with fruit maturity (Feng et al., 2003a). The literature reports inconsistent relationships between fruit firmness/maturity and cropload over a range of fruit crops. In a study on the effect of cropload on tomato fruit quality characteristics, it was reported that in contrast to fruit composition and fruit size, fruit firmness was only slightly affected by the cropload (Bertin et al., 2000; Bertin et al., 2001). Whereas with apple, light cropping resulted in a significant advance in fruit maturity; a similar result was reported for peaches (Palmer et al., 1997; Wu et al., 2005). In the case of kiwifruit, anecdotal evidence suggests that vines with light croploads attain fruit maturity earlier than vines carrying heavier croploads (Beever & Hopkirk, 1990). In one study it was found that kiwifruit fruit maturation was markedly delayed in a 1:1 leaf-to-fruit ratio treatment compared to fruit from a 5:1 ratio treatment (Seager et al., 1995).

3.4.3.2 Fruit DM and fruit firmness

No significant relationship ($P < 0.05$) was observed between fruit DM and fruit harvest firmness across the 3 seasons studied. Feng et al. (2003) reported a

positive correlation between DM and firmness when working with individual fruit, although the predictability of the relationship was low ($R^2=0.24$) (Feng et al., 2003a). Other workers have concluded that DM, SSC and firmness are not well correlated (McGlone & Kawano, 1998). Though firmness is considered the primary indicator of kiwifruit eating ripeness, it is not well related to other attributes of good eating quality.

3.4.3.3 Fruit weight and fruit firmness

Crisosto et al. (1999) reported that large Hayward kiwifruit softened at a slower rate compared to smaller sized fruit in coolstorage, but no such size related firmness variation at the time of harvest was found in the current study. Fruit size has been investigated as a potential maturity index in both Hayward and Allison kiwifruit, in both cases fruit weight was deemed to be a poor maturity index as it changed little during the harvest period (Crisosto et al., 1984; Srana et al., 2003). From the results in this study it is concluded that variation in fruit firmness at harvest is independent of variation in fruit weight.

3.4.3.4 Fruit maturity and fruit firmness

Alternative measures of fruit maturity produced the most significant correlations with fruit firmness. Across the seasons studied, between-vine differences in fruit maturity best explained the observed between-vine variation in fruit firmness. Of the measures of fruit maturity investigated, Ripeness index yielded the most significant correlations. At a vine level, the traditional measure of fruit maturity, (SSC), explained less of the variation in firmness ($R^2 = 0.17 - 0.54$) than that explained by the Maturity Index of Ripeness. The correlations between measures of fruit maturity and fruit firmness at harvest are lower than those reported by other investigators. For example, at an individual fruit level a negative correlation between fruit SSC and fruit firmness at harvest ($R^2 = 0.47$) was reported (Feng et al., 2003a). The present study compared average values per vine, so the poorer correlations could arise from variation in the relationships between individual fruit, or within vines. Such speculation is supported by the previous observation that, although harvested on the same day, fruit populations having significantly different maturities as indicated by SSC did not differ significantly in average

firmness (Benge et al., 2000b). Commercial and research experience has shown considerable variability in fruit firmness during and after storage (Pyke et al., 1996). From the current study it is hypothesised that much of this variation in firmness at harvest is established pre-harvest by variation in physiological maturity.

3.4.4 Between-fruitline relationships between Hayward fruit acidity and fruit weight and dry matter content

Fruitline acidity was found to be positively correlated with average fruit DM and independent of both fruit weight and maturity. Fruit acidity being independent of fruit maturity is consistent with previous reports as changes in titratable acidity during the later period of fruit growth are small (Crisosto et al., 1984; Walton & De Jong, 1990; Gonzalez Rodriguez et al., 1993; Ferrandino & Guidoni, 1999; Crisosto & Crisosto, 2001). A definitive relationship between fruit acidity and DM is not found in the literature. In the study of Burdon et al. (2004) statistically significant differences in acidic intensity were identified by the sensory panel between fruit DM categories, however, these did not show any consistent trend with measured DM. Marsh and co-workers (2004) made reference to unpublished work in which Hayward kiwifruit pre-sorted for DM indicated that low DM fruit had lower acidity. The low DM fruit were perceived to be less sweet and more acidic, despite having a lower TA, than high DM fruit. Presumably, such low DM fruit had a lower brix/acid ratio (Marsh et al., 2004).

The DM of fruit measured at-harvest is known to give a good prediction of the rSSC of the fruit (Jordan et al., 2000; Burdon et al., 2004). From this study it is also suggested that DM of fruit measured at harvest allows reasonable estimation of fruit acidity. Marsh and co-workers (2004) found no evidence of TA changing during the storage period at any of the storage temperature regimes investigated, this was consistent with the findings of previous studies (Matsumoto et al., 1983; MacRae et al., 1989b). Such findings suggest that estimation of fruit TA at harvest

will give a good prediction of fruit acidity when ripe (rTA). The combined predictions of rSSC and rTA enable estimation of the brix/acid ratio of the fruit which is an important aspect of fruit sensory quality (Fellers, 1991; Harker et al., 2002). Most Hayward kiwifruit have a DM at harvest in the range of 14-17% (Burdon et al., 2004), this implies rSSC and TA will range from 11.04-14.21% and 0.66-0.74% respectively. Such a range in rSSC and TA produces a range in the brix/acid ratio of 16.6-19.2. In apple, Harker and co-workers (2002) demonstrated that a difference of 0.08% TA was required before the average trained sensory panellist could detect a difference in acid taste. If there is equivalent taste discrimination in kiwifruit, then high DM fruit will be perceived as being sweeter and less acidic than low DM fruit, despite having higher acid contents. Indeed, in experiments using kiwifruit fruit pulps adulterated with sugars, higher SSC (with similar TA and acid concentrations) reduced perception of acidity and increased flavour acceptability (Rossiter, 2000). Elsewhere, it has been demonstrated that consumers prefer kiwifruit with a higher brix/acid ratio (Crisosto & Crisosto, 2001). Segregation of fruit on the basis of DM will also segregate on the basis of TA.

3.5 Conclusion

It was assumed that there existed a general correlation between fruit size, DM and acidity across seasons, orchards, vines and individual fruit. This hypothesis is rejected as the relationship was found to vary between seasons and between production scales.

At higher vine croploads more total carbon is allocated to the fruit sinks; at an individual fruit level, increasing croploads reduce both FW and DW allocations per fruit. The effect of cropload on DM was dependent on seasonal factors that caused FW and DW to vary. The implication is that orchard management decisions made regarding croploading will have predictable consequences for fruit weight but variable effects on DM. Between-vines the relationship between cropload and total DW allocated to fruit sinks was linear and did not flatten out at higher croploads, suggesting that DW allocations to fruit are not limited by DW production, at least up to the croploads observed in this study (≤ 65 fruit m⁻²).

Between-vine variation in fruit firmness was best explained by variation in fruit maturity. Of the measures of fruit maturity investigated, the ripeness index incorporating fruit SSC and DM gave the best relationships with average fruit firmness per vine. Potentially, such an index may be a more appropriate measure of commercial harvest maturity than the SSC currently used.

In conclusion, no general correlation exists between fruit size and DM, as the correlation is dependent on cultural and seasonal conditions. However, more often than not, DM is correlated with fruit size within a fruitline. Overall, grading for size segregates fruit for DM, and large count size fruit will often have higher DM than small sized fruit. This relationship has implications for not just the postharvest industry but also orchard practice. Between fruit-lines there is a positive correlation between fruit DM and fruit acidity. Segregation of the inventory on the basis on DM will also segregate on the basis of TA.

Chapter 4: Modelling of Spatial Variation in Hayward Kiwifruit Quality Characteristics across a Growing Region.

4.1 Introduction

Kiwifruit quality is of commercial interest. The literature reports variation in kiwifruit quality parameters between seasons (Sawanobori & Shimura, 1990; Hall et al., 1996), between producing countries (Pailly et al., 1995; Suezawa et al., 2003), between production regions (Walton & De Jong, 1990; Sawanobori & Shimura, 1990; Manson & Snelgar, 1995), between orchards (Snelgar et al., 1993) and within orchards (Praat et al., 2003a; Praat et al., 2005). In this chapter spatial variation in Hayward fruit quality parameters was investigated within the main production region of New Zealand, Te Puke. Knowledge about the spatial component of between-orchard variation is needed for the implementation of zonal management (Bramley, 2005).

In New Zealand, kiwifruit are grown in a wide range of climatic conditions and the vines in the various growing areas produce fruit of differing characteristics. In the southern areas of New Zealand, such as Riwaka, the winters are cool and vines in these areas tend to flower and crop heavily (Manson & Snelgar, 1995), producing lower dry matter content (DM: the ratio of dry weight to fresh weight) fruit (Anon, 2005). Conversely, in the northern areas, such as Gisborne, winters tend to be mild and summers warm. Under these conditions vines burst bud later and have reduced flower numbers (Manson & Snelgar, 1995), typically producing larger sized, high DM fruit (Anon, 2005). McPherson et al. (1994) compared kiwifruit budbreak and flowering between six growing regions of New Zealand

across four years and reported that the time of 50% budbreak varied by 32 days and the time of 50% flowering by 25 days, with cooler sites generally breaking bud earlier and producing more flowers (McPherson et al., 1994). Industry clearance data shows average fruit fresh weight to have varied by 10g between New Zealand growing regions in the 2004 season compared with only 5g in the 2003 season, and average fruit DM to have varied by 1.2% and 0.5% between growing regions in the 2004 and 2003 seasons respectively (Anon, 2005). Regional variation in fruit quality is not unique to New Zealand. Walton and De Jong (1990) reported that there were significant differences in quality between kiwifruit grown at different Californian locations. These differences were thought to be due to environmental differences between locations (Walton & De Jong, 1990). In Japan, Suezawa et al. (2003) noted significant differences in fruit quality of Koryoku kiwifruit between production areas.

Salinger and Kenny (1995) identified three climatic factors as being important determinants of an area's suitability for cultivation of Hayward kiwifruit: winter chilling; growing season thermal time; and annual rainfall (Salinger & Kenny, 1995). New Zealand has a complex topography which results in significant local modification of climate. It is well known that these local-scale modifications of climate are important for crop production (Skaar, 1980; Salinger & Kenny, 1995). For the New Zealand kiwifruit industry, the majority of kiwifruit is grown in the Bay of Plenty province with the bulk of production centered within the Te Puke region. As at 2001, the Te Puke region had 38% of the growing area of Hayward kiwifruit and accounted for 43% of New Zealand production. The wider Bay of Plenty province represented 77% by area and 82% by volume (Anon, 2001). The studies cited above describe variation in kiwifruit characteristics between growing regions; however, nested within between-regional variation there is within-region variation, the extent of which has yet to be determined. With the majority of New Zealand kiwifruit production being centered within a single region, an understanding of the magnitude and spatial component of within-region variation is of interest.

Geostatistics focuses on the detection, modeling, and estimation of spatial patterns and is centered around modeling and interpretation of the semivariogram (Rossi et al., 1992). The semivariogram is used to describe the relationship between variables at several discrete distance intervals (Figure 4.1), and has three main features (Habib et al., 1991):

1. The ‘nugget effect’ – the level of variation occurring at zero separation distances (Figure 4.1). In the current study between-orchard variation was modeled across a growing region and thus a nugget effect would relate to within-orchard variation (Bramley & Hamilton, 2004; Bramley, 2005). Within-orchard variation could arise through finer scale spatial variation within orchards, or within-orchard factors that are not spatially determined – such as management practices;
2. The variogram function increases with increasing separation distances; the further apart orchards are located the more spatially independent they are;
3. The range – the variogram function reaches a plateau at a point termed the sill (Figure 4.1). At this between-orchard separation distance, termed the range, orchards have no more spatial interaction and can be considered to be spatially independent. Observations are said to be spatially correlated when the separation distance between observations is less than the range of the semivariogram model (Johnson et al., 1996).

Semivariogram models provide the necessary information for kriging, which is a method of interpolating data at unsampled points. Kriging differs from other types of interpolation (e.g. weighted inverse distance methods and triangulation) in that it provides a measure of error associated with each predicted value (Rossi et al., 1992). Maps of kriged estimates provide a visual representation of the arrangement of the population and can be used to interpret spatial trends in variation. Monestiez et al. (1990) successfully applied geostatistics to analyse the spatial dependence of fruit weight, SSC, and leaf nitrogen content in peach trees (Monestiez et al., 1990). In orchard system research, geostatistics has been applied to model the spatial distribution of kiwifruit weight and DM across an orchard (Praat et al., 2003a).

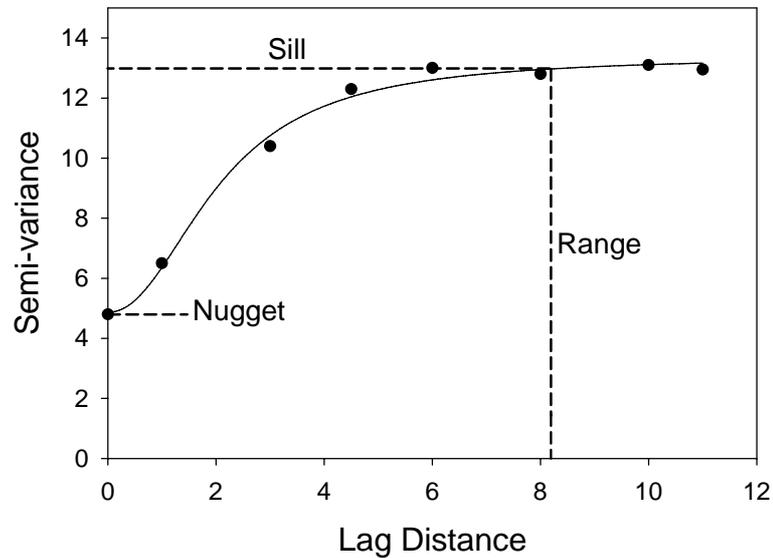


Figure 4.1. Example of experimental variogram, the spatial relationship described by a fitted model, illustrating the nugget, range and sill.

4.1.1 Chapter goals

The aim of the present study was to model the length of the fruit growth period (interval between flowering and harvest, used as a measure of the time taken to attain commercial maturity), average fruit weight and DM, and yield of orchards across the Te Puke growing region over four consecutive seasons (2001-2004). Spatial techniques were used to provide a visual representation of fruit quality and yield distributions across the growing region and to identify zones within the growing region producing fruit of distinctly different characteristics. To identify what variables might be driving the observed spatial variation, regression analysis was used to relate orchard position and altitude to the quality and quantity of fruit produced.

4.2 Materials and Methods

The study was conducted from May 2001 to June 2004 with *Actinidia deliciosa* (A. Chev.) C. F. Liang et A. R. Ferguson var. *deliciosa* ‘Hayward’ kiwifruit harvested from 72 commercial orchards in the Te Puke region (37°49’S, 176°19’E), New Zealand (Figure 4.2A). Fruit quality characteristics were determined for each individual fruit on a commercial kiwifruit grader (Compac™ grading equipment, Auckland, New Zealand) fitted with an Near infra-red (NIR) grading system (Taste Technologies Ltd, Auckland, New Zealand) for logging of fruit weights and counts, and non-destructive estimation of fruit DM.

At weekly intervals a calibration fruit set was used to determine a correction factor for NIR estimation of fruit DM, based on values derived from standard laboratory methods (McGlone & Kawano, 1998).

Orchard records were used to ascertain the timing of flowering and area under production for each orchard, from which yield was calculated as the number of export trays per canopy hectare (a New Zealand kiwifruit tray is ~3.5 kg). Local government records provided geographic coordinates and altitudes of each orchard property.

Geostatistics assumes normality in the test variables modeled; Kolmogorov-Smirnov tests were used to confirm that orchard yield, average fruit weight, DM and length of the fruit growth period were normally distributed between-orchards both within seasons and across seasons (data not shown).

To define the spatial components of between-orchard variation, variograms were modeled for each individual characteristic in each season. Initial parameter estimations for each experimental variogram were conducted using the PROC VARIOGRAM procedure of SAS (SAS Institute Inc., 2003). The data were then interpolated using block kriging with a global variogram, onto a 1km grid with VESPER software (Minasny et al., 2005) (Figure 4.2B).

The persistence of the spatial patterns of variation in quality parameters within the Te Puke growing region across seasons was investigated by using *k*-means clustering to group kriged predictions for each geographic point on the interpolation grid into zones producing fruit of distinct qualities and quantities. *K*-means clustering has been used previously to delineate management zones in a range of crops using such information as yield, fruit quality, elevation and soil electrical conductivity (Bramley & Hamilton, 2004; Bramley, 2005). In the present study, kriged predictions for each quality parameter of each geographic point were normalised within the overall distribution for that season to facilitate between-season comparisons independent of any seasonal effect. Geographic areas were assigned to cluster groupings based on the results of *k*-means clustering, determined using PROC FASTCLUS in the SAS system (SAS Institute Inc., 2003), in which each season's normalised quality measurements were used as a variate in the clustering.

The spatial structure of the kriged predictions and cluster groupings were quantified using Moran's I statistic (Jaynes et al., 2005). Moran's I statistic is similar in concept to correlation and ranges from -1 to 1. A Moran's I near -1 indicates that members of different clusters are evenly interspersed across the field like the coloured squares of a checkerboard. A Moran's I = 0 indicates a completely random distribution of the clusters and a value near 1 indicates that members of a cluster are grouped closely together in space.

The relationships between fruit quality and quantity, orchard location and altitude were modeled by regression using the REG procedure in SAS (SAS Institute Inc., 2003).

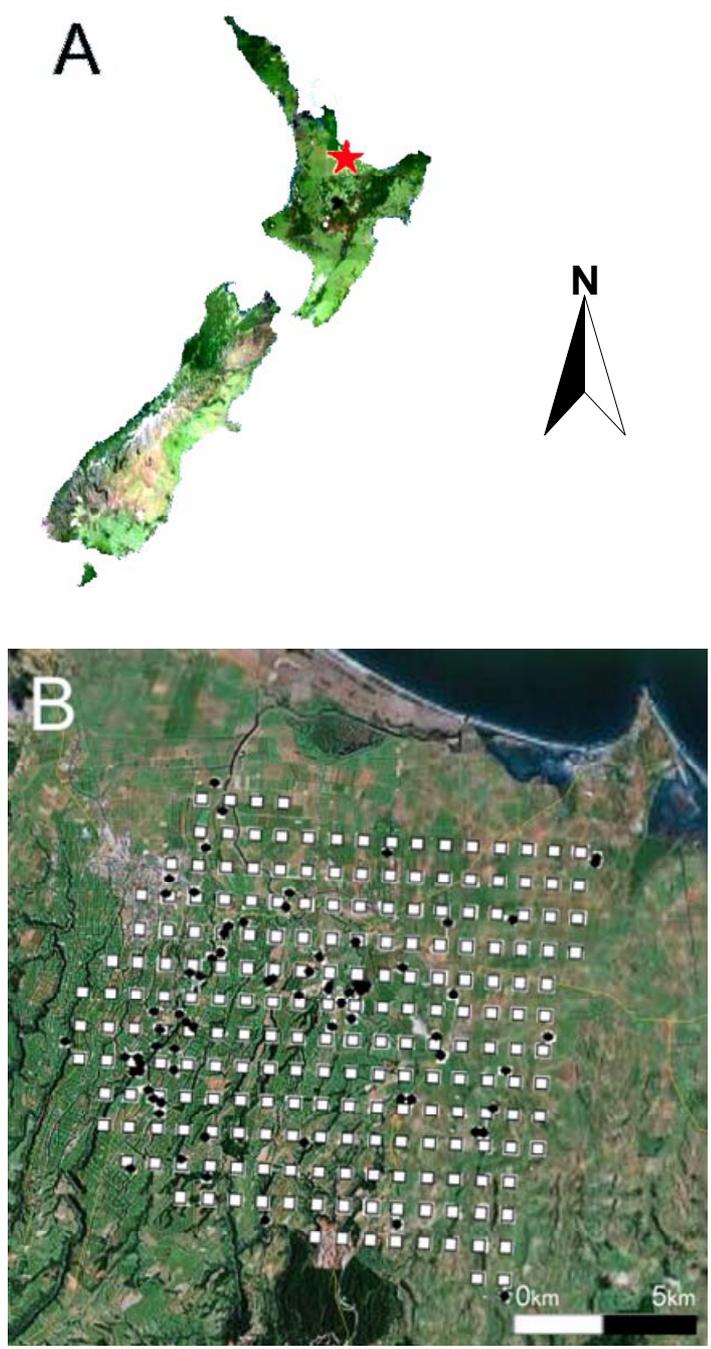


Figure 4.2. A: Geographic location of the Te Puke kiwifruit growing region within New Zealand. B: the location of sample orchards (●) within the interpolation grid (□), encompassing ~ 35,000 ha.

4.3 Results

4.3.1 Raw Between-orchard Variation in Fruit Quality

Across seasons, between-orchard variation in quality parameters was marked and the magnitude of the observed variation varied with the parameter considered. Yield was the most variable parameter between orchards, next the length of the fruit growth period, then the average fruit weight, whilst average fruit DM was the least variable (Table 4.1).

Table 4.1. Summary statistics of Te Puke Hayward kiwifruit orchard fruit parameters across consecutive seasons (2001-2004).

Characteristic	Season	Orchard Average	Standard Deviation	Coefficient of Variation (%)
Fruit DM (%)	2001	16.50	0.44	2.67
	2002	16.38	0.77	4.70
	2003	16.55	0.80	4.83
	2004	16.50	1.03	6.24
Fruit Weight (g)	2001	100.45	6.42	6.39
	2002	102.54	5.72	5.58
	2003	105.91	6.92	6.53
	2004	102.80	6.83	6.64
Fruit Growth Period (Days)	2001	195.21	10.38	5.32
	2002	182.97	12.15	6.64
	2003	176.82	14.26	12.19
	2004	174.31	15.55	8.92
Yield (Export Trays / Can ha)	2001	7217	2357	32.66
	2002	6981	2151	30.81
	2003	6801	2285	33.60
	2004	7721	2185	28.30

4.3.2 Modeling Spatial Variation in Fruit Quality

The spatial component of between-orchard variation was quantified by calculating variograms from average orchard values for each quality parameter in each season (Figure 4.3). Variograms were characterized by a lack of consistency in spatial trends between seasons. For example, comparing the DM 2001 and DM 2003 variograms with those of DM 2002 and DM 2004 illustrates variograms encompassing lower levels of variation. This is reflected in the low between-orchard CV in DM in seasons 2001 and 2003, compared to that observed in seasons 2002 and 2004 (Table 4.1). The slope of variograms varied across seasons: DM season 2004 and Yield season 2001 variograms exhibited steeper slopes than the other seasons. A steeper slope indicates that differences between orchards as a function of separation distance are greater. For all parameters, in all seasons, the nugget effect (the variogram y-intercept) was greater than zero, indicating that orchards separated by small distances were dissimilar, which in this study is suggestive of the contribution of within-orchard variation.

Maps of interpolated predictions of fruit parameters within individual seasons are presented in Figure 4.4. The predictions of fruit quality parameters appeared to illustrate marked spatial structure within-seasons across the growing region; however, there was limited consistency to these patterns between seasons. Moran's I for the kriged predictions were ≥ 0.74 confirming that the predictions tended to group together within the Te Puke region (Table 4.2). The exception was fruit DM in season 2002, which had a Moran's I of 0.57 indicating a more random distribution of fruit DM across the growing region in season 2002 (Table 4.2).

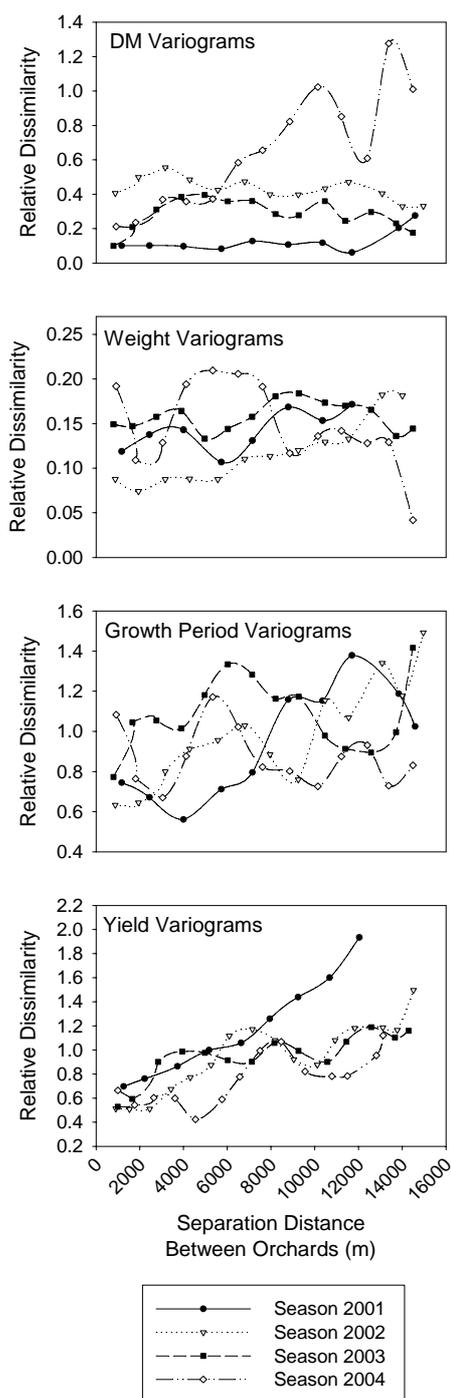


Figure 4.3. Variograms used to model spatial relationships of average fruit DM, average fruit weight, length of the fruit growth period (days) and yield (volume of export trays produced per canopy hectare) between Hayward kiwifruit orchards across the Te Puke growing region (2001-2004). Points are connected with lines to illustrate trends only.

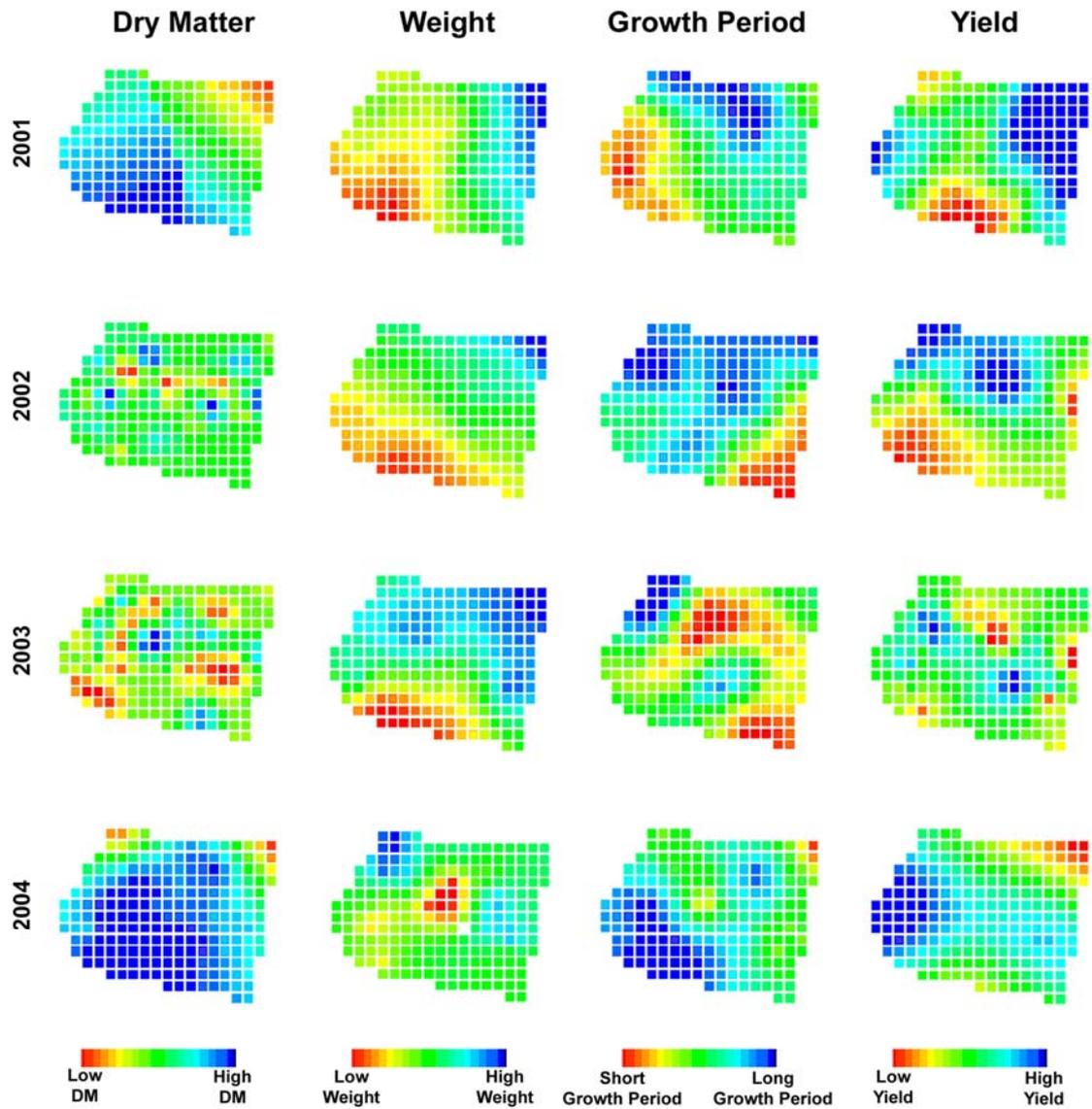


Figure 4.4. Modeled spatial variation of Hayward kiwifruit quality characteristics across the Te Puke growing region over consecutive growing seasons (2001-2004).

Table 4.2. Quantification of the spatial structure of kriged predictions of kiwifruit quality parameters over four seasons, and cluster groupings with Moran's I statistic.

Spatial Prediction	Quality Parameter			
	DM	Weight	Growth Period	Yield
Kriging 2001	0.92	0.97	0.96	0.93
Kriging 2002	0.57	0.92	0.92	0.90
Kriging 2003	0.74	0.93	0.81	0.83
Kriging 2004	0.85	0.91	0.91	0.92
<i>K</i> – means Clustering	0.77	0.88	0.74	0.84

4.3.3. Zonation of the Te Puke Growing Region

The properties of the model fitted to the experimental variogram form the basis of kriging; a poor model fit will result in kriged maps that do not accurately describe the spatial distribution of the fruit attributes. To test the accuracy of the kriged predictions in describing between-orchard variation within the growing region interpolated predictions were correlated with measured orchard characteristics (Table 4.3). For each orchard the measured fruit quality characteristics were compared with the predictions made for the geographic location of the orchard. Across seasons, kriging was better able to model the spatial distribution of orchard yield and fruit DM than the between orchard distributions of fruit growth period and fruit weight. Within seasons, there was a poor correlation between kriged predictions and actual measured orchard values for DM in 2001, weight in 2001 and 2003, and yield in 2004.

Table 4.3. Correlations of kriged predictions with measured orchard characteristics across the Te Puke growing region over consecutive seasons (2001-2004).

Characteristic	Period	R ²
Fruit DM (%)	Season 2001	0.09
	Season 2002	0.59
	Season 2003	0.84
	Season 2004	0.65
	All Seasons	0.58
Fruit Weight (g)	Season 2001	0.35
	Season 2002	0.41
	Season 2003	0.35
	Season 2004	0.75
	All Seasons	0.24
Fruit Growth Period (Days)	Season 2001	0.51
	Season 2002	0.44
	Season 2003	0.47
	Season 2004	0.48
	All Seasons	0.46
Yield (Export Trays / Can ha)	Season 2001	0.54
	Season 2002	0.72
	Season 2003	0.82
	Season 2004	0.36
	All Seasons	0.55

Clustering successfully delineated zones within the Te Puke growing region producing fruit of differing qualities; the location of zones are mapped in Figure 4.5, the fruit properties of orchards located within each zone are described in Table 4.4. The spatial distribution of the different quality populations was not random across the Te Puke region, but appeared to form contiguous areas (Figure 4.5). Moran's I for the clusters were ≥ 0.74 (Table 4.2) confirming that the kriged predictions of fruit quality parameters were more similar within clusters than between clusters (i.e. the clusters are real clusters). It is important to note that this spatial structure is not an artifact of the clustering procedure; clustering partitioned geographic points based on interpolated fruit quality predictions without using any spatial information. Rather, the resulting spatial structure of the

clusters reflected spatial correlation with some underlying phenomenon that affected fruit yields and quality.

The relative fruit properties of the zones were not consistent between seasons for all characteristics (Table 4.4), which is unsurprising considering the lack of consistency in variogram trends between years (Figure 4.3). Clustering by DM produced a 2 cluster solution. Orchards located in the cluster 2 zone (located in the north east and north west of the Te Puke growing region) produced fruit with a higher average DM than orchards located in cluster 1 both within seasons and across seasons. Clustering of geographic points on the basis of average fruit weight at harvest resulted in a 2 cluster solution in which cluster 1 contained orchards producing larger fruit than orchards in cluster 2 both within seasons and across seasons. Orchards located to the south west (higher altitude) consistently produced smaller sized fruit than lower altitude orchards to the north east of the region. Clustering of geographic points on the length of the fruit growth period produced a 3 cluster solution. Within seasons and between seasons clusters 1 and 2 contained orchards with longer growing seasons than those of orchards located at higher altitudes in the south west of the growing region (cluster 3). Clustering of geographic points on the basis of orchard yield gave two clusters but they were inconsistent in their differences across the seasons.

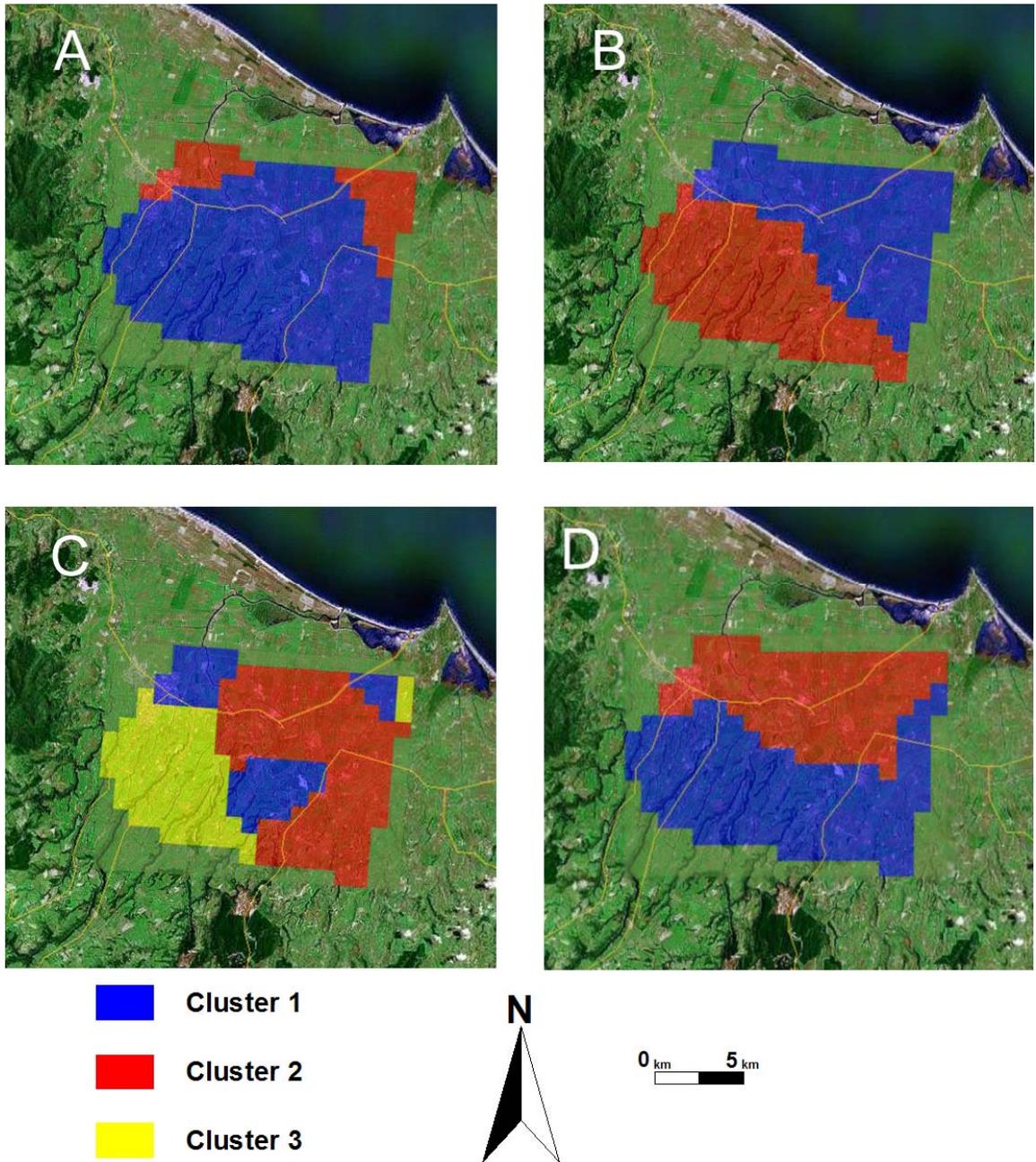


Figure 4.5. Physical location of Hayward kiwifruit orchard quality groupings across the Te Puke growing region as identified by *k*-means clustering. A: Orchard average fruit DM clusters; B: Orchard average fruit weight clusters; C: Length of fruit growth period clusters, indicative of time taken to attain commercial maturity; D: Orchard yield clusters. The fruit properties associated with each cluster are presented in Table 4.4.

Table 4.4. Comparison of fruit characteristics of Hayward kiwifruit quality zones identified within the Te Puke growing region by *k*-means clustering. Values presented are average fruit characteristics \pm 1 SEM measured for test orchards located within each cluster grouping (Figure 4.5).

Characteristic	Period	Orchard Grouping		
		Cluster 1	Cluster 2	Cluster 3
Fruit DM (%)	Season 2001	16.22 \pm 0.41	17.73 \pm 0.66	-
	Season 2002	16.71 \pm 0.23	17.95 \pm 0.35	-
	Season 2003	17.39 \pm 0.26	18.07 \pm 0.52	-
	Season 2004	17.14 \pm 0.26	18.66 \pm 0.47	-
	All Seasons	16.92 \pm 0.14	18.09 \pm 0.24	-
Fruit Weight (g)	Season 2001	103.35 \pm 2.21	99.01 \pm 1.18	-
	Season 2002	105.33 \pm 1.27	100.27 \pm 0.85	-
	Season 2003	106.44 \pm 1.29	105.50 \pm 1.41	-
	Season 2004	104.89 \pm 1.75	100.90 \pm 1.21	-
	All Seasons	105.26 \pm 0.77	101.65 \pm 0.64	-
Fruit Growth Period (Days)	Season 2001	198.13 \pm 2.44	193.90 \pm 2.72	187.99 \pm 0.99
	Season 2002	180.99 \pm 2.97	186.68 \pm 2.32	176.80 \pm 4.18
	Season 2003	174.75 \pm 4.01	180.02 \pm 2.52	167.69 \pm 3.63
	Season 2004	181.20 \pm 2.33	172.88 \pm 3.91	166.52 \pm 6.30
	All Seasons	183.23 \pm 1.87	182.99 \pm 1.60	172.03 \pm 2.90
Yield (Export Trays / Can ha)	Season 2001	7294 \pm 458	7089 \pm 836	-
	Season 2002	5782 \pm 393	8391 \pm 408	-
	Season 2003	6940 \pm 467	6596 \pm 465	-
	Season 2004	8179 \pm 520	7157 \pm 626	-
	All Seasons	6985 \pm 246	7313 \pm 288	-

4.3.4 Spatial variation across the region of within-orchard variability in DM

The previous analysis has modeled spatial variation in average orchard quality parameters across the Te Puke growing region – but what about within-orchard variability in these quality characteristics? What is the spatial component to within-orchard variability? Are there areas within the growing region that constantly produce fruit of more consistent quality?

Within-orchard variation in DM varied more between orchards than did average DM and, in fact, within-orchard variation in DM varied more between orchards than did any other characteristic studied (Compare Table 4.1 and Table 4.5). Maps of interpolated predictions of the distribution of within-orchard variability in fruit DM across the growing region within individual seasons are presented in Figure 4.6. The predictions of within-orchard variability in DM appeared to illustrate marked spatial structure within-seasons across the growing region; however, there was limited consistency to these patterns between seasons.

Table 4.5. Summary statistics of within-orchard variation in fruit DM between Hayward kiwifruit orchards across the Te Puke growing region over consecutive seasons (2001-2004). Within-orchard variation quantified as standard deviation; variation between orchards quantified as the standard deviation between orchards.

Season	Average Within-Orchard Variation	Variation Between Orchards	Coefficient of Variation (%)
2001	1.27	0.50	39.02
2002	1.12	0.45	40.50
2003	1.43	0.44	30.84
2004	1.16	0.31	26.37

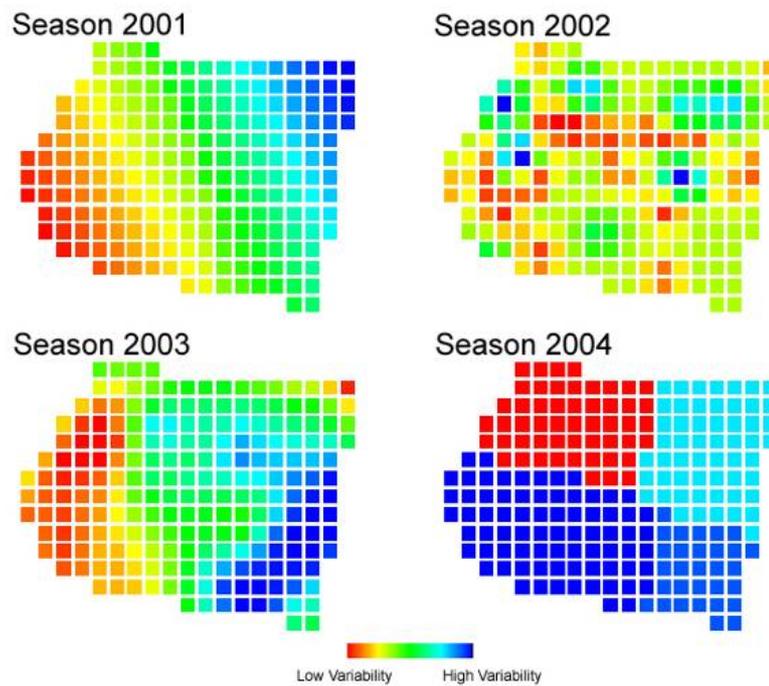


Figure 4.6. Modeled spatial variation of within-orchard variability in Hayward kiwifruit DM across the Te Puke growing region over consecutive growing seasons (2001-2004).

Clustering successfully delineated zones within the Te Puke growing region containing orchards producing more, or less variable fruit-lines. The location of the zones are mapped in Figure 4.7 and the levels of within-orchard variation in DM for the orchards located within each zone are presented in Table 4.4. Again, the location of orchards with similar levels of variability was not random across the growing region, but appeared to form contiguous areas (Figure 4.5). Orchards located in the east of the growing region generally produced fruit of a more variable DM (cluster 3) compared to that produced by orchards located in the west (cluster 2). However, differences in within-orchard variability between the orchard groupings were neither large nor consistent across seasons.

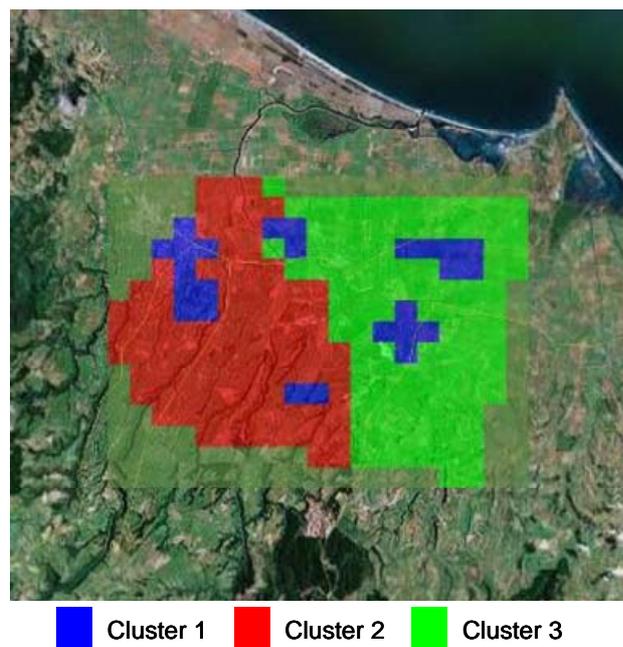


Figure 4.7. Physical location of Hayward kiwifruit orchard within-orchard DM variability groupings across the Te Puke growing region as identified by *k*-means clustering. The fruit properties associated with each cluster are presented in Table 4.6.

Table 4.5. Comparison of within-orchard variability in fruit DM Hayward kiwifruit quality zones identified within the Te Puke growing region by *k*-means clustering. Values presented are average fruit characteristics \pm 1 SEM measured for test orchards located within each cluster grouping (Figure 4.7).

Period	Orchard Grouping		
	Cluster 1	Cluster 2	Cluster 3
Season 2001	1.25 \pm 0.18	1.23 \pm 0.10	1.42 \pm 0.27
Season 2002	1.77 \pm 0.12	0.97 \pm 0.07	0.97 \pm 0.08
Season 2003	1.24 \pm 0.06	1.30 \pm 0.04	1.69 \pm 0.15
Season 2004	1.17 \pm 0.05	1.17 \pm 0.07	1.15 \pm 0.09
All Seasons	1.39 \pm 0.07	1.17 \pm 0.04	1.29 \pm 0.08

4.3.5. The Relationship between Orchard Altitude and Fruit Quality

To quantify the contribution of individual spatial components to the observed between-orchard variation across the Te Puke region, fruit quality characteristics were correlated with orchard location coordinates and altitude within each season of the study. In examining trends across all seasons, a seasonal term was included in the regression to account for between-season variation. Orchard location coordinates contributed little to the regression so only linear regression results of orchard altitude against orchard fruit quality parameters are presented (Table 4.6). The altitude of test orchards ranged from 0 to 260 m above sea level. Both average orchard values and within-orchard variability of fruit weight significantly ($P < 0.01$) declined with increasing orchard altitude: across seasons there was a 0.5g reduction in mean weight values and a 0.25 decline in within-orchard variability of fruit weight with each 25 m increase in orchard altitude. Across seasons average fruit DM was independent of orchard altitude and within-orchard variation in DM declined with increasing orchard altitude (0.023 per 25 m increase in orchard altitude, $P = 0.07$). Despite a significant ($P < 0.01$) correlation being noted between length of the fruit growth period and orchard altitude, the slope of the correlation was minimal (0.25 day increase in growth period with 25 m increase in altitude), suggesting that, in real terms, the length of the fruit growth period was unrelated to orchard altitude. The direction of the relationship between orchard altitude and yield varied between seasons and was insignificant across all seasons ($P > 0.05$).

Table 4.6. Summary results of linear regressions of Te Puke Hayward kiwifruit orchard altitude against fruit quality characteristics (2001-2004).

Characteristic	Period	Slope	R²	P
Orchard Average Fruit Weight (g)	Season 2001	-0.03	0.40	0.05
	Season 2002	-0.01	0.18	0.23
	Season 2003	-0.01	0.04	0.60
	Season 2004	-0.02	0.49	0.04
	All Seasons	-0.02	0.11	< 0.01
Within-Orchard Weight Variation (Stdev)	Season 2001	-0.0081	0.35	0.07
	Season 2002	-0.0004	0.00	0.94
	Season 2003	-0.0012	0.01	0.76
	Season 2004	-0.0034	0.11	0.38
	All Seasons	-0.0050	0.10	< 0.01
Orchard Average Fruit DM (%)	Season 2001	-0.0002	0.00	0.85
	Season 2002	-0.0006	0.03	0.65
	Season 2003	-0.0027	0.53	0.02
	Season 2004	0.0021	0.36	0.09
	All Seasons	-0.0004	0.01	0.88
Within-Orchard DM Variation (Stdev)	Season 2001	0.0003	0.01	0.78
	Season 2002	-0.0007	0.05	0.55
	Season 2003	-0.0012	0.40	0.05
	Season 2004	-0.0005	0.12	0.36
	All Seasons	-0.0009	0.21	0.07
Average Length of Fruit Growth Period per Orchard (Days)	Season 2001	-0.04	0.23	0.16
	Season 2002	0.01	0.02	0.69
	Season 2003	0.01	0.03	0.63
	Season 2004	0.05	0.26	0.16
	All Seasons	0.01	0.22	< 0.01
Orchard Average Yield (Export Trays / Can ha)	Season 2001	1.88	0.01	0.75
	Season 2002	-18.18	0.89	< 0.01
	Season 2003	3.74	0.05	0.54
	Season 2004	7.12	0.43	0.08
	All Seasons	-3.18	0.01	0.41

4.4 Discussion

4.4.1 Variation within the growing region

Orchard yield varied more than the length of the fruit growth period between orchards, which in turn varied more than average fruit weight. Average orchard fruit DM varied the least between orchards. Bramley (2005) reported that within-vineyard variation in grape quality attributes at harvest was considerably less than variation in yield.

In comparisons of fruit quality between New Zealand production regions, it has been reported that average fruit weights varied more between regions than did average DM (Anon, 2005). From studies of between-vine variation in fruit quality parameters within an orchard block, coefficients of variation for differences between vines in cropload ranged from 22% – 85%, 4% – 9% for average fruit weight, and 2% – 3% for average fruit DM over the three consecutive growing seasons of 2003-2005 (Refer Chapter 5). It has been suggested that kiwifruit fresh weight is more responsive to cultural practices than fruit dry weight (Palmer, 2006). From comparison with such previous studies, it can be concluded that independent of the production scale considered (between-region, within-region or between-vine), yield varies more than fruit weight which varies more than fruit DM.

As far as can be determined, this is the first study to report on variation in the length of the fruit growth period across a growing region; the length of the fruit growth period varied more between orchards across the region than did fruit weight and DM. The studies of Walton and De Jong (1990), Snelgar et al. (1993) and Pailly et al. (1995) indicate that the timing of budburst, flowering and the development of fruit maturity are primarily driven by growth temperatures; thus the length of the fruit growth period is a function of growth temperatures but also commercial maturity clearance protocols and their application (Walton & De Jong, 1990; Snelgar et al., 1993; Pailly et al., 1995). This is consistent with our findings where higher altitude orchards (assumed to be cooler) had a shorter

growing season as they flower later and meet commercial maturity standards earlier than lower altitude orchards.

4.4.2 Validity of spatial zonation

The spatial arrangement of fruit quality parameters across the Te Puke growing region is of interest because if parameters are spatially aggregated, then management practices can be targeted to specific areas within the region. In the present study we identified spatial patterns to the distribution of fruit quality characteristics across the Te Puke growing region within-seasons, but the spatial structure was variable between years. The spatial distribution of quality characteristics was unique for each characteristic modelled; as such no single location consistently produced ideal fruit (high yields of large sized, high DM fruit). Bramley (2005) encountered the same issue when attempting to delineate 'quality zones' within vineyards and reported little commonality in the spatial distribution of individual grape quality characteristics.

Variograms form the basis of spatial prediction. The literature suggests a minimum of 100 sample points are required to estimate a robust variogram (Bramley, 2005; Jaynes et al., 2005 and references there in). In terms of geostatistics, this study is therefore marginal in that it is based on only 72 orchards, albeit over four consecutive growing seasons. Despite this the kriged models were generally able to adequately describe the spatial variation observed between orchards in fruit quality characteristics. The kriged predictions for DM 2001, weight 2001, weight 2003 and yield 2004 were characterized by a strong spatial structure (Moran's $I \geq 0.92$) but had little correlation with measured orchard properties ($R^2 \leq 0.35$). The foundation of kriging is the spatial relationships described by the variogram; a poor variogram model will result in kriged predictions that do not accurately describe the spatial distribution of the fruit attributes. Presumably the models fitted to the variograms in these seasons did not accurately describe the spatial relationships between orchards. The kriged predictions of DM in season 2002 illustrated a more random distribution of fruit DM across the growing region (Moran's I of 0.57), suggesting there was little

spatial variation in this parameter in season 2002. Despite the lack of spatial aggregation in the 2002 season DM predictions (Moran's I approximating 0), kriging had a good fit with actual measured orchard DM values (R^2 of 0.59).

The year-to-year variation in variogram trends produced some temporally unstable predictions. The spatial patterns of yield distribution across the growing region were inconsistent across years. The spatial pattern of fruit weight and fruit DM distributions across the growing region were temporally stable. The only consistent spatial pattern in the distribution of the length of the fruit growth period across the region was the identification of a zone to the south west at higher altitudes which contained orchards producing fruit over a consistently shorter growth period. Davison (1990) noted that there was a consistent delay in flowering time of up to 7 days along a rise in altitude of 270 m within the Te Puke growing region (Davison, 1990). As a consequence we could expect higher altitude orchards to flower later and meet maturity standards earlier through cooler growth temperatures (Hallett & Jones, 1993), thus fruit from higher altitude orchards should grow and mature over a shorter period. We suggest the inability to delineate meaningful orchard yield zones is a result of non-spatially determined variation. Such variation would be influenced by orchard management practices and natural between-vine variation.

4.4.3 Regression analysis

Temperature is described as the major driver of all crop development. Yield variation in cereal crops across the UK was associated with temperature, primarily acting through its influence on the length of the growing period ($\pm 9\%$) and rainfall, mainly acting through reducing the growth period ($\pm 1-9\%$ depending on soil type) (Monteith, 1981). Salinger et al. (1995) investigated the influence of climatic factors on the baking quality of bread wheat and found a strong influence of temperature (positive) and rainfall (negative) on the quality of spring-sown wheat (Salinger et al., 1995). Climatic factors alone could cause wheat quality to vary by $\sim 50\%$. Salinger et al. (1995) proposed that wheat quality is affected by

short-term climate variability, and as such, variation in wheat quality could be expected to be associated with climatic variation among regions.

The altitudes of the orchards included in this study varied by 260 m, with the literature reporting an adiabatic lapse rate of $6^{\circ}\text{C km}^{-1}$ (Hallett & Jones, 1993); we could therefore expect average orchard temperatures to vary $\sim 1.56^{\circ}\text{C}$ between the modeled orchards. Temperature has been reported to have significant effects on kiwifruit growth and maturation (Snelgar et al., 2005a). From the literature we could expect fruit produced at higher altitude orchards to have experienced lower growth temperatures resulting in smaller sized fruit of lower DM (Hopkirk et al., 1989) and advanced development of commercial maturity as measured by SSC (Snelgar et al., 2005a).

Consistent with the literature, the two approaches used in the present study (zonal clustering and regression analysis) confirmed average fruit weight to decline with increasing orchard altitude. The literature suggests fruit DM declines with increasing orchard altitude but the results from the regression analysis showed fruit DM to be independent of orchard altitude, and a similar result was obtained with the zonal clustering. The literature and zonal clustering are in agreement for the length of the fruit growth period; it declines with increasing orchard altitude, although the regression analysis did not confirm this. It could be that the different commercial harvesting programs are masking any underlying relationship. The literature reports a negative correlation between growth temperatures and yield in New Zealand grown Hayward kiwifruit (Manson & Snelgar, 1995). The regression analysis found orchard yield to be independent of altitude. Differences between the clusters identified by zonal clustering were greatest in 2002, the same season in which there was a significant negative correlation between orchard yield and altitude.

4.4.4 Spatial variation in within-orchard variability of fruit DM

Within-orchard variability in fruit DM varied more between-orchards than did either average DM values or indeed any other fruit quality characteristic considered. There were strong spatial patterns to the distribution of within-orchard variability in DM within seasons; however there was limited consistency to these spatial patterns across years. Clustering identified populations of orchards in the west of the growing region at higher altitudes that produced less variable fruit at harvest than orchards located in the east of the region at lower altitudes. This was supported by the regression analysis that identified within-orchard variability in DM to decline with increasing orchard altitude.

Within-orchard variability in fruit DM is of commercial interest as it is an important component of industry measures of fruit-line taste quality (Woodward, 2003b). Grower taste payments are improved by increasing average fruit DM and/or reducing the variability in fruit-line DM (Woodward, 2003b). The pattern of spatial variation in average orchard DM and within-orchard variability in DM are different; the implication is that industry measures of fruit taste status that incorporate measures of both average and variability will have a different spatial distribution across the growing region to that of either average DM or variability in DM.

4.5 Conclusion

Orchard variability is not a new phenomenon; it is well known that the quality of fruit an orchard produces varies both within and between-orchards. What is unknown is the contribution of spatial variability to the total variation in crop quality. Within seasons there were spatial patterns to the distribution of fruit quality traits between orchards, however, there was limited consistency to these spatial patterns across seasons. Zones could be identified within the Te Puke growing region that contained orchards consistently producing fruit of distinct qualities (fruit weight, DM and length of the fruit growth period) across seasons. Spatial variation in orchard yield did not appear to follow such a temporally stable pattern across the growing region. Though the differences in fruit qualities between such zones were statistically significant they were not of sufficient magnitude to be commercially significant and warrant a change from uniform to zonal management. The spatial distribution within the region was unique for each quality characteristic considered, no single location contained orchards consistently producing ideal fruit (high yields of large sized, high DM fruit with low variability in DM). If zonal management is to be pursued then selection of zones could be based on groups of traits. For example, in one zone, management could target increasing fruit DM while maintaining fruit size, compared to a second zone where the management targets could be to increase both fruit size and DM.

Orchard management practices and harvest clearance systems are focused on minimizing the spatial variation that was being quantified here. It can be surmised that the absence of strong temporally consistent spatial distributions and weak correlations between parameters were a function of orchard management responding to vines and climate, layered on top of natural climatic variation and location effects. It is concluded that there is a spatial component to between-orchard variation, which potentially enables zonation of orchards on the basis of fruit weight, DM and length of the fruit growth period. However, the impact of spatial variation is diluted by that of non-spatial site-to-site variation.

Chapter 5: Within-Orchard Spatial Variation in Fruit Quality: The Potential for Zonal Management.

5.1 Introduction

Fruit quality attributes are not uniformly distributed within an orchard and, despite uniform management practices fruit production systems are particularly heterogeneous. Heterogeneity arises as a result of the interaction of a hierarchical series of interrelated variables (both biotic, such as competition between vines for soil nutrients, and abiotic, such as temperature) that fluctuate at many different spatial and temporal scales. The field of precision agriculture (PA) has arisen in answer to this inherent variability, to enable crop management to be targeted in a way that recognises that, far from being homogeneous, the productivity of agricultural land is inherently variable (Bramley & Hamilton, 2004).

PA is a management strategy that utilises information technology with the aim of improving production and minimising environmental impact; it also refers to the entire farming system which, in modern agriculture, includes the supply chain from the farm gate to the consumer (Taylor, 2004). The most common application of PA is zonal management where some differential action is introduced based on some aspect of spatial variability in a cropping system. In terms of kiwifruit production, adoption of PA strategies could simply involve selective harvesting of management zones to optimise fruit quality (Bramley et al., 2003), or differential applications of management interventions such as variable rate fertiliser applications.

PA is dependent on the existence of variability in product quantity and/or quality. This variability may be spatial and/or temporal. Most production variables fall into one of two categories - either temporally stable but spatially variable or both temporally and spatially unstable. The first can be referred to as seasonally stable properties and include soil physical properties. The second are seasonally variable and include amongst other things soil moisture and pest/disease/weed infestations (Moran et al., 1997). A further category includes variables that may also be temporally variable but have a stable spatial pattern, for example climatic variables such as incident radiation or temperature. If spatial variability does not exist then a uniform management system is both the cheapest and most effective management strategy and PA is redundant. In cropping situations the magnitude of temporal variability usually appears much greater than that of spatial. Given this large temporal variability, relative to the spatial variation, there is a need to determine if uniform or differential management is the optimal risk aversion strategy (McBratney et al., 1997).

Broadly speaking, the greater the variability in yield and quality within a cropping system, the greater the opportunity for PA (Taylor, 2004). However, the nature of the variation is also important. For example the magnitude of the variability may be too small to be economically feasible to manage or variability may be highly randomised across the production system making it impossible to manage with current technology (Pringle et al., 2003).

While many of the lessons learnt from PA applications in broad-acre cropping can be utilised, applications to horticulture offers new challenges. Horticultural systems in general have fixed perennial plants, thus there is a long-term scale involved compared to the annual nature of broad-acre cropping (Taylor, 2004). Management decisions are also capable of having a much larger impact on yield and quality in kiwifruit than that obtainable in broad-acre cropping systems, for example pruning and thinning strategies are known to greatly affect kiwifruit yield (Cooper & Marshall, 1987; Thorp et al., 2003a).

The most compelling argument for the adoption of zonal management strategies in kiwifruit production is the spatial variability that has been shown in vegetative growth, yield and fruit quality over the past few years (MacRae et al., 1990; Cooper & Marshall, 1991; Hall et al., 1996; Hall & McPherson, 1997; Currie et al., 1999; Woodward, 2001; Mowat & Amos, 2002; Praat et al., 2005). Because variability exists in fruit quantity and quality, there is an opportunity for site-specific management to improve the efficacy and profitability of production.

Viticulture is an example of a cropping system in which quality is perhaps a more important parameter than yield in determining the value of the crop (Taylor, 2004). In kiwifruit, crop value is driven by volume; however, NZ industry payment schedules are increasingly utilising premiums for fruit quality. If this trend continues kiwifruit growers may be in a similar situation to grape growers, where fruit quality is at least as important as volume in determining the value of fruit produced (Taylor, 2004). In viticulture it is generally considered that there is a trade off between yield and quality (Johnston & Robinson, 2001). Results presented in section 3.3.1 illustrate that in the case of individual kiwifruit vines there is a well established trade off between cropload and fruit size, but fruit DM is independent of cropload and fruit size. This suggests good yields of high DM fruit are achievable.

The key driver for the implementation of precision horticulture will be whether targeted orchard management practices can deliver an economic benefit over conventional uniform management. Significant variation in fruit quality has been shown across relatively small areas (c. 0.5 ha) for apples and grapes (Bollen et al., 2001), and this variation has been linked to orchard profitability (Praat et al., 2003b). Whelan and McBratney (2000) proposed the null hypothesis of precision agriculture stating that 'given the large temporal variation evident in crop yield relative to the scale of a single field then the optimal risk aversion strategy is uniform management' (Whelan & McBratney, 2000). Bramley and Proffit (1999) refuted this proposition suggesting that the adoption of PA was potentially highly profitable, and subsequently demonstrated that selective harvesting of grapes

could increase the value of production by over \$30,000/ha (Bramley & Proffitt, 1999; Bramley et al., 2003).

Before accepting a precision horticulture approach it must be determined whether patterns of within orchard variation are consistent from year to year (Bramley & Hamilton, 2004) and whether the crop displays enough variation – both in terms of magnitude and spatial distribution – to warrant a change from uniform management (Pringle et al., 2003). An improved understanding of variability is therefore required. Weiner and Solbrig (1984) expressed dissatisfaction with the traditional statistical measures of variation used in describing the highly dynamic temporal patterns in the structure of populations and proposed the use of methods developed in economics, including the Lorenz curve and Gini coefficient (G). The Lorenz curve is widely used in economics to describe the inequality of wealth distribution, where G summarises the total amount of inequality (Lorenz, 1905; Weiner & Solbrig, 1984).

Lorenz curves and G have become common tools in population biology but have received scant attention in addressing agronomic issues (Vega & Sadras, 2003). Relationships between G and crop yield have been reported in wheat (Pan et al., 2003; Sadras & Bongiovanni, 2004). He et al. (2005) noted that, conceptually, G is a different statistical parameter from traditional measures of population variance. While variance measures the extent to which individual observations of a data set are dispersed around their mean, and can be any value, G is an indicator of inequality, i.e. the degree of variation from a situation where all individuals are equal, and ranges between 0 and 1 in value (He et al., 2005). Sadras and Bongiovanni (2004) reported that G was suited to present crop heterogeneity in terms of inequality and to highlight the relative contribution of low- and high-yielding sections of the field to total paddock yield.

5.1.1 Chapter goals

Adoption of zonal management strategies requires an understanding of crop variability in time and space (Cuppitt & Whelan, 2001; Pringle et al., 2003). The present study investigated between-vine variation in fruit quantity and quality, and the resulting vine wealth characteristics across consecutive growing seasons to quantify both the magnitude and spatial component of variation. The hypothesis was tested that it is possible to identify vines that consistently produce high or low yield or quality and that such vines are spatially aggregated within the orchard area. Secondly, it was proposed that the spatial aggregation of such vines will be temporally consistent and of sufficient magnitude to enable implementation of zonal management strategies.

5.2 Materials and Methods

5.2.1 Study Site

Measurements of vine production and fruit quality were made on a commercial kiwifruit orchard in Te Puke, Bay of Plenty, New Zealand (37°49'S, 176°19'E), over three consecutive growing seasons from 2003-2005. The orchard area was selected because historical records indicated that the block produced a highly variable crop. The vines were mature (>10-year-old) *Actinidia deliciosa* (A. Chev.) C. F. Liang et A. R. Ferguson var. *deliciosa* 'Hayward' kiwifruit plants trained on a pergola trellis. The rootstock was unknown but assumed to be seedlings of open-pollinated *A. deliciosa* var. *deliciosa* 'Bruno', the most common rootstock used in the New Zealand kiwifruit industry. The orchard area studied was a 0.17 ha block (30 x 65 m) with rows 4.6 m apart and vines spaced at 4.5 m within rows (84 vines in total). Vines were uniformly managed under standard commercial practices (Sale & Lyford, 1990).

5.2.2 Fruit Measurements

Each season when the block attained commercial harvest maturity (6.2° Brix), vines were harvested individually. Fruit numbers and quality characteristics were determined on a commercial kiwifruit grader (Compac™ grading equipment, Auckland, New Zealand) fitted with a near infra-red grading (NIR) system (Taste Technologies Ltd, Auckland, New Zealand). For each fruit the grader measured fruit weight, and the NIR system provided a non-destructive estimation of fruit dry matter content (DM). A calibration fruit set was used to determine a correction factor between NIR estimates of fruit DM and a standard destructive measure of DM (McGlone & Kawano, 1998).

Following NIR assessment of fruit properties, random 30 fruit samples per vine were destructively assessed for firmness with a motorised penetrometer fitted with a 7.9mm head (HortPlus Ltd, Cambridge, New Zealand).

5.2.3 Statistical Analysis

5.2.3.1 Vine Wealth and Lorenz Curves

Income per individual vine was determined across seasons using the New Zealand industry payment schedules of 2004 (Zespri International Ltd, 2004) and reported as income/ha. The payment schedules were made up of a base fruit payment with a differential fruit payment for fruit size, and a premium payment for high DM fruit.

A discriminant analysis was performed in SPSS software to determine the contribution of individual quality parameters (vine cropload, fruit weight and fruit DM) to vine income.

Lorenz curves were constructed by ranking gross incomes per vine from lowest to highest, and the cumulative fraction of total income (y) was plotted against the cumulative fraction of the population (x). The upper limit of this curve is the $y = x$ line indicating perfect equality. G quantifies the area between the Lorenz curve and the line of perfect equality expressed as a fraction of the area under the $y = x$ line. It ranges from 0, when all units are equal, to a theoretical maximum of 1 in an infinite population in which all units but one yield 0 (Weiner & Solbrig, 1984). Polynomials were fitted to describe Lorenz curves in SigmaPlot (Version 8.0), and G was calculated from the fitted curves according to previous authors (Weiner & Solbrig, 1984; Harch et al., 1997).

5.2.3.2 Spatial structure of between-vine variation

The spatial structure of the between-vine variation was quantified using Moran's I statistic (Jaynes et al., 2005) following the methodology described previously (section 4.2).

5.2.3.3 Temporal stability of spatial variation

Two approaches, quartile scoring and *k*-means clustering were used to group vines into populations of distinct qualities in order to investigate the persistence of the spatial patterns of between-vine variation in fruit qualities.

Quartile scoring is a modification of the procedure developed by Diker et al. (2003) and subsequently modified by Bramley and Hamilton (2004). For this study average fruit qualities per season were assigned to one of four groups based on which quartile of the overall distribution for that year the vine performed in, within any given year. The resulting summation of scores across the three years provides a greater range of detail than the methods used by earlier authors. In the present study, quartile scoring identified vine populations of consistently high (quartile score ≥ 9) and low (quartile score ≤ 6) qualities. Vines with intermediate quartile scores (7-8) were discarded from the analysis because such vines could not be distinguished between being consistently average across years to those vines whose performance had varied from year to year (Diker et al., 2003).

The second method used to delineate vine populations of distinct fruit quality profiles was *k*-means clustering. This technique has been successfully used for the delineation of management zones using such information as yield, elevation and soil electrical conductivity (Cuppitt & Whelan, 2001; Bramley & Hamilton, 2004; Bramley, 2005). In the present study, the goal was to identify vine populations of similar fruit properties across seasons. Average fruit quality parameters per vine were normalised within each individual season against the average quality value produced by the orchard area in that season. This was done to facilitate between season comparisons of individual vine performance on a uniform scale. Each seasons normalised measurements were used as a variate in the clustering. Vine membership of high and low fruit quality clusters was determined using PROC FASTCLUS in the SAS system.

5.2.3.4 Modelling between-vine spatial variation

To define the range of spatial dependence of between-vine variation, variograms were calculated for each characteristic in each season using the PROC VARIOGRAM procedure of SAS. The data were then interpolated using block kriging with a global variogram, with VESPER software (Minasny et al., 2005). The validity of variograms in modelling the spatial structure of between-vine variation was assessed by comparison of interpolated predictions to measured vine characteristics.

5.3 Results

5.3.1 Magnitude of between-vine variation

Variation in fruit characteristics was marked, both between-vines within seasons and between seasons (Table 5.1). Over the study period, average vine incomes, croploads and fruit firmnesses at harvest increased; while average weights, DM and Brix (%) declined (Table 5.1). The 2003 season was characterised by lower vine incomes, croploads and fruit firmnesses, and higher average fruit weights, DM and Brix contents by vine than those seen in the subsequent seasons of 2004 and 2005 (Table 5.1). This can be attributed to a spring frost event in season 2003, with only vines located next to shelterbelts escaping damage and carrying what would be considered a normal commercial crop. Variation between vines, as measured by the coefficient of variation (CV), was highest for all quality parameters in that 'frost' year; the exception being fruit firmness whose variability between vines was least in 2003. The frost event of season 2003 may have accelerated fruit maturation on the vine and produced a crop of more uniformly advanced fruit maturity (lower firmness, higher brix). In the two subsequent 'normal' seasons of 2004 and 2005; average fruit characteristics per vine were higher and variability between vines was less (Table 5.1).

Between-seasons and within-seasons, in order of decreasing variability, were cropload, income, fruit firmness at harvest, fruit weight, fruit brix, and average fruit DM (Table 5.1).

5.3.2 Lorenz Curves and Gini Coefficients

Inequality (variation) in vine wealth was investigated using Lorenz curves and frequency distributions of vine incomes across three consecutive seasons (Figure 5.1). The season with the highest inter-vine variation was 2003 (Table 5.1), this is also apparent with the highest deviation of the 2003 Lorenz curve from the line of

perfect equality. This shows that the 2003 season crop was skewed towards lower incomes, with the bottom ~65% of vines contributing only 50% of total income, and is reflected in the high Gini coefficient of 0.208. In seasons 2004 and 2005 vine income was more homogeneous with Gini coefficients of 0.067 and 0.068, respectively, and lacking the extreme disparities seen in 2003.

Table 5.1. Summary statistics for fruit quality attributes at harvest of Hayward kiwifruit vines across consecutive seasons (2003-2005). n=84 vines.

Fruit Characteristic	Period	Vine Average	Standard Deviation	Coefficient of Variation (%)
Income (\$)	2003	38.95	29.12	74.8
	2004	126.49	31.19	24.7
	2005	149.67	36.16	24.2
	Across Seasons	105.04	57.59	54.8
Cropload (Fruit m ⁻²)	2003	9.0	7.6	84.4
	2004	34.7	8.6	24.8
	2005	42.7	9.3	21.8
	Across Seasons	28.8	16.7	58.0
Average Fruit Weight (g)	2003	109.8	10.0	9.1
	2004	98.1	3.8	3.9
	2005	96.9	4.9	5.1
	Across Seasons	101.6	8.9	8.8
Average Fruit DM (%)	2003	18.3	0.5	2.7
	2004	16.1	0.3	1.9
	2005	15.7	0.4	2.5
	Across Seasons	16.7	1.2	7.4
Average Firmness (KgF)	2003	5.9	0.4	7.0
	2004	8.3	1.0	12.1
	2005	8.2	0.6	7.3
	Across Seasons	10.5	2.5	24.1
Brix (%)	2003	8.9	0.6	6.8
	2004	8.9	0.5	5.2
	2005	7.3	0.3	3.7
	Across Seasons	8.3	0.9	11.1

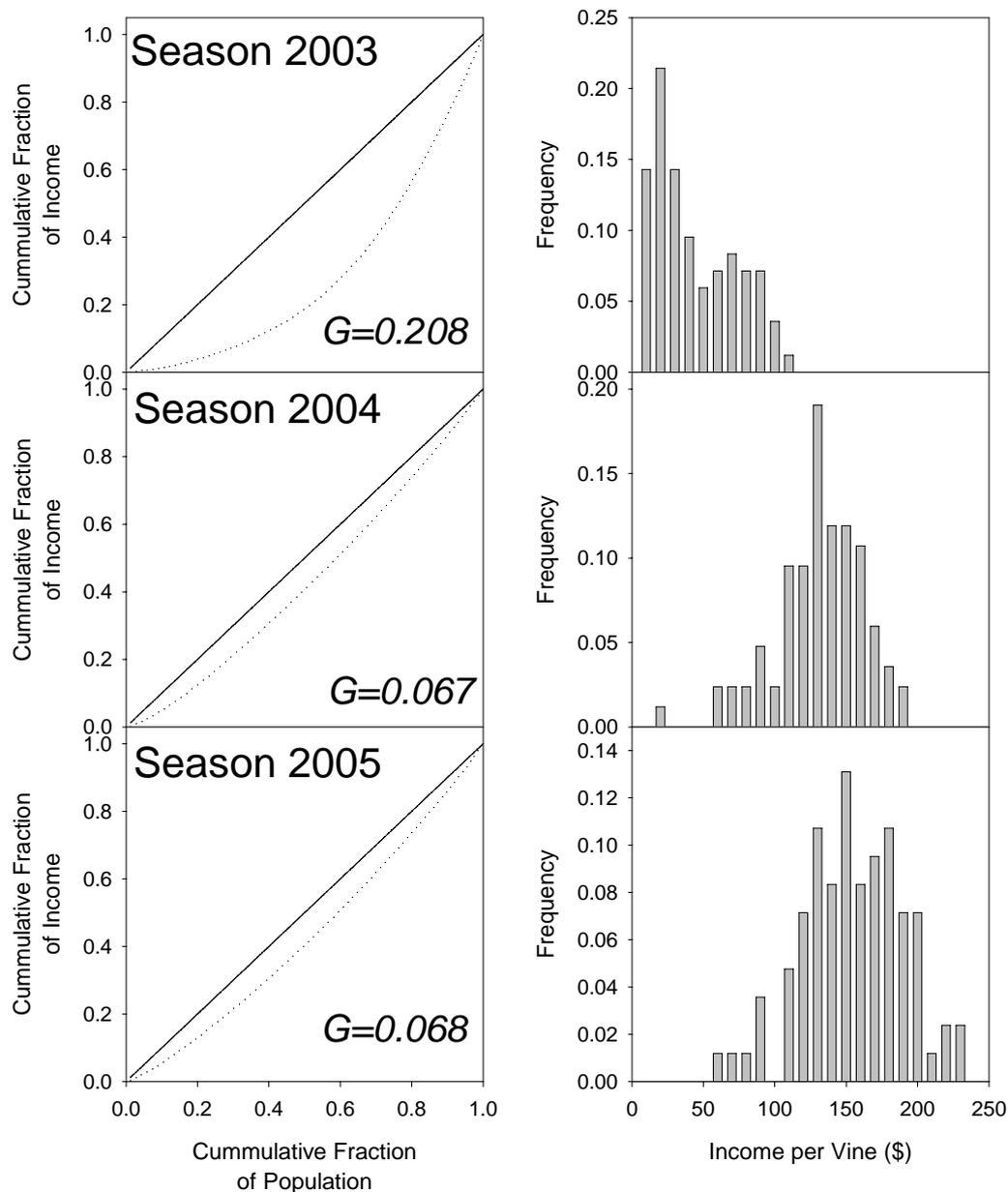


Figure 5.1. Lorenz curves and frequency distributions of gross income per Hayward kiwifruit vine across 3 seasons. Within each season the solid line represents the line of perfect equality, the dotted line represents the modelled Lorenz curve for the vine population within the season. The Gini-coefficient (G) is defined as the area between the line of perfect equality and the Lorenz curve, and is higher in inequitable populations (season 2003) than in equitable populations (seasons 2004 and 2005).

5.3.3 Spatial Component to Between-vine variation

Maps of fruit characteristics for each vine provide a visual representation of the spatial distribution of quality characteristics within the orchard block in each season and how these distributions varied between-seasons. Maps of between-vine variation in fruit quantity and quality characteristics within each season are presented in the appendix (Appendix Figures 9.1 – 9.6). Variograms were calculated for each season's data in order to quantify the spatial component of between-vine variation in fruit quality (Figure 5.2).

5.3.3.1 Income, Cropload, DM, Weight and Brix

The frost event of 2003 was the key event of the entire study period that created clear spatial relationships. The strong spatial pattern observed in 2003 is best described as a linear relationship with vines increasingly dissimilar with increasing separation distances. The season 2005 variograms were relatively flat and dominated by a large nugget effect (variation at zero separation distances) suggesting a non-spatial distribution of fruit quality characteristics between-vines across the orchard block in season 2005. The season 2004 variograms appear to have an intermediate level of spatially related variation, with a large nugget effect but then a linear relationship emerging at larger separation distances (possibly a lag effect of the previous season's frost event) (Figure 5.2).

5.3.3.2 Average fruit firmness at harvest

The between-vine spatial relationships in the distribution of average fruit harvest firmnesses across the orchard area were distinctly different from those of the other characteristics considered. The magnitude of spatial variation encompassed by the fruit firmness variogram models was least in 2003 and highest in 2004. This suggests that differences in fruit firmness between vines as a function of separation distance were least in 2003 and highest in 2004, such a conclusion is supported by the observation that fruit firmness variation across the orchard block was least in 2003 and highest in 2004 (Table 5.1). The season 2003 variogram had a consistent linear trend with increasing separation distances between vines (as

seen for the variables in season 2003). The season 2004 variogram exhibited an exponential trend indicating strong spatial relationships between vines in fruit firmness up to a separation distance of ~10m; at separation distances greater than 10m there was no spatial component to fruit firmness variation between vines. The season 2005 variogram was relatively flat and dominated by a nugget effect (variation at zero separation distances) suggesting a non-spatial distribution of fruit firmness at harvest between-vines across the orchard block in season 2005.

5.3.3.3 Validation of Variograms

To test the accuracy of the variogram models in describing spatial variation in quality characteristics between-vines, kriging was performed using the calculated variograms to make predictions of quality characteristics across the orchard test area. For each quality characteristic modelled, interpolated predictions were correlated with measured fruit characteristics per individual vine (Table 5.2). For all vine characteristics modelled, variograms were better able to describe between-vine variation in the ‘frost’ season of 2003. In the subsequent seasons of 2004 and 2005 variograms were progressively less accurate in modelling variation, suggesting an increasingly non-spatial distribution of quality characteristics between-vines in the latter seasons.

5.3.3.4 Quantification of spatial structure

Moran’s I statistic confirmed the variogram interpretation and validation. Moran’s I indicated a strong spatial structure to the distribution of fruit quality characteristics between-vines across the orchard block in 2003 and an increasingly random distribution of quality characteristics between-vines in the subsequent two seasons of 2004 and 2005 (Table 5.3). From the maps of between-vine variation (Appendix), we could have expected more abrupt differences in Moran’s I statistic between seasons 2003 and 2004-2005. However the variograms indicate there is generally a spatial structure to between-vine variation in season 2004. Season 2005 is characterised by flat variograms across all variables modelled, indicating a non-spatial distribution to between-vine variation and this is reflected in the low Moran’s I statistic in that year (Table 5.3).

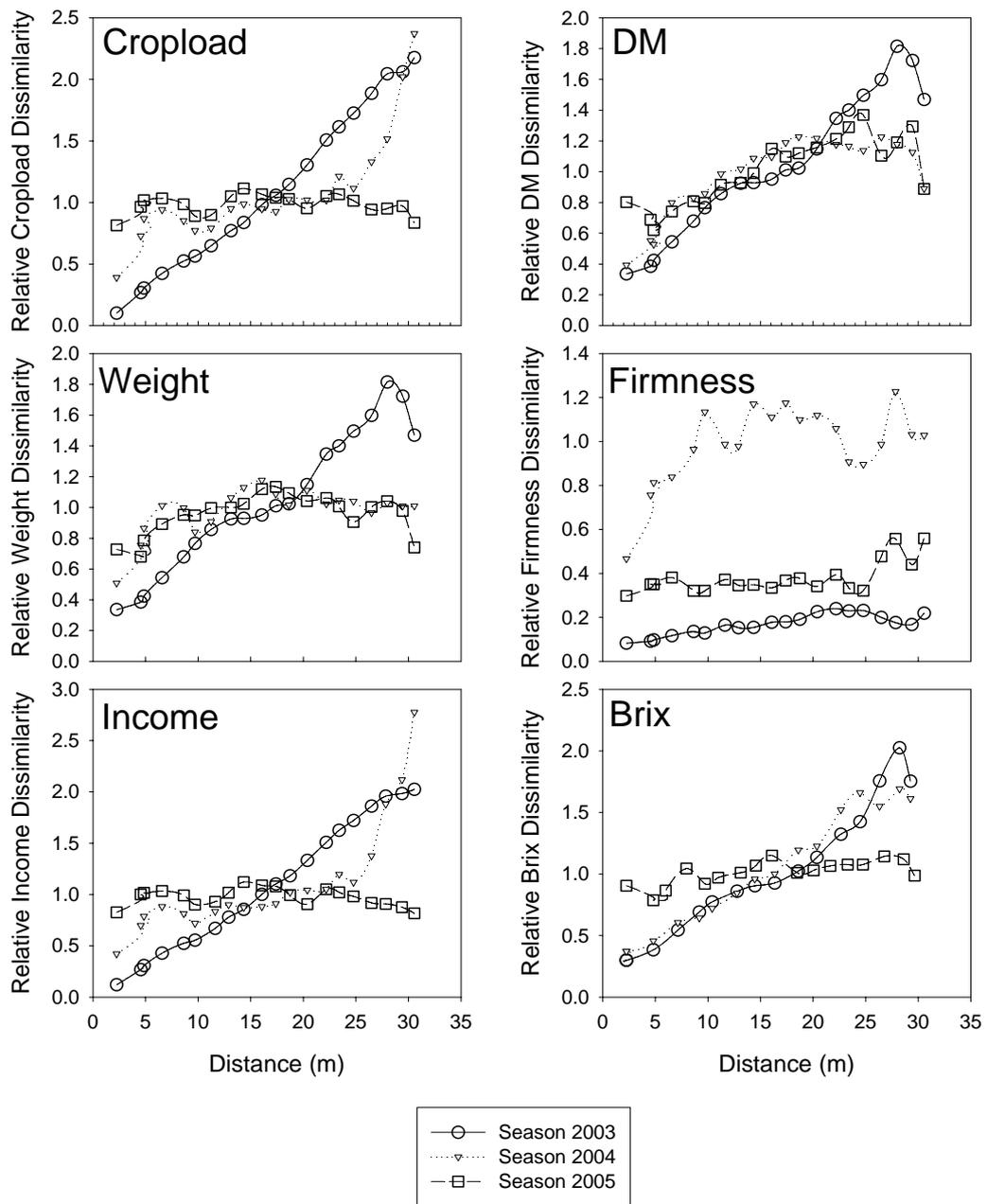


Figure 5.2. Spatial models of between-vine variation in fruit quality characteristics of Hayward kiwifruit vines. Variograms used to model the overall spatial correlation within each season. Experimental variograms were calculated for each season and points connected with lines to illustrate trends only.

Table 5.2. Accuracy of variograms in modelling between-vine variation in quality characteristics. Correlations between predicted vine characteristics and measured vine characteristics across consecutive growing seasons.

Vine Characteristic	Period	R²	P
Income	Season 2003	0.80	< 0.01
	Season 2004	0.16	< 0.01
	Season 2005	0.19	< 0.01
Cropload	Season 2003	0.78	< 0.01
	Season 2004	0.37	< 0.01
	Season 2005	0.17	< 0.01
Average Fruit Weight	Season 2003	0.77	< 0.01
	Season 2004	0.40	< 0.01
	Season 2005	0.39	< 0.01
Average Fruit DM	Season 2003	0.72	< 0.01
	Season 2004	0.67	< 0.01
	Season 2005	0.35	< 0.01
Average Fruit Firmness	Season 2003	0.58	< 0.01
	Season 2004	0.51	< 0.01
	Season 2005	0.01	0.358
Average Fruit Brix	Season 2003	0.65	< 0.01
	Season 2004	0.65	< 0.01
	Season 2005	0.20	< 0.01

Table 5.3. Spatial structure of between-vine variation of Hayward kiwifruit quality characteristics across consecutive growing seasons (2003-2005). Spatial structure was quantified with Moran's I statistic.

Period	Quality Parameter					
	Income	Cropload	Weight	DM	Firmness	Brix
Season 2003	0.73	0.75	0.67	0.59	0.49	0.57
Season 2004	0.24	0.46	0.50	0.62	0.50	0.58
Season 2005	0.05	0.19	0.23	0.21	0.01	0.04

5.3.4 Vine groupings

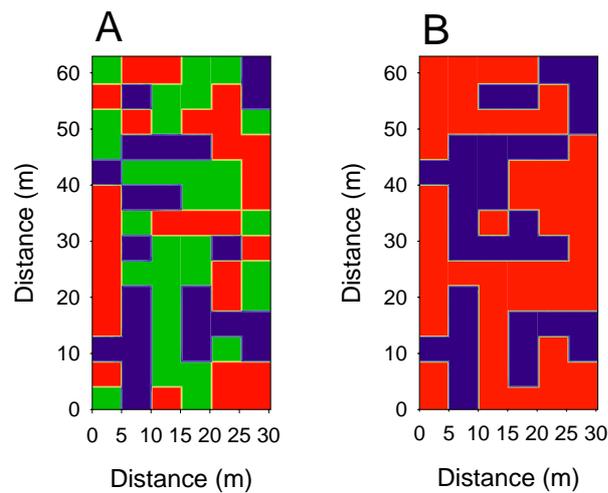
The temporal stability of the spatial patterns identified were investigated by grouping vines into consistently high and consistently low performing categories using the two different approaches of quartile scoring and *k*-means clustering; this was done to assess the feasibility of zonal management strategies. Both approaches identified similar vines within the orchard block that had consistent fruit quality characteristics across seasons (Figures 5.3 and 5.4), suggesting there was a temporally stable pattern to the location of these vines. Average fruit qualities responded in the same way whatever the grouping method used, (quality increased with increasing quartile score, and quality increased with cluster group), although the rate of response varied with season (Table 5.4). The fruit characteristics were significantly different between the vine populations identified.

To further test the validity of the vine income typings (high/low income) and quantify the contribution of individual fruit quality parameters to vine income, a discriminant analysis was conducted. This was able to correctly classify 83.7% of vines to their correct income type (high/low income, quartile scoring/clustering) based on season, vine cropload, average fruit weight and DM. Of the predictors, cropload was given the greatest weighting in the discriminant function, and further analysis demonstrated that cropload differed significantly ($P < 0.05$) between the high and low income vine types identified with quartile scoring and *k*-means clustering. This result demonstrates that vine income was determined primarily by vine cropload.

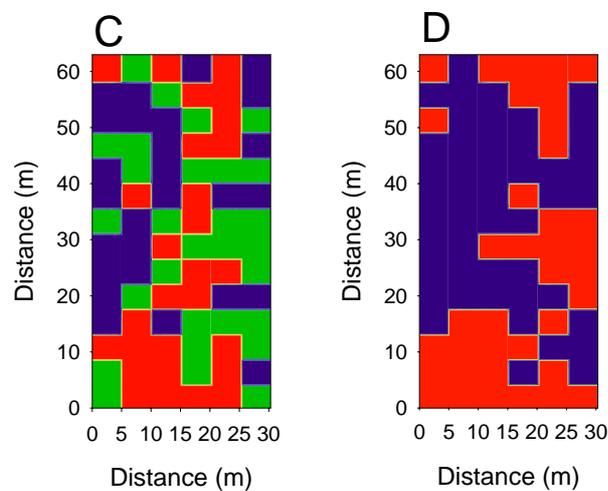
The spatial structure to the location of high and low quality vine populations was quantified with Moran's I statistic (Table 5.5). The values of < 0.50 for the vine populations identified for income, cropload, fruit firmness and DM at harvest indicate the spatial distribution of these vine populations within the orchard block was more random than spatially aggregated, and therefore not conducive to the adoption of zonal management strategies. Higher Moran's I statistics for the vine

populations identified for fruit weight (Figure 5.4 C-D) and maturity (Brix) at harvest (Figure 5.3 E-F) indicate these vines occupy more contiguous areas within the orchard block and may offer better opportunities for zonal management, however the spatial structure of these groupings was still weak (Moran's I 0.44 – 0.58).

Income



Firmness



Brix

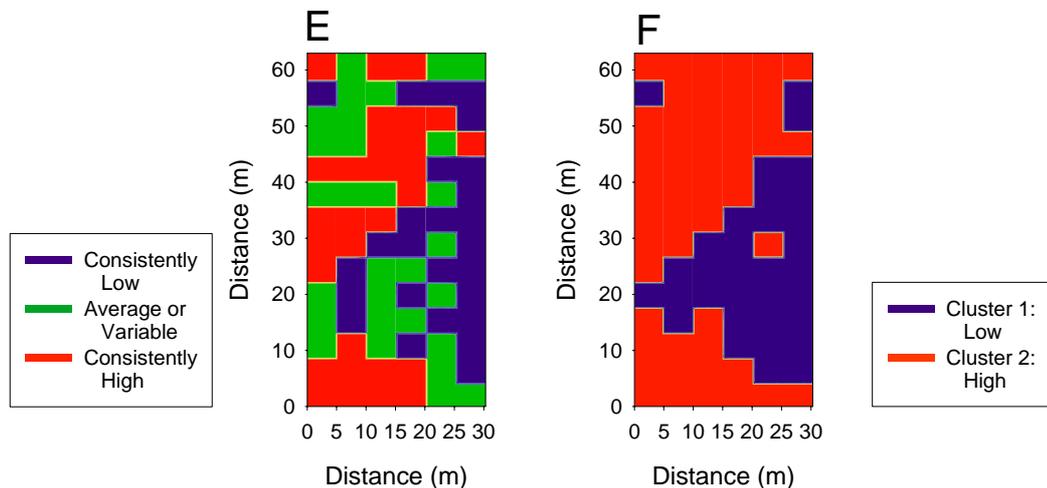
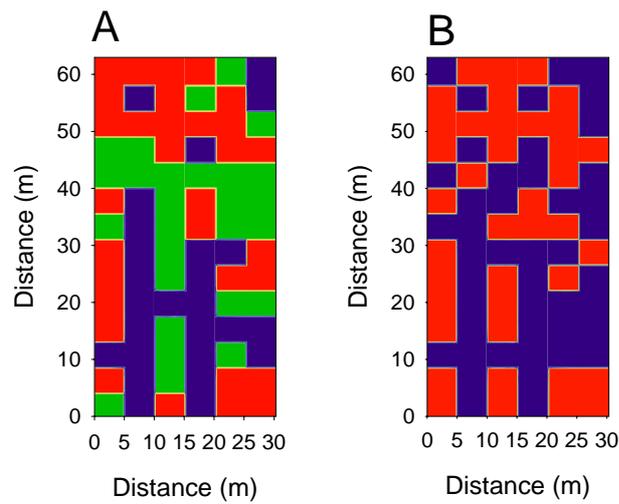
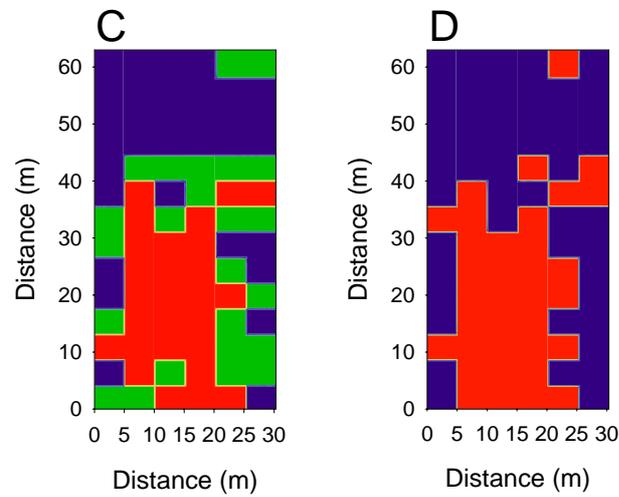


Figure 5.3. Location of Hayward kiwifruit vine Income, Firmness, and Brix populations within the orchard block. Vine populations with distinct quality profiles were delineated using quartile scoring (A,C,E) and k-means clustering (B,D,F) for vine income (A,B), average fruit firmness at harvest (C,D), and average fruit brix content (%) per vine (E,F). The properties of the vine populations are presented in Table 5.4. The x-axis represents rows and the y-axis the distance along rows, with each cell representing an individual vine.

Cropload



Weight



DM

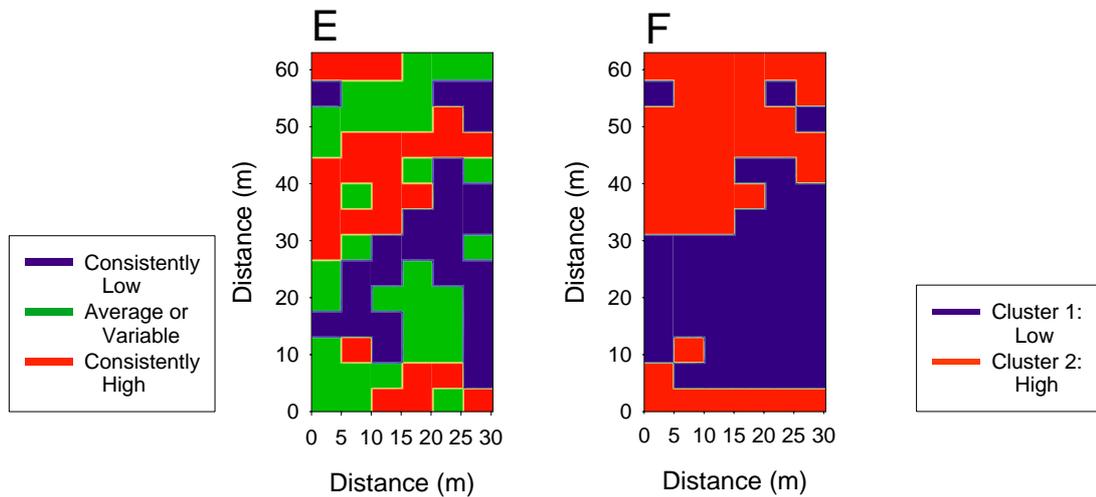


Figure 5.4. Location of Hayward kiwifruit vine Cropload, Weight and DM populations within the orchard block. Vine populations with distinct quality profiles were delineated using quartile scoring (A,C,E) and k-means clustering (B,D,F) for vine cropload (A,B), average fruit weight per vine (C,D), and average fruit dry matter content (%) per vine (E,F). The properties of the vine populations are presented in Table 5.4. The x-axis represents rows and the y-axis the distance along rows, with each cell representing an individual vine.

Table 5.4. Fruit quality characteristics of Hayward kiwifruit vine populations identified through *k*-means clustering and quartile scoring. Values presented are means \pm 1 SEM. For the quartile scoring approach, a score of ≤ 6 was considered to be consistently low, a score ≥ 9 was deemed to be high. Vines with intermediary scores (7-8) could not be distinguished between being consistently average across years to those vines whose performance has varied from year to year (as discussed in methods section).

Vine Parameter	Period	K – Means Clustering		Quartile Scoring	
		Cluster 1	Cluster 2	Low Quartile Score (≤ 6)	High Quartile Score (≥ 9)
Income (\$ per vine)	Season 2003	28.5 \pm 3.82	45.7 \pm 4.39	25.0 \pm 4.52	48.6 \pm 5.68
	Season 2004	104.8 \pm 4.49	140.6 \pm 3.64	107.9 \pm 6.08	143.0 \pm 5.23
	Season 2005	147.1 \pm 6.25	151.4 \pm 5.12	126.5 \pm 5.16	163.4 \pm 6.89
	All Seasons	93.4 \pm 5.71	112.6 \pm 4.61	86.5 \pm 6.14	118.3 \pm 6.38
Cropload (Fruit m ⁻²)	Season 2003	7.9 \pm 1.05	10.2 \pm 1.30	4.8 \pm 1.07	12.8 \pm 1.48
	Season 2004	30.6 \pm 1.12	39.4 \pm 1.16	28.5 \pm 1.46	40.6 \pm 1.34
	Season 2005	36.5 \pm 1.05	49.6 \pm 0.95	36.2 \pm 1.41	48.8 \pm 1.27
	All Seasons	25.0 \pm 1.23	33.1 \pm 1.68	23.2 \pm 1.69	34.1 \pm 1.78
Average Fruit Weight (g)	Season 2003	105.1 \pm 1.19	116.4 \pm 1.39	102.8 \pm 1.32	118.2 \pm 1.27
	Season 2004	96.2 \pm 0.46	100.7 \pm 0.51	95.4 \pm 0.55	101.4 \pm 0.52
	Season 2005	94.3 \pm 0.52	100.5 \pm 0.68	93.2 \pm 0.59	100.7 \pm 0.78
	All Seasons	98.5 \pm 0.60	105.9 \pm 0.91	97.2 \pm 0.66	106.7 \pm 1.04
Average Fruit DM	Season 2003	18.5 \pm 0.08	18.2 \pm 0.07	18.1 \pm 0.08	18.5 \pm 0.09
	Season 2004	15.9 \pm 0.03	16.4 \pm 0.03	15.9 \pm 0.03	16.4 \pm 0.03
	Season 2005	15.5 \pm 0.05	15.9 \pm 0.04	15.4 \pm 0.08	15.9 \pm 0.05
	All Seasons	16.6 \pm 0.12	16.9 \pm 0.09	16.5 \pm 0.14	17.0 \pm 0.13
Average Firmness (KgF)	Season 2003	5.64 \pm 0.04	6.21 \pm 0.05	5.66 \pm 0.06	6.10 \pm 0.07
	Season 2004	7.93 \pm 0.12	8.80 \pm 0.17	7.67 \pm 0.13	9.12 \pm 0.16
	Season 2005	8.40 \pm 0.06	8.04 \pm 0.12	7.99 \pm 0.09	8.39 \pm 0.14
	All Seasons	7.32 \pm 0.11	7.68 \pm 0.13	7.11 \pm 0.13	7.87 \pm 0.16
Average Fruit Brix	Season 2003	8.88 \pm 0.11	8.96 \pm 0.09	8.65 \pm 0.12	9.19 \pm 0.11
	Season 2004	8.43 \pm 0.07	9.15 \pm 0.03	8.39 \pm 0.08	9.19 \pm 0.03
	Season 2005	7.04 \pm 0.04	7.38 \pm 0.03	7.04 \pm 0.05	7.45 \pm 0.03
	All Seasons	8.12 \pm 0.09	8.49 \pm 0.07	8.03 \pm 0.10	8.61 \pm 0.10

Table 5.5. Spatial structure of Hayward kiwifruit vine populations identified as producing consistently distinct fruit qualities across consecutive growing seasons (2003-2005). Spatial structure was quantified with Moran's I statistic.

Vine Parameter	Population Grouping	
	Quartile Scoring	Clustering
Income	0.18	0.19
Cropload	0.42	0.13
Weight	0.57	0.50
DM	0.46	0.30
KgF	0.45	0.30
%Brix	0.44	0.58

5.3.5 Relationship between income and Gini coefficient

The results presented in section 5.3.2 suggest that there was a positive relationship between orchard area income and vine homogeneity (a negative relationship with the value of G). The Gini coefficients for the populations of high and low income vines identified by quartile scoring and clustering were determined and correlated with the average income of each vine wealth group (Figure 5.5). As predicted the high income groups had lower Gini coefficients than those of the low income groups, meaning high income groups were characterised by a greater level of homogeneity between vines.

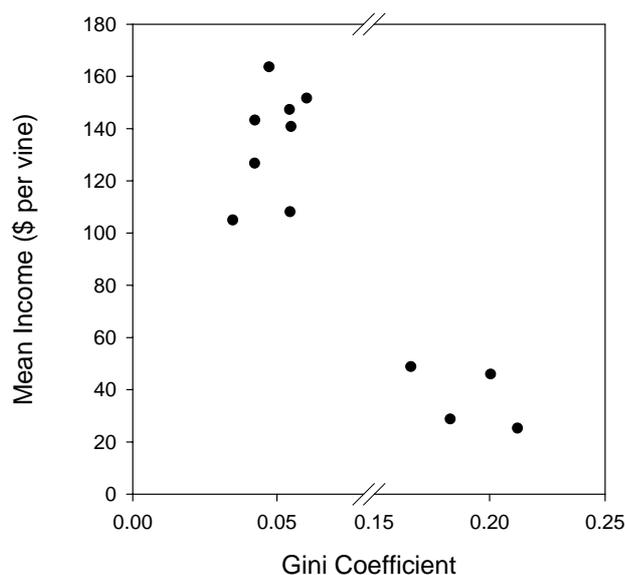


Figure 5.5. Relationship between income and Gini coefficient (G) of Hayward kiwifruit vines: Comparison between high and low income vine populations as identified by quartile scoring and clustering for each season studied (2003-2005).

5.3.6 Within-vine variation in fruit dry matter content

As in the previous chapter, the analysis has focussed on between-vine variation of average values of quality characteristics – variation in quality occurring *within* a single vine, and how such variability varies between-vines is also of interest, (refer to section 4.4.5). Measures of variation in fruit DM are incorporated in indexes used by industry to identify high DM fruit-lines (Zespri International Ltd, 2005a). Within-vine variation in fruit DM was highest in the ‘frost’ season of 2003 and was both lower and less variable between-vines in the subsequent ‘normal’ seasons of 2004 and 2005 (Table 5.6 and Appendix 9.7). Within-vine variation in fruit DM varied more between vines than did average fruit DM values, and varied more than did average fruit brix and average fruit weight (Table 5.1).

The similarity in the location of vine groupings within the orchard area obtained by the two approaches of quartile scoring and k -means clustering was suggestive of the spatial distribution of within-vine variation in DM being temporally stable

(Figure 5.6). Moran's I statistic was used to quantify both the spatial structure of between-vine variation in within-vine variation in DM and the spatial structure of the vine groupings identified by quartile scoring and *k*-means clustering (Table 5.8). Moran's I approximating 0 indicated a random spatial structure; vines producing fruit with similar levels of variation in DM were not located in contiguous zones within the orchard area.

Table 5.6. Summary statistics for within-vine variation in dry matter content of Hayward kiwifruit vines across consecutive seasons (2003-2005). n=84 vines. Within-vine variation was quantified as standard deviation in DM; Between-vine variation in within-vine variation in DM was quantified as the standard deviation between-vines.

Period	Average Within-vine Variation	Variation Between-vines
2003	0.85	0.13
2004	0.62	0.06
2005	0.62	0.08

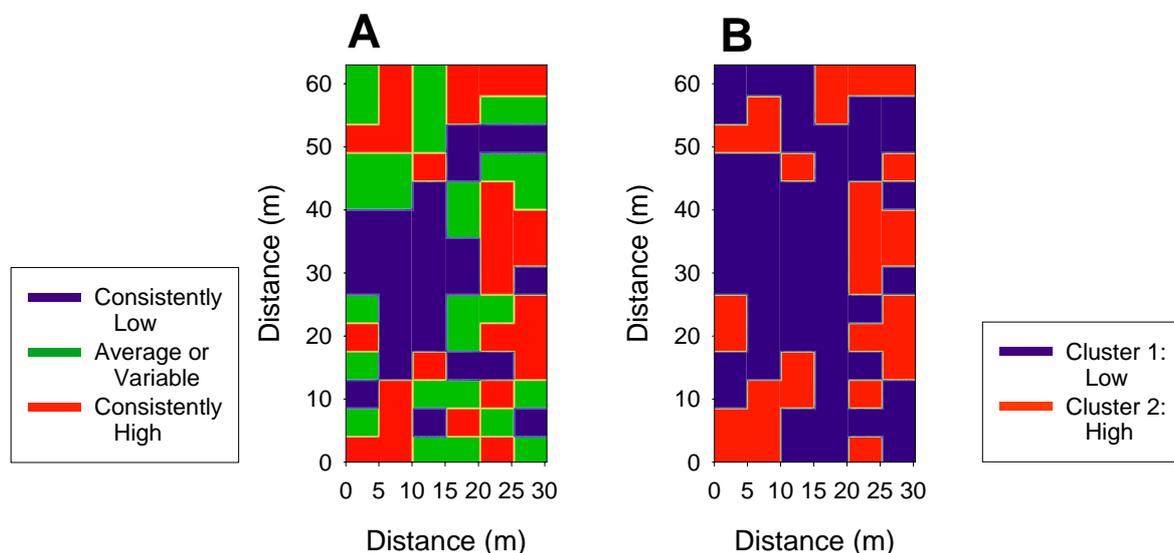


Figure 5.6. Location of Hayward kiwifruit vine populations within the orchard block delineated on the basis of within-vine variation in fruit dry matter content using quartile scoring (A) and *k*-means clustering (B). The x-axis represents rows and the y-axis the distance along rows, with each cell representing an individual vine. The properties of the vine populations are presented in Table 5.7.

Table 5.7. Within-vine DM variability characteristics of Hayward kiwifruit vine populations identified through *k*-means clustering and quartile scoring. Values presented are means \pm 1 SEM. For the quartile scoring approach, a score of ≤ 6 was considered to be consistently low, a score ≥ 9 was deemed to be high. Vines with intermediary scores (7-8) could not be distinguished between being consistently average across years to those vines whose performance has varied from year to year (as discussed in methods section).

Period	K – Means Clustering		Quartile Scoring	
	Cluster 1	Cluster 2	Low Quartile Score (≤ 6)	High Quartile Score (≥ 9)
Season 2003	0.80 \pm 0.01	0.94 \pm 0.03	0.79 \pm 0.02	0.93 \pm 0.02
Season 2004	0.59 \pm 0.01	0.68 \pm 0.01	0.58 \pm 0.01	0.67 \pm 0.01
Season 2005	0.60 \pm 0.01	0.66 \pm 0.02	0.56 \pm 0.02	0.68 \pm 0.02
All Seasons	0.67 \pm 0.01	0.76 \pm 0.02	0.64 \pm 0.01	0.76 \pm 0.02

Table 5.8. Spatial structure of within-vine variation in DM between vines of Hayward kiwifruit across consecutive growing seasons (2003-2005). Spatial structure was quantified with Moran’s I statistic.

Level	Spatial Structure	Moran’s I
Individual Vines	Season 2003	0.17
	Season 2004	0.15
	Season 2005	0.46
Vine Groupings	Quartile Scoring	0.35
	Clustering	0.22

5.4 Discussion

5.4.1 Magnitude of between-vine variation

If zonal management strategies are to be pursued it is important that the magnitude of variation be first examined. If the magnitude of variation is too small to economically justify the additional cost of zonal management then uniform management is the preferred management strategy (Cuppitt & Whelan, 2001). A comparison of the levels of variability observed between-seasons illustrates that 2003 was the most variable and least equitable season with the greatest potential for zonal management. The subsequent seasons of 2004 and 2005 displayed reduced but still significant levels of between-vine variation and inequality. Between- and within-seasons, in order of increasing magnitude of between-vine variation, were average DM, weight, Brix, within-vine variation in DM, firmness at harvest, vine income, and cropload. In terms of magnitude of variation, cropload offered the greatest potential for zonal management and average fruit DM the least.

5.4.2 The spatial component to between-vine variation

The previous components of variance study (section 2.4.3) quantified the contribution of between-vine variation to the total variance in fruit quality traits. This chapter illustrated that there was a spatial component to this between-vine variation within an orchard area. There was a temporally stable spatial pattern to between-vine variation; therefore between-vine variation was neither solely a random vine effect nor attributable to spatial patterns arising from transient climatic events.

The spatial component of between-vine variation was modelled using standard geostatistical approaches. Validation of the spatial models demonstrated that

spatial variation was well described in the ‘frost’ season of 2003 and less so in the subsequent ‘normal’ seasons of 2004 and 2005. It was concluded that the frost event of 2003 produced extreme spatial variation as vines were differentially affected. The spatial relationships in 2004 and 2005 were weaker and different in nature to those seen in 2003 indicating that the primary drivers of spatial variation had changed. Despite the variable magnitude of spatial relationships between seasons, temporally consistent spatial patterns in the distribution of fruit quality traits across the orchard area were identified. Previous research has not always found variation in cropping systems to be spatially consistent. Variation in grain yields has been reported as being spatially inconsistent from year to year in a continuous maize-soybean cropping system (Lamb et al., 1996). In other instances temporally stable spatial variation has been reported for grape (Bramley & Hamilton, 2004; Bramley, 2005), apple (Praat et al., 2003a), and in the case of kiwifruit some limited temporally consistent spatial variation has been noted in fruit DM (Praat et al., 2005).

5.4.3 Potential for zonation of the orchard area

The approaches used in the present study to construct potential management zones used vine production measurements to directly identify areas within the cropping system where plants respond similarly over years. Such methods assume that, if crop production patterns are similar over time, then the areas must respond similarly to weather variability and management inputs and may function as effective management zones (Lark & Stafford, 1997; Lark, 2001). Similar methods have been used previously to successfully delineate management zones for corn (Jaynes et al., 2003), wheat and maize (Yamagishi et al., 2003), and soybean (Jaynes et al., 2005). In the present study measures of kiwifruit quality were used and vines identified that consistently produced fruit of distinct qualities across seasons. The location of these vines within the orchard area was consistent across seasons. This is important as given a certain level of spatio-temporal stability in crop variability it is possible to use historical records to predict site-

specific responses for future crops, and conversely if temporal variability is high then historical data cannot be used with confidence for predictive management strategies (Pringle et al., 2003).

It proved possible to identify vines within the orchard test area that consistently produced fruit of distinctly different characteristics and to demonstrate that there was a consistent spatial pattern to the location of these vines. However, practical zonation of the orchard area was difficult and adoption of zonal management is probably unfeasible. No vine population was identified that consistently produced ideal fruit (high croploads of large sized, high DM fruit). Each quality trait exhibited a unique spatial distribution within the orchard area so that any zonation would need to be based on individual traits or groups of traits depending on whether zonation of each management intervention or entire management system was pursued (as per chapter 4). Discriminant analysis revealed that income and between-vine variation in income was primarily determined by cropload. However, as payment schedules move towards a greater weighting on fruit quality attributes, volume will no longer be the key driver of income. Indeed, within the New Zealand industry, the taste payment (based on fruit DM content) of the 2005 season was 20% and 55% of total fruit value for Hayward and Hort16A kiwifruit respectively (Zespri International Ltd, 2005a). An increased impact of fruit quality on financial returns may provide impetus for zonation of kiwifruit production areas based on fruit quality traits.

The location of vines consistently producing fruit of different weights and Brix contents illustrated greater aggregation than that noted for the other characteristics investigated. The aggregation of these vine populations was more uniform and offered greater potential for zonation of the orchard area studied. Through zonation on the basis of maturity (Brix) there is the prospect to harvest part of the block earlier. This could reduce reject rates through reduced exposure to adverse weather conditions and potentially earn additional premiums for early supply of fruit. Zonation of the orchard block on the basis of fruit size could enable orchard management to be targeted to specific areas of the orchard typically producing smaller sized fruit.

In regards to vine croploads, average DM, variability in DM and average fruit firmness at harvest, the lack of aggregation in the location of the high and low quality vine populations identified does not lend itself to effective zonation of the orchard area and suggests uniform management practices may be more appropriate. Cropping systems exhibiting strong spatial structure, such as contiguous zones of similar crop productions are more conducive to site-specific management practices (Pringle et al., 2003). The caveat to the present findings is that the orchard area studied was relatively small, larger production areas may display a greater degree of temporally stable spatial variation and be more favourable for effective zonation of production areas. Indeed the majority of previous PA investigations have focused on broad acre cropping systems over larger production areas than that studied here (Jaynes et al., 2003; Yamagishi et al., 2003; Jaynes et al., 2005).

The general lack of aggregation in the location of vines with similar quality characteristics suggests that the spatial patterns identified were the result of individual vine effects rather than environmental effects. These vine effects may be genetic, resulting from the use of seedling rootstocks, or the cumulative impact of the individual vine histories. Differences in early growth and development are compounded with time, leading to highly dynamic patterns in the structure of populations (Harper, 1977). Presumably such differences would be exacerbated in a perennial cropping system such as kiwifruit.

5.4.4 Describing variation with Lorenz curves and Gini coefficients

The agronomic relevance of G was that high income vine groups were more homogeneous (lower G) compared to low income vine populations (higher G , greater inequality between vines). However, the relationship between G and income could be considered to be largely driven by the difference between season 2003 and the 2004-05 seasons. The spring frost event led to higher Gini coefficients in season 2003 as vines were differentially affected, as such

differences in G could be damage related as opposed to yield potential related. Pan et al. (2003) used Lorenz curves and Gini coefficients to characterise variation in wheat crops along a gradient of water availability in China. They found an inverse relationship between harvest index and G , which is consistent with the inverse relationship between grain yield and G identified by Sadras and Bongiovanni (2004) and the inverse relationship between vine income and G suggested from the present work. Pan et al. (2003) reported the range of G between wheat crops to be from 0.067 to 0.190, while the study of Sadras and Bongiovanni (2004) observed a range of 0.027 to 0.191 in G . These reported values of G are comparable to those observed in the present study (0.035 – 0.212). The use of Lorenz curves enabled Sadras and Bongiovanni (2004) to readily illustrate that 50% of a maize crop contributed approximately 20% of paddock yield; they noted this information was valuable to growers yet was not self evident from yield maps. In the present study Lorenz curves illustrated the inequalities between vines in wealth generation across a single orchard area over time.

Pringle et al. (2003) highlighted the importance of deciding whether a crop displays enough variation - both in terms of magnitude and spatial distribution – to warrant a change from uniform management to site-specific management. Lorenz curves and G potentially provide this information – presenting crop heterogeneity in terms of inequality, and highlighting the relative contribution of low- and high yielding sections of the block to total orchard block income. There is a need to identify a threshold G value which indicates that variation is of a sufficient magnitude to justify a change from uniform management. A further issue is that in assessing the potential for zonal management, Lorenz curves and G provide no information of the spatial nature of the variation.

5.5 Conclusion

The initial hypothesis can be accepted that there are vine populations consistently producing fruit of distinct qualities and that there is a spatial structure to the location of such vines within the test orchard area. There is significant variation between-vines in the quality of fruits produced across a single uniformly managed orchard area. There is some consistency across time to the performance of vines, and within the orchard area vines could be identified that behaved in similar ways across years. The second hypothesis, that the spatial aggregation of vines producing fruit of distinct qualities was of sufficient magnitude to enable practical zonation of the orchard area, is rejected for the production area investigated.

The general lack of aggregation in the location of vines with consistent performance and the location of vine groups being unique for each quality characteristic make the adoption of zonal management strategies impractical in the test orchard area. A single zone consistently producing fruit of high quality in all attributes investigated could not be identified. Despite the magnitude of variation, the lack of spatial structure in between-vine variation within the small orchard area studied and the between-vine scale of the variation has negative implications for the adoption of zonal management strategies.

Chapter 6: Temperature effects on Hayward fruit quality.

6.1 Introduction

In section 1.9.1.1 the current state of knowledge on the impact of temperature on kiwifruit quality was reviewed with the accepted consensus being that temperature is the key driver of all crop development. In chapter 4 spatial variation in Hayward fruit quality characteristics were examined across a growing region and orchard altitude was found to correlate with many aspects of fruit quality. It was suggested that differences in orchard altitude would equate with differences in growth temperatures and that these differences in growth temperatures were the primary determinant of the observed variation in fruit quality between orchards. In the present study agrometeorological models were used to examine the relationship between growth temperatures and subsequent fruit DM at harvest. Such an analysis can provide insights into the periods during fruit growth when temperatures influence fruit development, and whether the influence is positive or negative. Secondly, the effect of temperature on canopy development and maturation was investigated in an attempt to elucidate a potential physiological mechanism for temperature effects on fruit development.

6.1.1 Temperature affects fruit quality development in fruit crops

The literature indicates that climate is the primary determinant of crop yield and quality with temperature being the key driver of all crop development. Photosynthesis in apple is at an optimum at temperatures of 30°C while the optimum for fruit growth is 25°C (Lakso et al., 1995). In the case of glasshouse grown tomato, low temperatures reduced absolute volume growth rates and

delayed the time at which the absolute growth rate became maximal (Adams et al., 2001). Warmer temperatures throughout grape development produce berries with higher total soluble solids levels (Tonietto & Carbonneau, 2004). There is a high correlation between cumulative temperature above 10°C during grape development and sugar concentration in berries (Dokoozlian & Kliewer, 1996; Bergqvist et al., 2001). Photosynthesis is near its optimum in grapes between 18-35°C while optimum temperatures for berry growth are between 20-25°C (Ribereau-Gayon, 2000). Many studies have shown that temperature influences kiwifruit vine and fruit development (Hopkirk et al., 1989; Gorini & Lasorella, 1990; Hall et al., 1996; Seager et al., 1996; McPherson et al., 2001a; Richardson et al., 2004; Snelgar, 2004; Snelgar et al., 2005a; Snelgar et al., 2006), these are reviewed below.

6.1.2 Modelling Hayward kiwifruit dry matter content

Dry weight (DW) accumulation in Hayward kiwifruit during the growing season approximates a simple exponential curve (Richardson et al., 1997a), while fresh weight (FW) follows a more complex single- or double-sigmoid pattern (Hall et al., 1996). The interaction of the DW and FW accumulation curves gives the pattern for change in fruit DM. The differences between the DW and FW accumulation patterns suggest that the relative rates of uptake of water and carbohydrate by kiwifruit must change during the season (Hall et al., 2006). Such a change in accumulation patterns is not the case in some other fruit species, apple for example (Lakso et al., 1995), where the exponential pattern can be applied to fruit growth as a whole.

Hall et al. (2006) presented a model describing kiwifruit fruit development based on water and carbohydrate dynamics; this model was able to reliably describe the development of fruit DM during the growth period and the authors discussed how growth temperatures would influence model parameters (Hall et al., 2006).

Using average seasonal DM values across seven years from the Te Puke region (New Zealand), Snelgar et al (2006) modelled average DM at harvest as a function of growth temperatures. The authors found that, for the seasons 1997-2003, the average fruit DM was most highly correlated with average temperatures during the spring and summer growth periods:

$$\text{DM} = 17.6 + (0.57 \times T_{\text{November}}) - (0.50 \times T_{((\text{Jan} + \text{Feb} + \text{March}) / 3)}) \quad R^2 = 0.82$$

The addition of a term based on average temperatures during the autumn growth period improved the model fit ($R^2 = 0.91$) (Snelgar pers. com, 2006). The authors concluded that the model provides useful information on when temperature has an affect on fruit quality and whether the effect is positive or negative.

6.1.3 Temperature affects Hayward canopy development and vine carbon balance

Snelgar et al. (2005) reported on the response of fruit growth to changes in temperature and, from this same heating experiment, we analyse the response to elevated spring growth temperatures of canopy development, flower quality and photosynthesis on the same Hayward kiwifruit vines. The aim was to quantify canopy development and use the modelling framework of Greer et al. (2004) to predict what the effect of elevated growth temperatures would be on vine carbon balance in an attempt to understand the differences in fruit quality between heating treatments reported previously by Snelgar et al. (2005).

The hypothesis was that spring heating of vines would promote canopy development and maturation, and this would have beneficial effects on subsequent fruit growth. Previous studies on kiwifruit have shown that shoot elongation, leaf appearance rates, growth rates and photosynthesis are all optimal at 20-25°C and reduced at temperatures above 30°C and below 10°C (Laing, 1985; Morgan et al., 1985; Greer, 1996). Spring temperatures in the New Zealand kiwifruit growing

regions have been reported to be in the order of 12-15°C (Warrington & Stanley, 1986); spring heating of vines would move growth temperatures closer to the optimal range of 20-25°C. Buwalda et al. (1991) demonstrated that warmer early growth temperatures accelerated leaf maturation (Buwalda et al., 1991). From controlled environment studies, Greer et al. (2003) reported that shoot photosynthetic and respiration rates were affected by temperature, with a net carbon acquisition of 450 g shoot⁻¹ for 28/22°C-grown vines compared with 253 g shoot⁻¹ for 17/12°C-grown vines over an entire growing season (Greer et al., 2003). Thus it might be expected that vines grown under elevated temperatures have a larger pool of assimilate available for fruit growth. The results of Greer and Jeffares (1998) suggest that vines at cool temperatures will produce enough carbon to fully support either vegetative growth or fruit growth, but perhaps not both (Greer & Jeffares, 1998). Similarly, it has been suggested that kiwifruit fruit growth is particularly source-limited early in development (Buwalda & Smith, 1990). In contrast, because vines at warm temperatures produce significant surpluses of carbon, these vines should be able to fully support shoot and fruit growth. Fruit sink strength is also affected by temperature; fruit grown at elevated temperatures are stronger sinks earlier in development compared with fruit grown at cool temperatures (Greer et al., 2003).

The size and quality of kiwifruit flowers has also been shown to be important in determining final fruit size. Several authors have found that early flowers had larger ovaries with more locules and ovules than late flowers on the same vine and that they produced larger fruit (Lawes et al., 1990; Lai et al., 1990; Cruz-Castillo et al., 1992; Patterson et al., 1999). In the study of Patterson et al. (1999) ovary weight at flowering was closely related to final fruit weight at harvest and it was noted that final fruit size has been linked to receptacle or ovary size at anthesis in apple (Denne, 1963), apricot (Jackson & Coombe, 1966), and tomato (Bohner & Bangerth, 1988). McPherson et al. (2001) reasoned that, because flower bud differentiation of kiwifruit occurs only three weeks before budbreak, flower quality might be influenced by temperature conditions prior to anthesis (McPherson et al., 2001a).

6.1.4 Chapter goals

The model of Snelgar et al. (2006) for the influence of temperature on between-season variation in DM was tested against data from orchards within a single growing region within seasons. The hypothesis tested was that higher temperatures during the spring growth period have a positive effect on subsequent fruit DM.

The hypothesis was proposed that elevating spring growth temperatures would promote canopy development and maturation, lead to the production of higher quality flowers and production of a larger pool of assimilates for which fruit growth was a relatively stronger sink. As a result, heating would produce larger fruit with higher DM. The present study reports on the canopy and photosynthetic characteristics of spring heated vines in the previously published work of Snelgar et al. (2005) and used the approach of Greer et al., (2005) to model the effect of heating treatments on vine carbon balance. Snelgar et al. (2005) demonstrated that increasing temperature during spring advanced the date of flowering by 17 days and increased the rate of shoot elongation by $6 \text{ mm d}^{-1} \text{ }^{\circ}\text{C}^{-1}$. The fruit on these early flowering vines were larger and had a higher DM (+1.2 units) than control fruit during the first part of the season. The objective of the present study was to link these reported differences in fruit quality characteristics to differences in ovary size, early season canopy development, and carbon balance between spring heating treatments of Hayward kiwifruit vines and compare canopy growth trends with those observed in ‘real-world’ orchards.

6.2 Methods

6.2.1 Experimental design

Mature *Actinidia deliciosa* (A. Chev.) C. F. Liang et A. R. Ferguson var. *deliciosa* ‘Hayward’ kiwifruit vines were warmed 2 - 5 °C above ambient temperatures by enclosing them in temperature controlled plastic tunnel houses during the 2002 spring growth period. Heating treatments were applied for 6 weeks following budburst (18 October 2002 to 27 November 2002). For the heating period eight uncovered vines were used as ambient controls, four vines were heated by ~2.5 °C above ambient (warm), and four vines were heated ~5.0 °C above ambient (hot). The experimental design has been described previously (Snelgar et al., 2005a).

6.2.2 Field Monitoring

Eight commercial kiwifruit orchards were selected for monitoring from the Te Puke growing region (Bay of Plenty, New Zealand, 37°49’S, 176°19’E). Orchards were selected based upon historical records indicating production of a range of fruit qualities and were located at differing altitudes. We assumed that differences in orchard altitude would be reflected in differences in spring growth temperatures. Vine canopies were monitored at regular intervals from budburst until leaf drop with growth temperatures being logged hourly with temperature micro-loggers (HortPlus Ltd, Cambridge, New Zealand) suspended in the canopy from budburst through till leaf drop for the 2003 growing season.

6.2.3 Canopy and fruit development

Leaf area index (LAI) was determined for each vine by digital hemispherical canopy photography (Nikon Coolpix 990 camera fitted with an FC-E8 fisheye adapter) analyzed with Gap Light Analyzer v2.0 (Simon Fraser University, British

Columbia, Canada) following previously published methodology (Clearwater et al., 2004). Canopies of heated vines were photographed at regular intervals from 22 October until 3 December 2002; canopies of monitor orchards were photographed at regular intervals from 11 October 2002 through till leaf-drop in July 2003.

Fifty representative sun-exposed leaves for each heating treatment were randomly selected at regular intervals for determination of average leaf size per treatment. After removal of the petioles, lamina area was measured using a leaf area meter (LI3100, Li-Cor, Nebraska, USA). The leaves were then dried at 65°C to a constant weight.

As each heating treatment reached mid-bloom, the ovary diameter was measured on a selection of fully open flowers using electronic callipers (Bower Instruments, Bradford, United Kingdom). The callipers were modified to prevent compression of flower tissues by reducing the spring tension between the measuring arms and adding flat plates to the calliper jaws (McPherson et al., 2001a).

6.2.4 Photosynthesis

6.2.4.1 Photosynthetic surveys

Photosynthesis and stomatal conductance of leaves under ambient conditions were recorded during November 2002 using a portable photosynthesis system (LI6400, Li-Cor, Nebraska, USA). For these measurements, the light source was removed from the photosynthesis system, and chamber temperature set to the ambient air temperature of each treatment (15-20°C). Photosynthesis was recorded (13/11/2002) between 10.00 h and 15.00 h on randomly selected, fully expanded, sun-exposed leaves on non-terminating shoots. This assessment date equated to -14, -3 and 3 days post fruit set for vines in the ambient, +2.5°C and +5.0°C treatments. To compare ambient photosynthesis between heating treatments under light-saturated conditions, the data were filtered to exclude measurements when irradiance at the leaf surface was $<1200 \mu\text{mol m}^{-2} \text{s}^{-1}$.

To investigate ontogenetic differences in leaf development between heating treatments it was assumed that properties of the sequence of leaves down a shoot were representative of the developmental patterns of individual leaves under the various temperature regimes. Randomly selected non-terminated shoots were chosen and photosynthetic characteristics recorded for each leaf along the shoot from base to tip. Photosynthesis of leaves along selected shoots were measured with light intensity held at $1500 \mu\text{mol m}^{-2} \text{s}^{-1}$ and chamber temperature set to the ambient air temperature of each treatment (22-30°C).

Mean photosynthesis (A), stomatal conductance (g_s), and leaf internal CO_2 concentration (c_i) was compared using analysis of variance (ANOVA) with vine nested within heating treatment. Pairwise comparisons were conducted using the Tukey's HSD test at the 5% level.

6.2.4.2 CO_2 response (A/C_i) curves

The photosynthetic response of randomly selected, fully expanded, sun-exposed leaves to light and CO_2 was recorded on 21-22 November 2002 using a portable photosynthesis system fitted with an LED light source (LI6400 and 6400-02B, Li-Cor, Nebraska, USA). For these measurements the chamber temperature was set to the ambient air temperature of each treatment (17-22°C). Chamber CO_2 concentration was set to $385 \mu\text{mol mol}^{-1}$, declining to a minimum of 50 and then raised to a maximum of $1200 \mu\text{mol mol}^{-1}$ through the course of each A/C_i curve determination. Plots of photosynthesis as a function of intercellular CO_2 concentration (C_i) were fitted with the mechanistic model of von Caemmerer and Farquhar (1981) and the parameters J_{max} and V_{cmax} estimated by non-linear regression (Photosyn Assistant, Dundee Scientific, Dundee, UK). The mechanistic model of photosynthesis proposed by Farquhar et al. (1980) states that photosynthetic rate is the minimum of two possible limitations: Rubisco activity (represented by the parameter V_{cmax}) and electron transport or RuBP regeneration (represented by the parameter J_{max}) (Farquhar et al., 1980). These parameters are calculated from the CO_2 response (A/C_i) curve (von Caemmerer & Farquhar, 1981).

6.2.5 Carbon acquisition model

The model of Greer et al. (2004) extends that of Buwalda (1991) and is based on previous controlled environment studies on shoot leaf area expansion (Seleznyova & Greer, 2001), photosynthesis and carbon economy of kiwifruit shoots (Greer, 1996; Greer & Jeffares, 1998; Greer, 1999; Greer, 2001) and on canopy architecture (Seleznyova et al., 2002). Greer et al. (2004) demonstrated that the model when used in conjunction with a simple empirical approach to calculate canopy photosynthesis provided satisfactory estimates of carbon accumulation (Buwalda, 1991; Greer et al., 2004).

Rates of photosynthesis and respiration were multiplied by the subtending canopy leaf area of the sun and shade leaves for each hourly period over the course of heating. The resultant net acquisition of CO₂ was then summed over the sun and shade leaves to determine net carbon acquisition per unit of canopy area (m⁻²) over the heating period till flowering. Net carbon acquisition was calculated from the grams of carbon per µmol CO₂ (Greer et al., 2004).

6.2.6 Regression analysis: Fruit dry matter content at harvest and growth temperatures

Hourly temperatures were recorded in a subset of the orchards described in section 6.2.2 using temperature micro-loggers (HortPlus Ltd, Cambridge, New Zealand) suspended in the canopy. Measurements were initiated in the winter of 2002 and continued through till autumn 2005.

Each season when orchards attained commercial maturity (> 6.2 Brix) fruit DM was determined for each individual fruit on a commercial kiwifruit grader (Compac™ grading equipment, Auckland, New Zealand) fitted with an Near infra-red (NIR) grading system (Taste Technologies Ltd, Auckland, New Zealand).

The temperature model of Snelgar et al. (2006) was developed to describe between season variations in fruit DM, we tested this models suitability for describing between orchard variations in DM within seasons, using the published model parameters. New regressions incorporating terms of differing biological significance were developed in an attempt to improve model fits in describing between-orchard variation in DM compared to that of the model of Snelgar and co-workers (2006).

Growth temperatures were correlated with average fruit DM per orchard at the time of harvest using the REG procedure in SAS (SAS Institute Inc., 2003).

Growth temperature terms for the regression models were grouped by either calendar month, calendar seasons or fruit developmental stages. Calendar seasons were defined as being spring (October, November, December), summer (January, February, March), and autumn (April, May), no term for winter was used (Snelgar et al., 2006). Fruit growth developmental stages were defined as cell division (0-55 days after anthesis (DAA)), cell expansion (55-130 DAA) and cell maturation (>130 DAA) (Hopping, 1976).

6.3 Results

6.3.1 Canopy Development

Total canopy development varied strongly in response to spring temperature regime. Heating produced a curvilinear pattern of canopy development, while the ambient vine's canopy density developed in a linear fashion (Figure 6.1). The rates of canopy development were estimated from the slope of the linear portion of the LAI time courses (Figure 6.1), which showed the rates of canopy development in heated vines to be 2 - 2.5 times that of ambient vines. Rates of canopy development were $0.085 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$ and $0.072 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$ for heated vines ($+5.0^\circ\text{C}$ and $+2.5^\circ\text{C}$ respectively), compared with the $0.034 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$ for vines in ambient conditions (Figure 6.2a). Heating reduced the time taken to attain a full canopy and heated vines reached their maximal LAI more than 20 days earlier than vines under ambient conditions.

From the flowering dates reported previously for this experiment (Snelgar et al., 2005a), the modelled LAI at the time of fruit set was 2.51, 2.32 and 1.81 for $+5.0^\circ\text{C}$, $+2.5^\circ\text{C}$ and ambient vines respectively (Figure 6.1). When compared with the absolute maximal LAI reached by the vines, the LAI at fruit set were 93%, 92% and 87% of the final values for $+5.0^\circ\text{C}$, $+2.5^\circ\text{C}$ and ambient vines respectively (Figure 6.2b). Integration of the LAI time course data (Figure 6.1) provided an estimate of total leaf area per vine per treatment for the spring growth period of budburst through to flowering. Integrated LAIs per vine for the treatments were: 54.16, 81.77 and $94.43 \text{ m}^2 \text{ m}^{-2}$ for the ambient, $+2.5^\circ\text{C}$ and $+5.0^\circ\text{C}$ treatments respectively.

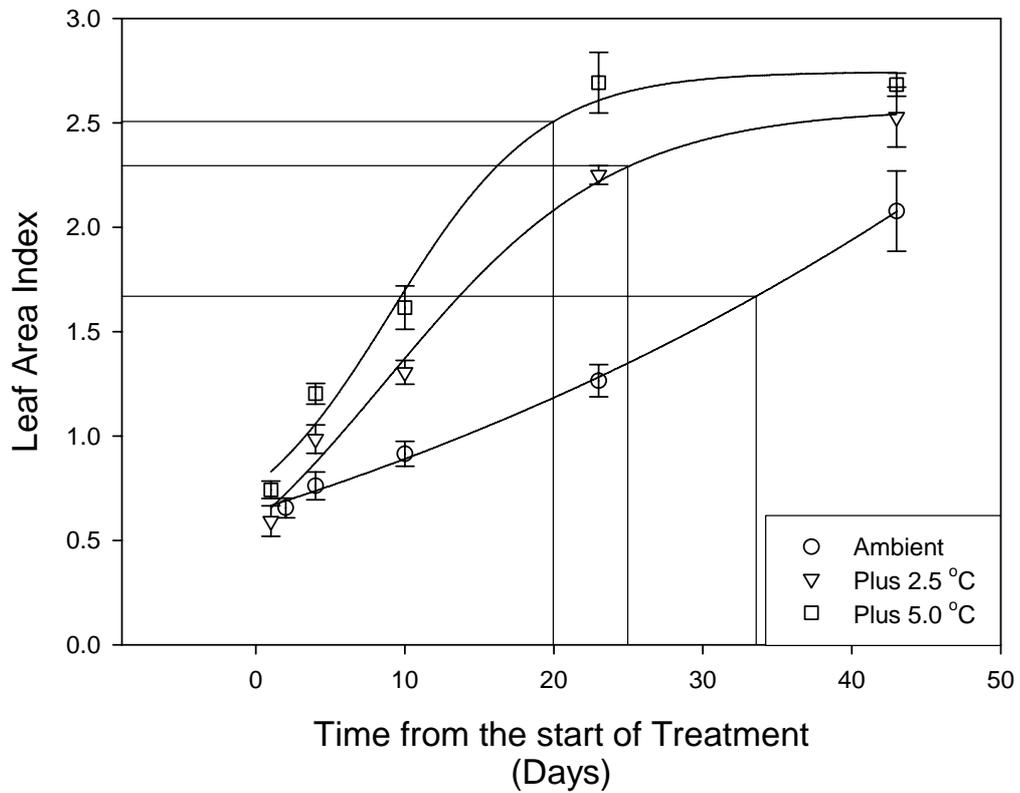


Figure 6.1. Time course of leaf area index (LAI) development of Hayward kiwifruit vines under differing growth temperature regimes from 22 October to 3 December 2002. The rate of canopy development was estimated by the slope of the linear portion of the LAI time course. Each point on the graph is the average vine LAI per treatment \pm 1 SEM, where 8 vines were under ambient conditions and 4 vines were under each heating treatment (+2.5°C and +5.0°C). Vertical lines represent the average time of fruit set per treatment, with horizontal lines estimating LAI at the time of fruit set.

Similar results were noted in the monitor orchards where rates of canopy development ranged from $0.019 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$ at the coolest orchard to $0.061 \text{ m}^2 \text{ m}^{-2} \text{ d}^{-1}$ at the warmest site (Figure 6.2a). The proportion of the maximal LAI attained by the time of flowering increased with growth temperature (Figure 6.2b). Heated vines in tunnel houses had attained a greater proportion of their maximal LAI by the time of flowering than that of monitor orchards at similar temperatures (Figure 6.2b). This may have arisen through a ‘greenhouse effect’, as opposed to a temperature effect; however the absence of an appropriate control (tunnel house covered vine grown at ambient temperature) means that it was not possible to quantify any such effect. Another possibility is that the difference between treatments was a pruning/management difference. Overall, the trend was that the higher the temperature during the spring growth period, the faster the rate of total canopy development and the greater the proportion of the maximal LAI reached by flowering (Figures 6.1 and 6.2).

6.3.2 Leaf Growth Rate

Across treatments, average leaf size per treatment increased in a curvilinear pattern. The rate of increase in average leaf size in heated vines was 2 - 2.5 times that of ambient vines (Figure 6.3). Rates of average leaf size increase were $8.41 \text{ cm}^2 \text{ m}^{-2} \text{ d}^{-1}$ and $7.24 \text{ cm}^2 \text{ m}^{-2} \text{ d}^{-1}$ for heated vines ($+5.0^\circ\text{C}$ and $+2.5^\circ\text{C}$ respectively), compared with the $3.4 \text{ cm}^2 \text{ m}^{-2} \text{ d}^{-1}$ for vines in ambient conditions. Heating also increased the final average size of fully expanded leaves. At the final assessment date heated vines had an average leaf size of 294 cm^2 and 297 cm^2 ($+5.0^\circ\text{C}$ and $+2.5^\circ\text{C}$ respectively), compared with the 222 cm^2 for control vines. Heating reduced the time taken for average leaf size to plateau ; average leaf size of heated vines stopped increasing ~14 days earlier than ambient vines.

Regressing the rate of total canopy development (linear slopes of LAI time courses per vine – summarized per treatment in Figure 6.1) against the time course of average leaf size (Figure 6.3) indicated both total canopy development

and leaf size increased in proportion suggesting the majority of early season canopy development was driven by leaf expansion ($R^2 = 0.83$).

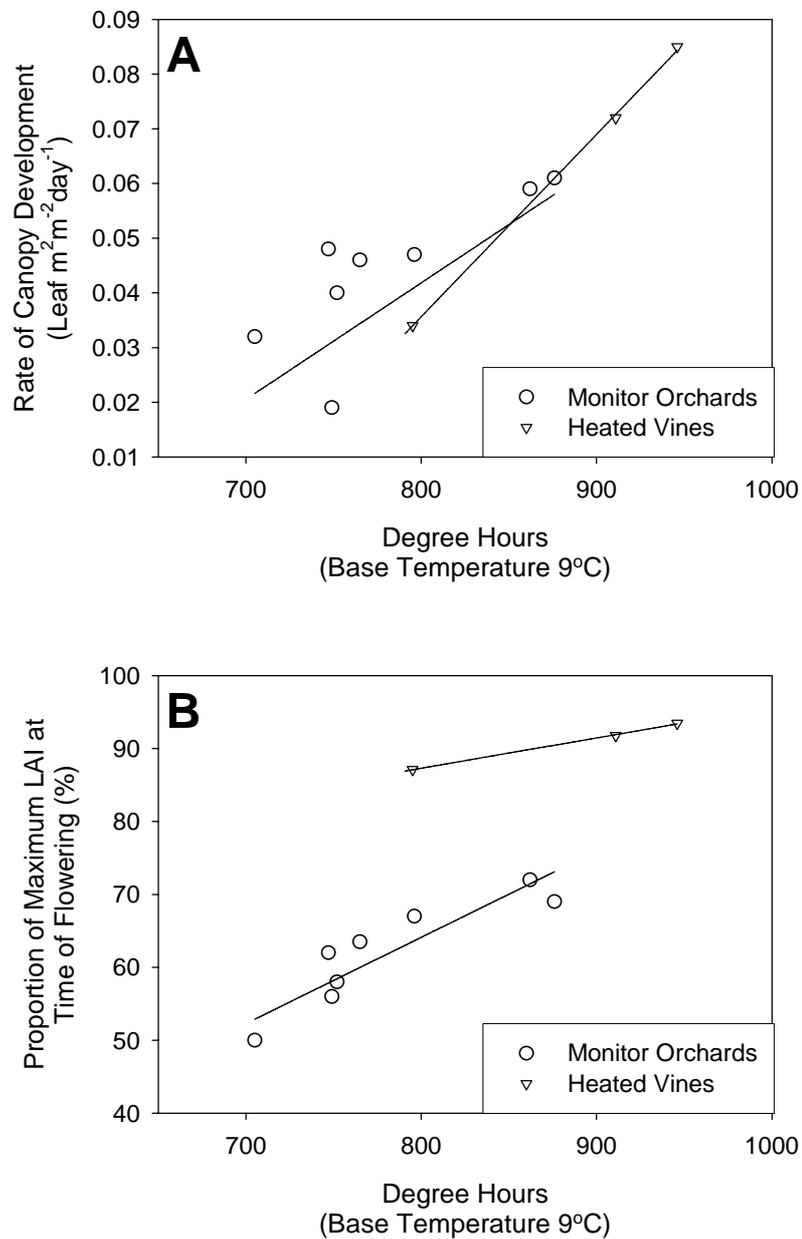


Figure 6.2. Relationships between Hayward kiwifruit canopy development and spring growth temperatures in monitor orchards and experimental vines during the period from budburst to flowering. A: Rate of canopy development (slope of linear portion of LAI time course) as a function of temperature; B: Percentage of maximal LAI attained by time of flowering as a function of temperature.

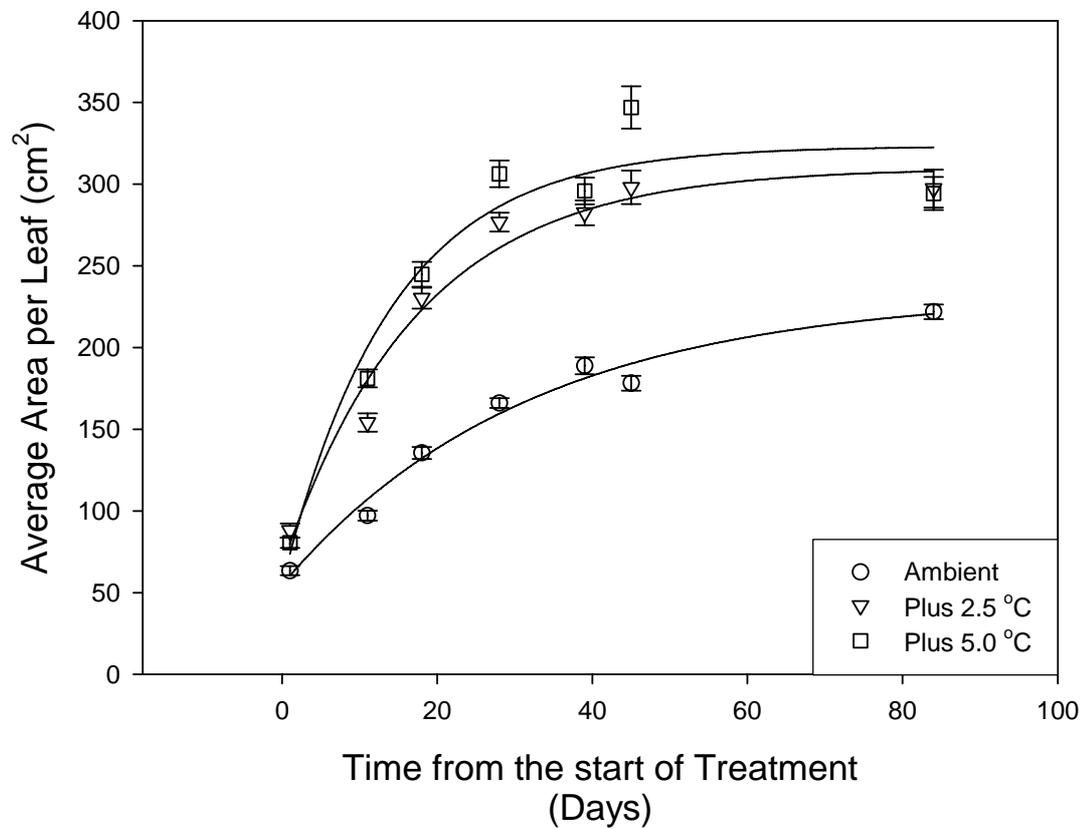


Figure 6.3. Timecourse of average leaf size of Hayward kiwifruit vines under differing growth temperature regimes from October 2001 to January 2002. The rate of increase was estimated from the slope of the linear portion of the curves. (Each point is the mean value of >50 leaves per treatment \pm 1 SEM).

6.3.3 Photosynthetic surveys

A , g_s , and $VpdL$ increased with increasing growth temperature (Table 6.1). The key result is that photosynthetic rates and stomatal conductance were higher at higher temperatures. There was no significant difference in C_i between heating regimes. The effect of the tunnel house plastic on light can be seen in the heated vines having lower ambient light levels (~23% lower) than the uncovered control vines (Table 6.1).

Table 6.1. Photosynthesis (A_{max}), Stomatal conductance (g_s), Leaf internal CO₂ concentration (c_i), Vapor pressure deficit (Leaf) ($VpdL$), and irradiance levels (PAR_i) of Hayward kiwifruit vines under differing growth temperature regimes. The data was filtered to exclude photosynthetic measurements where $PAR_i < 1200$. Values (means \pm 1 SEM) in the same row with different letters are significantly different (Tukey's HSD, $P < 0.05$).

Characteristic	Vine Temperature Regime		
	Ambient	Plus 2.5°C	Plus 5.0°C
Leaf Temperature (°C)	20.8 \pm 0.27 a	22.3 \pm 0.29 b	24.1 \pm 0.19 c
A ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)	8.93 \pm 0.57 a	10.36 \pm 0.84 a	17.03 \pm 1.57 b
g_s ($\text{mol H}_2\text{O m}^{-2}\text{s}^{-1}$)	0.124 \pm 0.006 a	0.126 \pm 0.011 a	0.291 \pm 0.046 b
c_i ($\mu\text{mol mol}^{-1}$)	238.2 \pm 6.16 a	217.09 \pm 6.86 a	230.54 \pm 5.66 a
$VpdL$ (kPa)	1.25 \pm 0.03 a	1.42 \pm 0.04 b	1.46 \pm 0.05 b
PAR_i ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	1808.16 \pm 58.42 a	1396.27 \pm 46.90 b	1397.72 \pm 32.41 b

6.3.4 CO₂ Response Curves

The relationships between the rate of CO₂ assimilation and the partial pressure of CO₂ in the intercellular spaces (AC_i curves) between the differing temperature regimes are presented in Figure 6.4. Analysis of the properties of the AC_i curves using the framework of the von Caemmerer and Farquhar (1981) mechanistic model of photosynthesis indicated there were significant differences in model parameters between temperature treatments (Table 6.2). There was a significant effect of heating on respiration ($P < 0.01$), V_{cmax} ($P = 0.04$) and the ratio of $J_{max}:V_{cmax}$ ($P < 0.01$); no significant difference between treatments was noted for the J_{max} parameter. Heating increased V_{cmax} without affecting the J_{max} parameter, and as a consequence the $J_{max}:V_{cmax}$ ratio declined.

Leaves used in the CO₂ response curve determination were destructively tested for specific leaf area (SLA); heating increased SLA (Table 6.3).

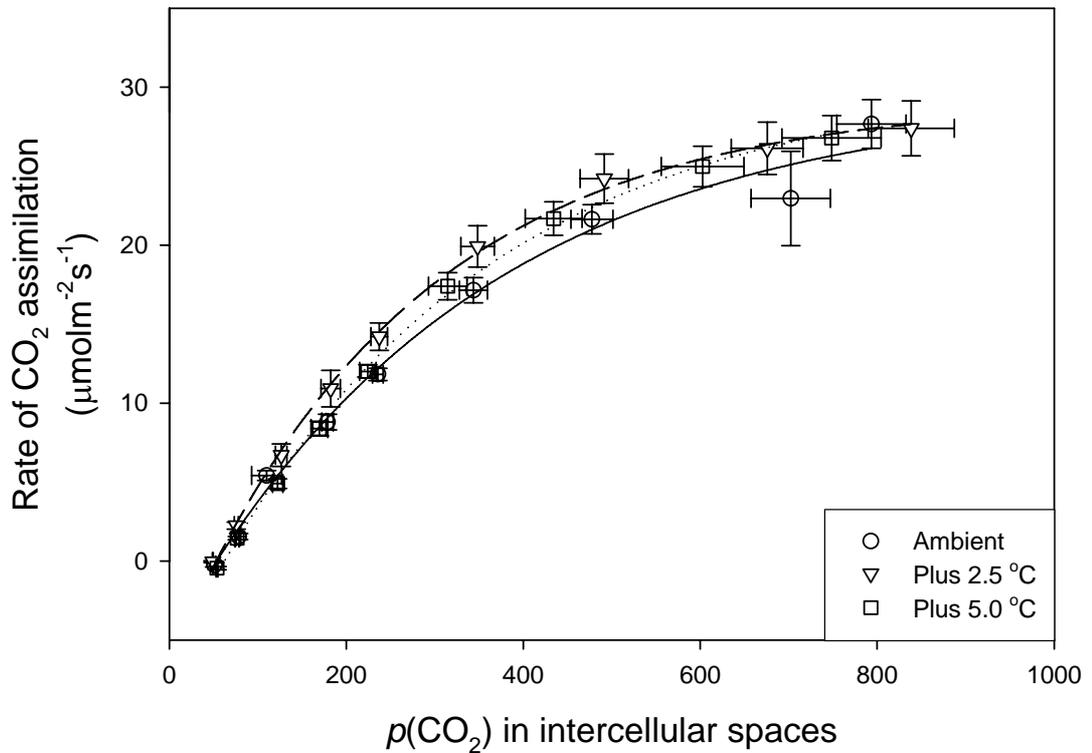


Figure 6.4. The relationship between the rate of CO_2 assimilation and the partial pressure of CO_2 in the intercellular spaces for Hayward Kiwifruit leaves under differing growth temperature regimes as at 21-22/11/2002. Each data point is the mean value of 10 leaves per treatment ± 1 SEM. Curves were fitted to illustrate trends between treatments: Ambient (solid line), Plus 2.5°C (dashed line), and Plus 5.0°C (dotted line).

Table 6.2. Parameters of the Farquhar and von Caemmerer (1980) mechanistic model of photosynthesis estimated from AC_i curves of Hayward kiwifruit leaves under differing growth temperature regimes as at 21-22/11/2002. Values (means \pm 1 SEM) in the same row with different letters are significantly different (Tukey's HSD, $P < 0.05$).

Characteristic	Vine Temperature Regime		
	Ambient	Plus 2.5°C	Plus 5.0°C
Leaf Temperature (°C)	21.35 \pm 0.92 a	23.63 \pm 1.13 b	28.07 \pm 1.30 c
Respiration ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)	2.43 \pm 0.08 a	1.23 \pm 0.13 b	1.55 \pm 0.21 b
J_{max} ($\mu\text{mol electrons m}^{-2}\text{s}^{-1}$)	154 \pm 9.21 a	156.5 \pm 11.01 a	144.8 \pm 11.88 a
V_{cmax} ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$)	46.19 \pm 3.16 a	50.51 \pm 3.13 a	59.12 \pm 3.96 b
$J_{\text{max}} : V_{\text{cmax}}$	3.35 \pm 0.07 a	3.12 \pm 0.20 a	2.44 \pm 0.06 b

Table 6.3. Growth temperature effects on leaf characteristics of Hayward kiwifruit vines. Values (means \pm 1 SEM) in the same column with different letters are significantly different (Tukey's HSD, $P < 0.05$).

Vine Temperature Regime	Specific Leaf Area ($\text{cm}^2\text{gDW}^{-1}$)
Ambient	78.37 \pm 3.94 b
Plus 2.5°C	99.19 \pm 6.49 a
Plus 5.0°C	92.48 \pm 12.99 ab

6.3.5 Photosynthetic maturation

Of the photosynthetic properties tested, only the progression of A and C_i between leaves down shoots varied significantly with growth temperature ($P < 0.05$). The patterns of photosynthetic rate (A) and internal leaf CO_2 concentration (C_i) along shoots, and how this varied in response to growth temperature are presented in Figure 6.5. Newly emerging leaves in elevated growth temperatures had higher A and lower C_i than emerging leaves in ambient conditions. Heating reduced the variation in A and C_i between distal and basal leaves; rates of A and C_i between leaves along shoots were more uniform when shoots were heated (Figure 6.5). Mature leaves under the $+2.5^\circ\text{C}$ regime were photosynthesizing at a higher rate than leaves in ambient and $+5.0^\circ\text{C}$ regimes. From distal to basal leaves along the shoot, general trends of increasing A and decreasing C_i with increasing leaf age were noted.

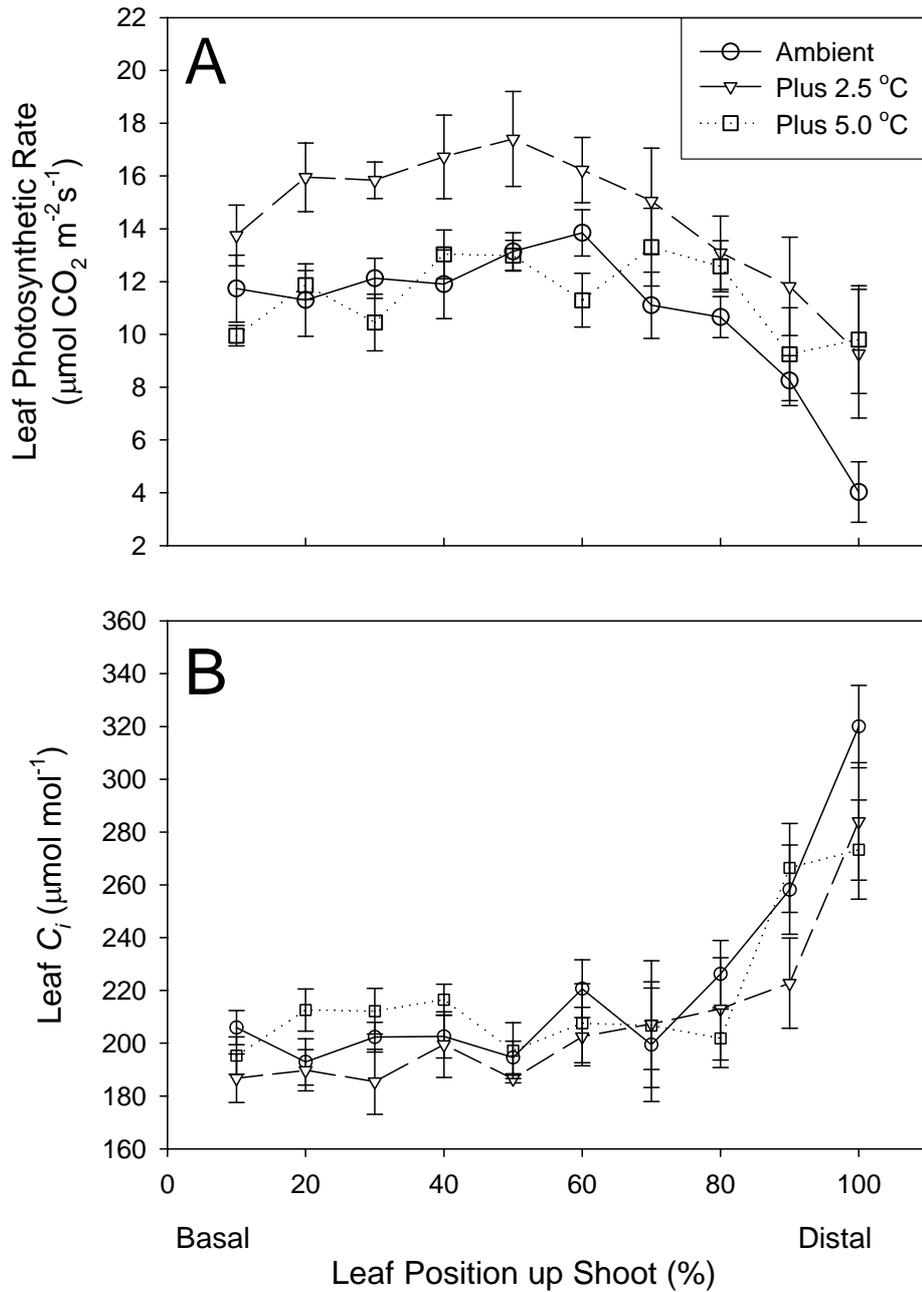


Figure 6.5. Photosynthetic properties of leaves along shoots of Hayward kiwifruit vines under differing growth temperature regimes. A: Leaf photosynthesis (A); B: Leaf internal CO₂ concentration (C_i). Leaf position along the shoot was standardized and assigned to positional groups; the points presented in the graph are the average photosynthetic property at that shoot position group ± 1 SEM.

6.3.6 Ovary Diameter

Ovary diameter was measured on randomly selected flowers at each treatment's mid-bloom date: 10/11/2002, 16/11/2002 and 27/11/2002 for +5°C, +2.5°C and ambient treatments respectively. Heating significantly reduced ovary diameter at flowering ($P < 0.01$), however no significant difference in ovary diameter was observed between the +2.5°C and +5.0°C treatments (Table 6.4).

Table 6.4. Ovary diameters of Hayward kiwifruit flowers under differing growth temperature regimes assessed at mid-bloom date. Values (means \pm 1 SEM) in the same column with different letters are significantly different (Tukey's HSD, $P < 0.05$).

Vine Temperature Regime	Average Ovary Diameter (mm)
Ambient	13.10 \pm 0.05 a
Plus 2.5°C	12.68 \pm 0.05 b
Plus 5.0°C	12.84 \pm 0.04 b

6.3.7 Net carbon acquisition

Following the modelling approach of Greer et al. (2004) the estimated net carbon acquisition per unit canopy area for the 7 day period up to flowering was 20.7, 21.89 and 31.41 g carbon per m² for ambient, +2.5°C and +5.0°C treatments respectively.

6.3.8 Modelling fruit dry matter content at harvest with temperature

The only model able to significantly describe the observed variation between-orchards within individual seasons was that using individual monthly means separated into day and night terms (Table 6.5 and Figure 6.6). However, this model was unable to significantly describe the observed between orchard variation in 2005. The previously published model of Snelgar et al. (2006) for prediction of between-season variation in average DM was the most suited for consistently describing the observed variation between-orchards within seasons (Figure 6.6). Neither inclusion of separate monthly terms, seasonal terms or terms for individual fruit developmental stages, nor separation of terms into day and night temperatures (either seasonal, or fruit developmental stage) improved model fits (Table 6.5).

Table 6.5. Correlations of predicted orchard average DM to observed orchard values using a range of temperature models over consecutive seasons (2002-2005).

Model	Season	n	R²	P
Snelgar et al. (2006) model	2003	6	0.51	0.11
	2004	9	0.21	0.22
	2005	5	0.51	0.18
Individual monthly means	2003	7	0.29	0.21
	2004	9	0.13	0.35
	2005	5	0.04	0.75
Individual monthly means divided into day and night terms	2003	7	0.83	< 0.01
	2004	9	0.51	0.03
	2005	5	0.12	0.57
Seasonal means divided into day and night terms	2003	7	0.11	0.47
	2004	9	0.17	0.27
	2005	5	0.17	0.49
Mean temperatures per fruit developmental stage	2003	7	0.02	0.76
	2004	9	0.28	0.14
	2005	5	0.53	0.16
Mean temperatures per fruit developmental stage divided into day and night terms	2003	7	0.49	0.08
	2004	9	0.07	0.50
	2005	5	0.29	0.35

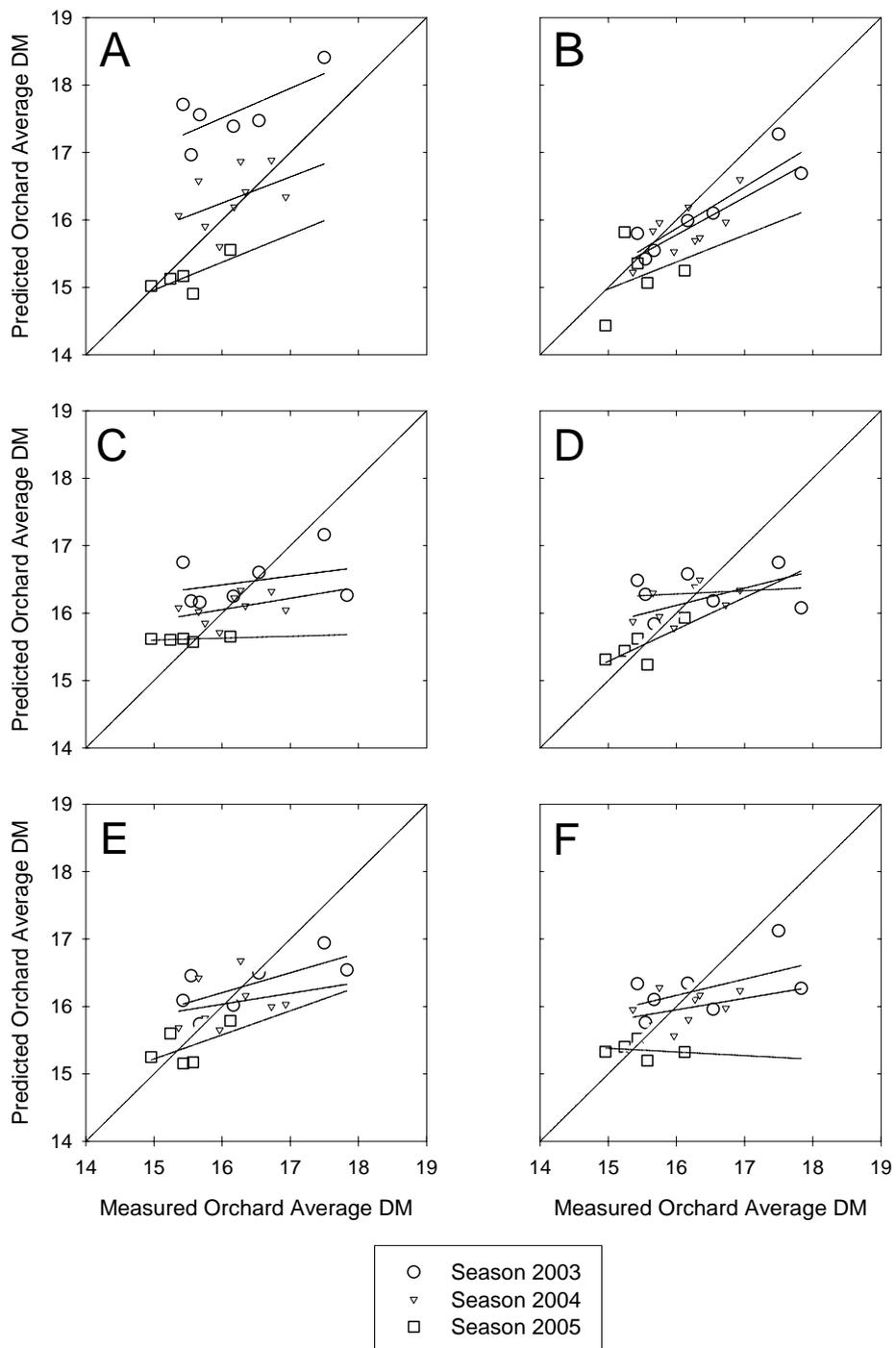


Figure 6.6. Linear relationships between predicted orchard average fruit DM and actual orchard average fruit DM over three consecutive seasons (2003-2005). A: Snelgar et al. (2006) model. B: Individual monthly means. C: Individual monthly means divided into day and night terms. D: Seasonal means divided into day and night terms. E: Mean temperatures per fruit developmental stage. F: Mean temperatures per fruit developmental stage divided into day and night terms.

6.4 Discussion

6.4.1 Modelling fruit dry matter content at harvest with temperature

The previously published model of Snelgar et al. (2006) was developed to understand between-season variation in fruit DM, yet this model also proved suitable for describing between-orchard variation within seasons. This illustrates that both between-seasons, and between-orchards within any given season, growth temperatures were associated with the quality of fruit produced and the effect of temperature varied during the growing season. High temperatures in spring were associated with higher fruit DM and high temperatures during summer with lower fruit DM. This conclusion is consistent with previous agrometeorological studies where it has been demonstrated that across 34 consecutive seasons ~60% of grain yield variability could be explained by meteorological variables and that different aspects of grain quality were differentially affected by growth temperatures at different developmental stages (Chmielewski & Kohn, 1999a; Chmielewski & Kohn, 1999b; Chmielewski & Kohn, 2000).

Refining the model of Snelgar et al. (2006) by better defining the timing of temperature effects by linking growth temperatures with the separate stages of fruit development (Hopping, 1976) did not improve the fit except for individual monthly means divided into night and day values. However, this model included many terms that reduced the associated degrees of freedom and model robustness.

The analysis implies that warm temperatures during the spring growth period will result in fruit with a higher DM, and this appears consistent both between-seasons and between-orchards within seasons. This could be due to either a direct effect of temperature on flower development and pollination (McPherson et al., 2001a), or an indirect effect such as higher temperatures accelerating canopy development and thus improving the supply of photosynthates to fruit at a critical time of the season (Piller et al., 1998). This latter hypothesis is explored below.

6.4.2 Canopy Development

Heating increased the rate of canopy development (Figure 6.1) and the rate of average leaf expansion (Figure 6.3). Between-orchards higher spring growth temperatures accelerated rates of total canopy development (Figure 6.2).

Regressing the rates of increase in average leaf size against the rate of total canopy development across heating treatments suggested the majority of early canopy development is driven by leaf expansion. Heated leaves had a larger final size than that of ambient leaves.

Similar results for the heating treatments were reported by Snelgar et al. (2005), where it was noted spring heating increased the rate of shoot elongation by $6 \text{ mm d}^{-1} \text{ }^{\circ}\text{C}^{-1}$, and that heated vines produced a much denser canopy. In early November, when all shoots were pruned so that 5 leaves remained past the last fruit, an average of 0.4 kg FW was removed from control vines, but 1.1 kg FW was removed from each hot vine (Snelgar et al., 2005a).

After the first cluster of kiwifruit leaves (initiated the previous season) has emerged at budburst, temperature increases the rate of appearance of leaves at the shoot tip, reduces the time between individual leaf emergence, the leaves expand faster to their final size, and reach a larger final size (Seleznyova & Greer, 2001). The accelerated rates of total canopy development (Figures 6.1 and 6.2) and average leaf size (Figure 6.3) occurring at elevated growing temperatures in the present study suggest that at any given time, heated vines will have more, and larger sized leaves.

6.4.3 Photosynthetic properties

6.4.3.1 Photosynthetic survey

The key finding was that when vines were heated in spring, photosynthetic rates and stomatal conductance were higher at elevated temperatures, with C_i being unaffected by temperature. These observations, that photosynthetic rates and

stomatal conductance were higher at elevated temperatures, agree with previous reports that demonstrated that maximal rates of Hayward kiwifruit leaf photosynthesis increase with growth temperature (Laing, 1985). A comparison of the light response curves of *Eucalyptus* plants demonstrated that the maximal rate of net photosynthesis was affected by the growth temperature (Battaglia et al., 1996). Previous work in which the contribution of stomatal conductance has been studied have agreed that this is a major factor in photosynthetic acclimation to changing growth temperatures (Makino et al., 1994; Correia et al., 1999; Ellsworth, 2000; Medlyn et al., 2002b). Under ambient light conditions we noted no significant relationship between C_i and growth temperature. Previously it has been illustrated that the ratio of intercellular to ambient CO_2 concentration, which reflects the coupling between stomata and photosynthetic CO_2 assimilation, was unaffected by elevated CO_2 concentration as well as by changes in light and temperature (Lambreva et al., 2005).

6.4.3.2 AC_i curves

Differences between heating treatments in parameters of the Farquhar et al. (1980) mechanistic model of photosynthesis presented in Table 6.2 indicated that increasing growth temperatures progressively increased the V_{cmax} parameter without affecting the J_{max} parameter and as a consequence decreased the $J_{\text{max}}:V_{\text{cmax}}$ ratio. The V_{cmax} parameter was 9% and 28% larger in +2.5°C and +5.0°C vines compared to that of vines in ambient conditions. Photosynthetic rates (A) were significantly higher in +5.0°C heated vines than those of ambient and +2.5°C vines; leaf internal CO_2 concentrations did not differ between temperature regimes (Table 6.1). Taken together these results suggest that vines under ambient and +2.5°C conditions were operating at similar points on a common AC_i curve while +5.0°C vines were photosynthesizing at a higher rate on a different AC_i curve. Consequently we conclude that heating of vines by +5.0°C affected the biochemical development of leaves. Changes in activities of Rubisco, other Calvin cycle enzymes, or electron transport with growth temperature have been frequently reported (Berry & Bjorkman, 1980; Badger et al., 1982; Maruyama et al., 1990; Holaday et al., 1992; Makino et al., 1994; Medlyn et al., 2002b; Demirevska-Kepova & Feller, 2004). For example, Makino et al. (1994)

reported that growth temperature affected the AC_i curve of rice, where the V_{cmax} parameter increased with rising growth temperature.

In this study the $J_{max}:V_{cmax}$ ratio declined significantly with increase in growth temperature (Table 6.2), indicating higher carboxylation capacity relative to electron transport capacity (light reaction capacity). In effect, there was more capability to fix carbon relative to capturing the energy to fuel fixation. In a review of gas exchange studies, it was noted that the $J_{max}:V_{cmax}$ ratio declined strongly with increase in measurement temperature across all the 19 gas exchange studies reviewed (Medlyn et al., 2002a; Medlyn et al., 2002b).

6.4.3.3 Photosynthetic development

Newly emerging leaves on heated vines had higher photosynthetic rates than that of emerging leaves in ambient conditions. The differences in photosynthetic rates between distal and basal leaves along shoots in heated vines were smaller than those in ambient shoots. Taken together this is indicative of higher growing temperatures promoting photosynthetic rates and accelerating leaf photosynthetic development. Buwalda et al. (1991) reported that maximal photosynthetic capacity was not attained until 3-5 months after leaf emergence, when A_{sat} was 16-17 $\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$ (Buwalda et al., 1991). The photosynthetic measurements presented in Table 6.1 indicate that at ~54 days after budburst leaf A_{sat} was 52.5% of this potential maximum for ambient vines, but 100% of this potential maximum for +5.0°C vines, supporting the conclusion that heating promoted the photosynthetic maturation of leaves.

Kiwifruit shoot elongation, leaf appearance rates, growth rates and photosynthesis are all optimal at 20-25°C and reduced at temperatures above 30°C and below 10°C (Laing, 1985; Morgan et al., 1985; Greer, 1996). On the day of measurement for the photosynthetic developmental curves (25/11/2002), the average leaf temperature per treatment was 24.5, 26.4 and 30.1°C for ambient, +2.5°C and +5.0°C conditions respectively. As such, photosynthetic rates in the +5.0°C could have been inhibited by too high a temperature, thus explaining why leaves of shoots in the +2.5°C treatment had the higher photosynthetic rate than that of the +5.0°C treatment (Figure 6.5).

6.4.4 Ovary Diameter

Heating advanced flowering by 17 days (+5°C) and 11 days (+2.5°C) and compressed the flowering period to 4.3, 6.1 and 9.4 days respectively for +5°C, +2.5°C and ambient treatments (Snelgar et al., 2005a). The original hypothesis was that higher temperatures pre-flowering would increase flower ovary size and this would be reflected in spring-heated vines producing larger fruit. However, heating above ambient significantly ($P < 0.01$) reduced ovary diameter by 12%, while the small differences in ovary diameter between the two heat treatments were insignificant (Table 6.4). If it is assumed that ovaries are spherical, then heating reduced ovary volumes by 9.3% and 10.1% for the +2.5°C and +5.0°C treatments respectively compared with the volumes of ovaries in ambient conditions. Presumably the smaller ovary size at fruit set of heated vines was offset by an advanced date of fruit set and a subsequently longer fruit growth period: 6.01% and 9.84% longer fruit growth period for the +2.5°C and +5.0°C treatments respectively compared with that of controls (Snelgar et al., 2005a). It is concluded that heating promoted ovary maturation over growth. This is consistent with the finding of McPherson et al. (2001) who observed a negative correlation between ovary fresh weight at anthesis and temperature. McPherson et al. (2001) found that although fruit weight was correlated with ovary weight in any one season, this relationship was not consistent enough to be used as a predictor in the following season.

6.4.5 Vine carbon balance

Despite the date of fruit set being advanced by heating (Snelgar et al., 2005a), heated vines had a denser total canopy and a greater proportion of their maximal LAI at the time of fruit set than vines in ambient conditions (Figures 6.1 and 6.3). A fuller canopy at fruit set has the potential to provide a larger pool of assimilates to fruit growth and to be a less actively growing vegetative sink competing for this assimilate. Vegetative growth is a stronger sink than fruit growth (Richardson et al., 2004). Following the modelling approach of Greer et al. (2004) we predict that elevated growth temperatures favour a more positive vine carbon balance with net carbon acquisition over the flowering period being 6% and 52% higher for the +2.5°C and +5.0°C treatments respectively compared to that of ambient vines. Changes in partitioning, and the additional carbon allocated to the larger vegetative biomass of heated vines will mitigate some of the potential carbon gain. However, the literature suggests that kiwifruit vines grown in higher spring temperatures will have a more positive carbon gain because of faster development, higher leaf area and photosynthetic rates (Greer et al., 2003). According to the carbon acquisition and utilisation model of Buwalda (1991), fruit growth is the largest carbon sink in the vine post-flowering with fruit growth being limited by carbon availability throughout the growth period, but primarily during the first 50 days following flowering (Buwalda, 1991). Higher growth temperatures were predicted to increase net carbon acquisition during the flowering period; a more positive carbon balance during this critical period will have beneficial effects on the development of fruit quality characteristics.

Greer et al. (2004) estimated net daily carbon acquisition for the whole kiwifruit vine to increase rapidly in spring to reach approximately $50 \text{ g vine}^{-1} \text{ day}^{-1}$, equating to 32.4 g C m^{-2} , which is comparable to the range in carbon acquisition of $20.7 - 31.41 \text{ g C m}^{-2}$ estimated for experimental vines in the current study. It must be noted that the predicted differences in net carbon acquisition between ambient and warm treatments are not as large as anticipated. The original hypothesis was that differences in carbon acquisition between treatments would

be primarily associated with differences in leaf area. The model of Greer et al. (2004) separates the canopy into two leaf classes: sun and shade. At the time of flowering, the differences between treatments were in the volume of shade leaves not sun leaves. Shade leaves make little positive contribution to net carbon acquisition (Greer et al., 2004), thus the differences between heating treatments in carbon acquisition reported here were more a function of differences in photosynthetic rates of the sun leaf class. The partitioning of the canopy area into two classes of sun-exposed and shaded leaves provides for a relatively simple description of the canopy that has been used elsewhere (Green et al., 1995; Raulier et al., 1999). Consistent with this approach, Greer and Halligan (2001) demonstrated that kiwifruit leaves grown under two very different PFDs (250 and 1100 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively) showed a classic separation into sun and shade light responses, with differences in photon yield and P_{max} . There were relatively small differences in both parameters, suggesting that the classification of the two leaf classes was a reasonable compromise for the whole canopy (Greer & Halligan, 2001).

6.5 Conclusion

It is predicted that warm temperatures during the spring growth period will result in fruit with a higher DM, and this appeared to be consistent both between-seasons and between-orchards within seasons. The indirect effect of temperature on fruit growth was investigated by examining canopy development and modelling the effect of elevated temperature on vine carbon balance.

Higher growth temperatures during spring increased the rate of total leaf area development through accelerating the rates of shoot elongation, leaf expansion, and promoting final leaf size. Elevated temperature affected the biochemical development of the leaf photosynthetic apparatus; photosynthetic rates were increased per unit leaf area through faster photosynthetic maturation of leaves and because leaves were closer to optimal temperatures for photosynthesis, yielding a higher net carbon acquisition rate. In terms of flower quality, heating accelerated ovary maturation over growth. It is concluded that higher spring growth temperatures favoured a more positive carbon balance, which in turn had beneficial effects on the development of fruit quality characteristics.

Chapter 7: Concluding Discussion

7.1 Thesis aim

Quantify the magnitude, sources and distribution of variation in fruit quality traits within kiwifruit populations and identify opportunities for the management of this variation.

Supplying markets with consistently superior fruit has the potential to stimulate consumer demand while maintaining the premium pricing enjoyed by the New Zealand kiwifruit industry in the international market place. Conversely, provision of consumers with fruit of inconsistent quality that does not satisfy expectations has negative market implications. There will be various pre- and post-harvest ways to achieve the goal of consistently supplying the export markets with the highest quality fruit possible. A greater understanding of how fruit quality traits vary within and between fruit populations is required to enable industry to manage variation in fruit quality attributes.

The use of NIR to non-destructively assess the quality characteristics of individual fruit from 96 commercial orchards, comprising 550 fruit-lines, across four consecutive seasons, resulting in a dataset of measurements made on 146.7 million individual fruit is a unique aspect of this study. In the short-term, NIR technology enables postharvest segregation for the management of variability in fruit quality. In the long term NIR also provides industry with a fruit quality monitoring tool that can ultimately aid industry in improving the quality of fruit produced. This thesis has used NIR as a tool for monitoring fruit quality and combined the data with orchard information to investigate opportunities for the management of the variation in fruit quality traits, with a particular focus on fruit DM. The main findings from this thesis are presented below and the implications for industry discussed.

7.2 What is the scale of variation?

The first objective of this thesis was to identify the amount of variability that is being produced by Hayward kiwifruit orchards. Significant variation in fruit quality was observed between-seasons, between-orchards, and between-vines within an orchard. From comparison of CVs between quality traits, it was concluded that independent of the production scale considered (between-orchard or between-vine) cropload was more variable than fruit weight which varied more than fruit DM. This is an unsurprising conclusion with cropload and fruit weight being less constrained by the biology of the kiwifruit vine and more responsive to management interventions than fruit DM. Hayward DM is typically in the range of 14-17%, large deviations from this range are not biologically possible. Despite the relatively small magnitude of variation occurring in fruit DM, such variation has major implications for industry.

The volume of export grade Hayward fruit produced by the New Zealand industry in season 2006 was ~68 million trays, with a mean DM of 16.6 and a standard deviation in DM of 1.1 (Zespri International Ltd, 2006a). We have demonstrated that the assumption of normality can be used to predict the proportion of fruit within a population with specific quality criteria (chapter 2), therefore the volume of this seasons fruit with specific quality criteria can be predicted. The Japanese market is the key export market for the New Zealand industry, and the Japanese have requested that Hayward fruit have a minimum rSSC ≥ 13 (Zespri International Ltd, 2005c). We predict that ~16.87 million trays (~25%) of the current seasons crop are potentially unacceptable for the Japanese market.

Furthermore, ~4.2 million trays of fruit are estimated to have an unacceptably low DM that will subsequently ripen into fruit with rSSC $\leq 12\%$. In season 2004/2005 the Japanese market bought 9.1 million trays of NZ Hayward fruit (Zespri International Ltd, 2005c), the opportunity is that in the current 2006 season there is a predicted volume of 10 million trays of fruit of a sufficiently high DM to guarantee an rSSC ≥ 15 potentially available for the Japanese market. The challenge facing the industry is in managing the variability in fruit quality and ensuring only fruit of the highest quality is shipped to the premium export markets.

7.3 Where should the management effort be focused?

Variability in quality is inherent in the nature of fruit. A component of this variation arises from within the plant. Additional variability is introduced between individual plants, within an orchard (chapter 5), and between geographically separated orchards (chapter 4) by differences in management, site, plant material, environment and climate. Within an orchard and within individual vines, management techniques may influence the variation in a fruit population by differentially affecting individuals within that population. Knowledge of the relative magnitude of the different sources of variation in quality parameters will help focus management practices on minimising variation.

A macro- and micro-analysis of the components of variance in fruit weight and DM was presented in chapter 2. Between-orchard variation was significant. However, the majority of variation occurred within-fruitlines, within-orchards, and within seasons. The within-fruitline component of variation was investigated separately, and it was demonstrated that both between-vine and within-vine variation were significant. Within-vine variation was dominant. This suggests that the focus of management should be on reducing the variation occurring within-fruitlines within-orchards, and that such variation is largely attributable to variation occurring within individual vines. This conclusion is in agreement with the belief that orchard management strategies focusing on uniformity (uniformity of croploads, cane spacings, woodtype, summer pruning, and winter buds per unit area) favours the production of consistently high quality crops (Mulligan, 2002; Mulligan, 2004; Zespri International Ltd, 2005b; Buxton et al., 2006).

7.4 How can this variation managed?

7.4.1 The potential for zonal management

Zonal management is a potential pre-harvest segregation tool for the management of the inherent variability in fruit quality traits. The potential for zonal management was studied at two scales: between-orchard and between-vine within an orchard. Within seasons there were spatial patterns to the distribution of fruit quality traits, however, there was limited consistency to these spatial patterns across seasons. Zones could be identified that contained orchards consistently producing fruit of distinct qualities across seasons, and similar zonation was possible within the individual test orchard area. Though the differences in fruit quality between such zones were statistically significant, they were not of sufficient magnitude to be commercially significant and warrant a change from uniform to zonal management. It was concluded that though the location of an orchard within the Te Puke region or the location of a vine within the test orchard area did have an effect on the quality of the fruit produced, this effect was diluted by non-spatial site-to-site variation which we attributed largely to differences in orchard management practices. Zonation between orchards or between areas within-orchards should not be where the effort in managing variation should be concentrated, unless it is zonation within individual vines.

7.4.2 Orchard management

Kiwifruit quality is a function of multiple characteristics that need to be considered holistically rather than individually. In chapter 5, a holistic approach was examined by comparing income generation between individual vines. Orchard gate return is perhaps the greatest motivator for changing orchard management practices. With the current payment schedules, grower returns are primarily driven by volume, and until this changes the production of high yields will remain the optimal financial return strategy. The industry is signalling that

future payment schedules will put a greater weighting on rewarding the production of high quality fruit (Zespri International Ltd, 2005a), this should incentivise growers to focus on quality rather than yield. However, there is no definitive trade-off between yield and kiwifruit quality. We identified orchards that consistently produced high yields of large sized high DM fruit. This provides evidence that orchard management can consistently achieve the production of ‘ideal’ fruit. What practices are these top performing orchards following that enable them to consistently produce ideal fruit?

While there is no clear trade-off between yield and fruit quality, there is a negative trade-off between vegetative growth and fruit growth. Trade-offs between vegetative vigour and fruit quality are well established in apple (Toldam Andersen & Hansen, 1995). We speculated that one of the benefits of warmer spring growth temperatures accelerating canopy development was that by the time of fruit set a greater proportion of the maximal leaf area was established and the vine had a more favourable carbon balance for early fruit growth. The accumulation of DW by the fruit was found to be approximately linear, with the rate of DW accumulation established within 50 days of fruit set (chapter 2). We conclude that the early fruit growth period is critical for establishing the potential for the production of high quality fruits.

The relationships between the temperatures experienced during the fruit growth period and the DM of fruit at harvest were explored (chapter 6). We demonstrated that previously published models describing relationships between growth temperatures and fruit DM, derived from observations of between-season variation (Snelgar et al., 2006), were also suitable for describing much finer scale between-orchard DM variation. Both the study of Snelgar et al. (2006) and the work presented in section 6.4.1 reached similar conclusions, a warm spring and cooler summer favours the production of high DM fruit at harvest. Heating vines during the spring growth period was found to favour a more positive carbon balance (chapter 6), which in turn had beneficial effects on the development of fruit quality characteristics. A cooler spring will forewarn the industry of the potential of producing a low DM crop and provide the opportunity for corrective

action to be taken on-orchard, conversely a warmer summer period may require more intensive canopy management to control vegetative vigour which will out-compete fruit for resources to the detriment of fruit quality.

What orchard management practises are available for manipulating the rate of canopy development and growth temperatures during the critical periods of fruit growth? Reflective mulches have been demonstrated to increase temperatures within production systems and influence fruit quality of mandarin (Richardson et al., 1993), peach (Jackman et al., 2004), strawberry (Locascio et al., 2005) and watermelon (Andino & Motsenbocker, 2004). The addition of vertical shelter is known to increase growth temperatures in orchard systems (Sudmeyer et al., 2002; Carberry et al., 2002). The establishment of orchards on sites with good aspect will obviously influence growth temperatures; however, for established orchards altering aspect is not an option. Application of fertiliser prior to budbreak has been reported to promote canopy development. Nitrogen has been implicated in both bud-break (Walton et al., 1991) and in the rate of canopy development (Smith & Miller, 1991b; Buwalda & Meekings, 1993). Forcing earlier budbreak, with hydrogen-cyanamide for example, is not recommended. The period between budbreak and flowering are considered to be coupled (McPherson et al., 1992; McPherson et al., 2001b), earlier budbreak will result in earlier flowering. Therefore, the canopy may not be any more mature at the time of flowering than if bud break was later, and presumably early fruit growth will experience cooler growth temperatures which has negative consequences for fruit quality (Snelgar, 2004; Snelgar et al., 2005b).

Within fruit-lines there was a positive correlation between mean fruit weight and variability in fruit weight, compared to DM distribution parameters where mean values were independent of levels of variation (section 2.4.2). Orchard management interventions targeting fruit size will increase average fruit size and potentially fruit DM but also lead to higher fruit size variation within the population (chapter 2). The effect on the level of variation in DM varies depending on the technique used. For example, trunk girdling has been demonstrated to increase mean values and reduce variability in both fruit weight

and DM (Zespri International Ltd, 2006b), compared to cane girdling which can increase both mean values and the levels of variability in fruit weight and DM (Anon, 2005) .

Within- and between- fruit populations the relationship between FW and DM varied (chapter 3). This result demonstrates that differences in cultural practices can have major impacts on fruit development. Despite the identification of a general relationship between fruit size and DM at an individual fruit level, orchard management practices targeting an increase in fruit size may not also increase fruit DM. The effect will be dependent on how the size increase is achieved. For example, carrying higher croploads will have negative consequences for fruit FW and DW but variable effects on DM that depend on the seasonal and/or cultural practices that cause fruit FW and DW to vary (chapter 3). The DW allocations to fruit are not limited by total DW production, at least up to the croploads observed in this study (≤ 65 fruit m^{-2}), therefore there is potential for orchards to raise both average fruit size and DM.

7.4.3 Managing variation postharvest

Currently the industry uses a sub-sampling strategy to identify high- and low-DM fruitlines within the inventory and direct fruit to specific markets accordingly. Estimation of the proportion of fruit with specific quality criteria can be achieved by assuming normality (chapter 2). Knowledge of how quality traits are distributed within fruit populations facilitates the use of postharvest segregation technologies, such as NIR. The assumption of normality enables estimation of the fruit volumes potentially recoverable by different grading scenarios, which in turn facilitates packhouse management.

The identification of a loose correlation between fruit size and DM within fruitlines offers the greatest short term opportunity for post-harvest management of variation in DM within the New Zealand industry (chapter 3). Overall, the traditional grading of fruit into count sizes also segregates for DM, and large fruit (lower count size) will often have higher DM than small sized fruit (higher count size). For example, if a fruit-line was close to the threshold for meeting market

DM requirements then one could have some confidence that the heavier count sizes of fruit would meet market standards (have a higher mean DM and potentially a reduced level of variation in DM within the count size). It can be speculated that the Japanese market is aware of this relationship as historically they have only accepted larger sized fruit. Constraints on the supply chain mean it is not practical to manage fruit-line DM status down to individual count sizes, however, it may be possible to manage the inventory by groups of count sizes within fruit-lines. Such an approach would maximise the volume of high DM fruit available for supply to premium markets. Furthermore, a positive correlation was identified between fruit-line DM and acidity (chapter 3). Segregation of the inventory on the basis of DM will also segregate on the basis of TA.

7.5 Future work

7.5.1 Better descriptors of quality trait distributions within fruit populations

Evidence was presented that the majority of fruit populations demonstrated significant deviations from normality (chapter 2). Hort16A flesh colour, used by industry as a measure of fruit maturity (Patterson et al., 2003), is an example of a characteristic that is known to be non-normal (Minchin et al., 2003). What theoretical distributions better describe the distribution of fruit quality characteristics within fruit populations? It is suspected that beta distributions (skewed normal distributions) or log normal distributions may better describe actual distributions but the ease of assuming normality and the associated calculation for predicting the proportion of fruit with specific quality criteria within fruit populations leads us to suggest that despite the assumption of normality not being ideal, it achieves industry goals of identifying high- and low-quality fruit populations.

The accuracy and robustness of predictions of fruit volumes with specific quality criteria can be improved by further research into better descriptions of quality trait distributions. Once there are robust and accurate descriptions of fruit quality distributions at harvest, the focus can move to investigating fruit quality distributions as they develop on the vine. Approximation to a theoretical distribution offers the potential for the development of predictive models that project forward initial fruit quality distributions to harvest (De Silva et al., 1997). Such predictive models would aid understanding of what impact orchard management practices have on subsequent fruit quality.

7.5.2 The effect of specific management interventions on the relationships between fruit quality traits

The present study was observational in nature; vine characteristics were not manipulated directly, the underlying factors causing variable relationships between fruit quality traits are largely unknown. It can be speculated that it is possible to determine what orchard management decisions cause the relationships to vary, and use this information to better manage the crop. For example, the between-vine comparisons presented in chapter 2 showed that the frost event of 2003 resulted in different relationships between fruit size and DM compared to that seen in the later seasons. Frosting caused drastic shoot thinning; further research could investigate shoot removal as a pruning strategy to manipulate the relationships between fruit quality traits.

7.5.3 Zonation of the vine: The potential for selective harvesting

The analysis of the sources of variation in fruit weight and DM presented in chapter 2 demonstrated that the majority of variation occurred within individual vines. Further work should therefore investigate the spatial component of the variation in fruit qualities within individual vines. Such studies could determine the potential for selective harvesting of zones within the canopy to effectively manage variability in quality traits within fruit populations. Spatial variation

within individual plants in fruit quality traits has been identified in other fruiting systems. Spatial patterns to within-plant variation in fruit quality traits have been identified for peach (Marini & Trout, 1984; Monestiez et al., 1990; Crisosto et al., 1997), apricot (Audergon et al., 1991), and apple (Jackson et al., 1971; Broom et al., 1998). Selective picking and delayed harvesting are practices commonly applied with these fruit crops to minimize the effects of these variations. By contrast, kiwifruit is one of the few crops where fruit are strip picked in a single harvest.

The work of Habib and co-workers (1991) demonstrated spatial relationships between fruit within individual vines for the quality characteristics of weight, DM, SSC and TA. These relationships were subsequently quantified further by Smith et al. (1994) who found that the greatest proportion of fruit with superior characteristics (required size and shape, above average SSC and flesh firmness) were located in the denser parts of the canopy, while fruit with less desirable characteristics were from the extremities of the canopy. The study of Pyke et al. (1996) reported that SSC tended to be higher in fruit from the ends of the leader than in fruit from nearer the centre of the vine. Fruit from the proximal ends of canes, near the leader, tended to have higher SSC than fruit from the distal ends of the canes (Pyke et al., 1996). Fruit from short shoots near the tips of canes had a greater incidence of physiological pitting, compared to fruit from long shoots near the base of canes (Thorp et al., 2003b). Further work is required to investigate the potential for practical within-vine zonal management.

7.5.4 The use of eating quality traits in storage profiling

The premise of this thesis has been that the industry wishes to manage the inherent variability in fruit quality to better meet consumer expectations. Managing the inventory by fruit eating quality characteristics raises the question as to whether such quality traits bear any relationship with fruit storage performance. Previous work has examined the link between fruit quality at harvest and the subsequent storage performance of fruit (Benge, 1999; Benge et al.,

2000a; Feng et al., 2003a). There is some evidence that fruit maturity and DM at harvest relate to the subsequent incidence of storage disorders and postharvest softening (Tagliavini et al., 1995; Davie, 1997; Clark et al., 2004). Inventory management can be improved if consistent relationships are established between fruit quality traits and fruit storage performance, and a robust storage profiling model developed. Fruit susceptible to quality deterioration could be prioritised for early load-out, product with high storage potential could be set aside for later load-out; thereby minimising on-shore fruit losses and repacking costs. The proviso is that fruit predicted to be either of poor eating quality or poor keeping is not supplied to the premium markets.

The ripeness index presented in chapter 3 was found to best correlate with between-vine variation in fruit firmness. The ripeness index uses variables that are already measured as standard practice but may add value to inventory management in identifying fruit-lines that are riper and potentially susceptible to quality deterioration in storage. Further work could investigate the use of the ripeness index in storage profiling.

7.6 Conclusion

The industry goal is to supply export markets with fruit of consistently higher quality than that produced by competing suppliers. To help achieve this we have identified opportunities for the management of variation in fruit quality traits both pre- and post-harvest.

The potential for zonal management was investigated. A spatial component to variation was identified both between-orchard and between-vine. However, the effect of spatial variation was diluted by that of non-spatial variation and therefore, zonation between orchards or between areas within-orchards should not be where the effort in managing variation is concentrated.

On orchard we are recommending strategies targeting uniformity and rapid establishment of the canopy. Carrying higher croploads can have negative consequences for fruit weight but variable effects on DM. The DW allocations to fruit are not limited by DW production, at least up to the croploads observed in this study (≤ 65 fruit m^{-2}). There is the clear potential for many orchards to improve fruit size, dry matter content and fruit uniformity.

Post-harvest, the traditional practice of grading fruit into count sizes generally also segregates for DM, and large count size fruit will often have higher DM than small sized fruit. We recommend that fruit-line DM status be managed in the inventory, not only by maturity area as is the current practice, but by groups of similar count sizes.

Chapter 8: References

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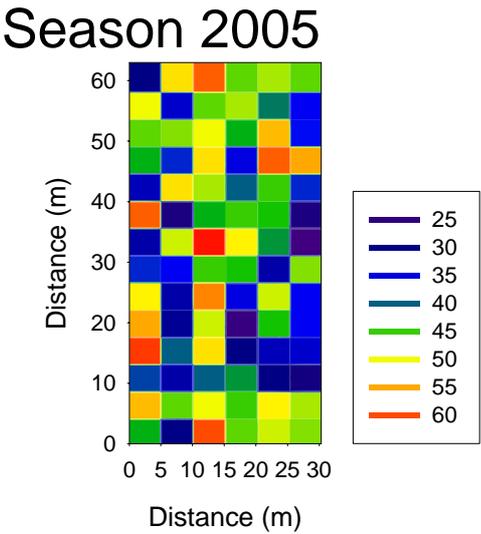
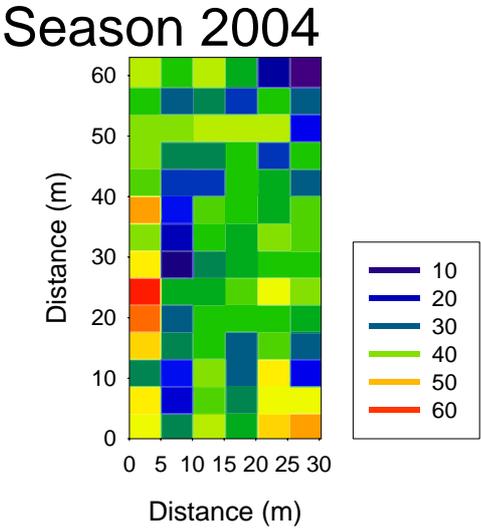
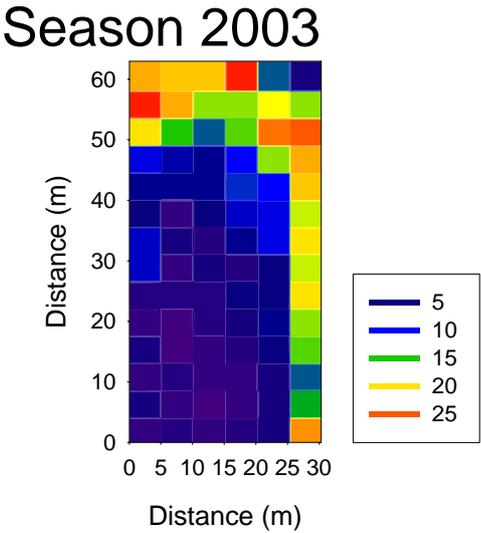
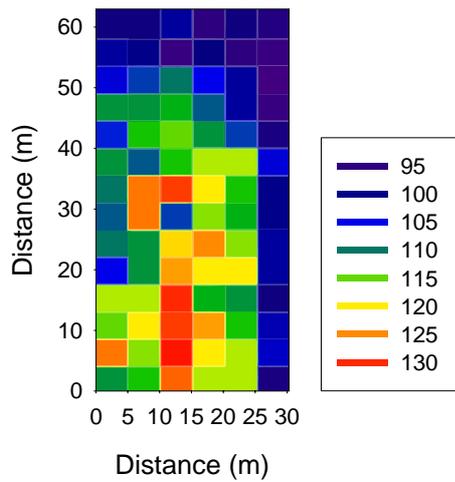
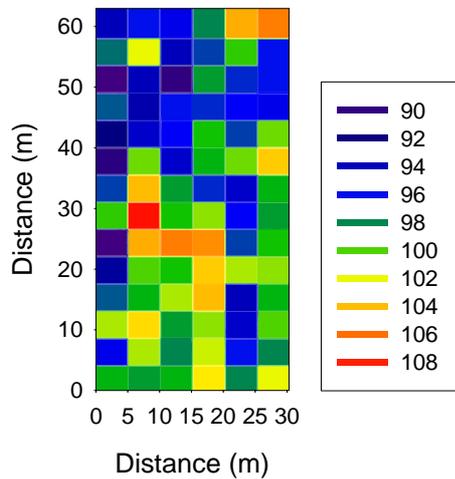


Figure 9.2. Raw variation in ‘Hayward’ kiwifruit vine cropload (fruit m⁻²) per individual vine within a 0.17 ha Te Puke orchard block. Each season is mapped on its own scale to highlight between vine variation within any one season, and differences of scale between seasons.

Season 2003



Season 2004



Season 2005

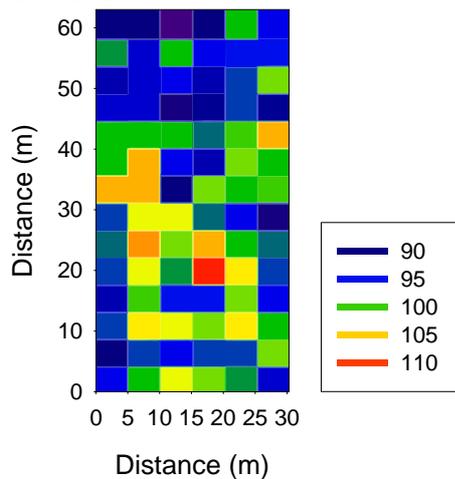
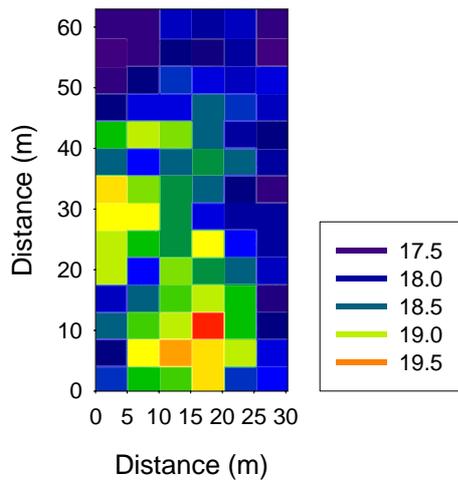
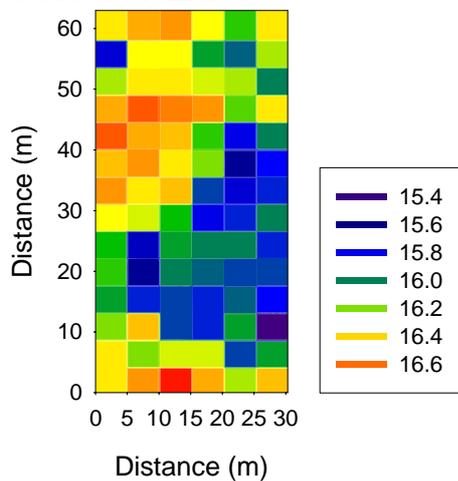


Figure 9.3. Raw variation in 'Hayward' kiwifruit average fruit weight (g) per individual vine within a 0.17 ha Te Puke orchard block. Each season is mapped on its own scale to highlight between vine variation within any one season, and differences of scale between seasons.

Season 2003



Season 2004



Season 2005

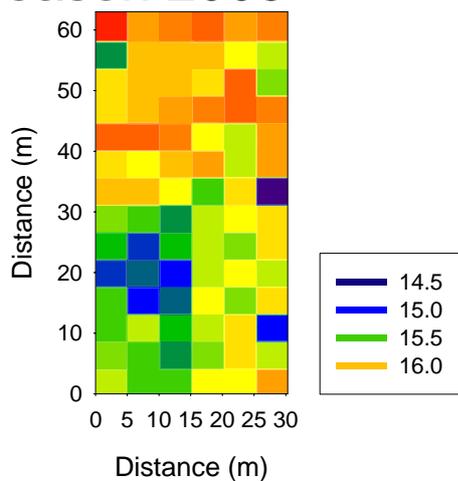
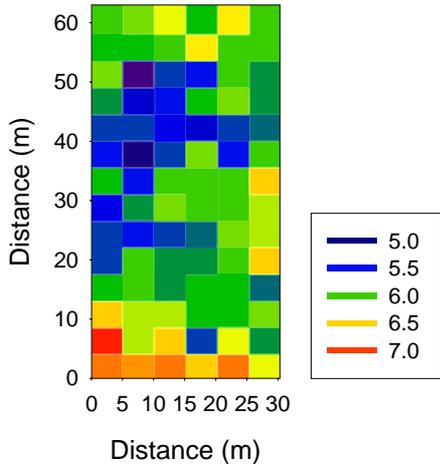
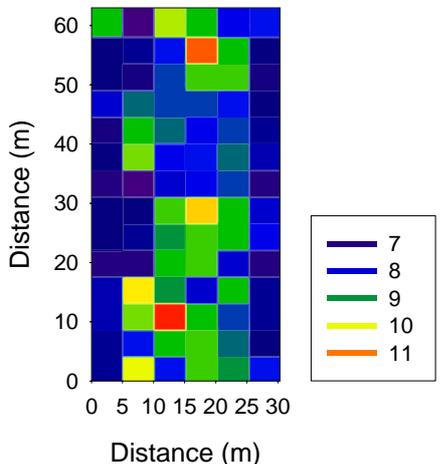


Figure 9.4. Raw variation in 'Hayward' kiwifruit average fruit dry matter content (%) per individual vine within a 0.17 ha Te Puke orchard block. Each season is mapped on its own scale to highlight between vine variation within any one season, and differences of scale between seasons.

Season 2003



Season 2004



Season 2005

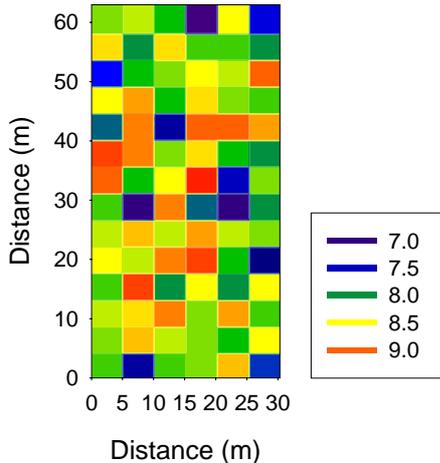
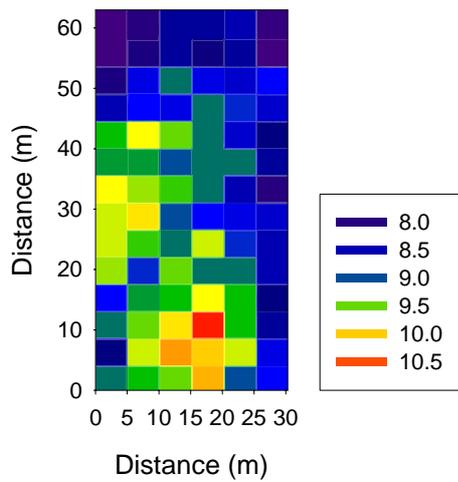
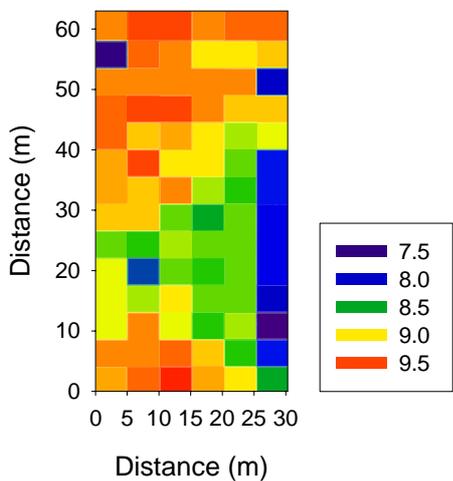


Figure 9.5. Raw variation in ‘Hayward’ kiwifruit average fruit firmness at harvest (KgF) per individual vine within a 0.17 ha Te Puke orchard block. Each season is mapped on its own scale to highlight between vine variation within any one season, and differences of scale between seasons.

Season 2003



Season 2004



Season 2005

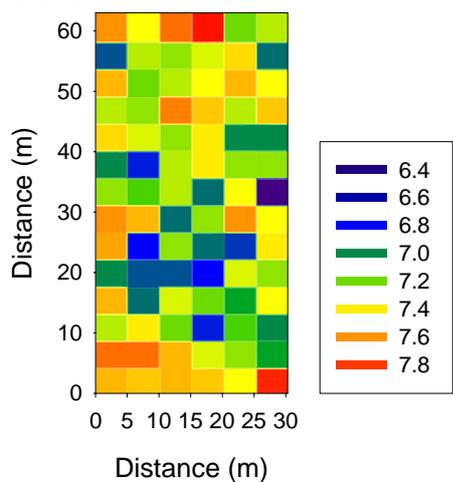


Figure 9.6. Raw variation in 'Hayward' kiwifruit average fruit Brix content (%) per individual vine within a 0.17 ha Te Puke orchard block. Each season is mapped on its own scale to highlight between vine variation within any one season, and differences of scale between seasons.

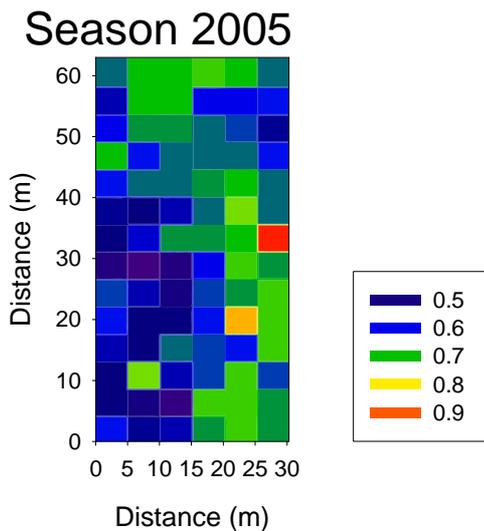
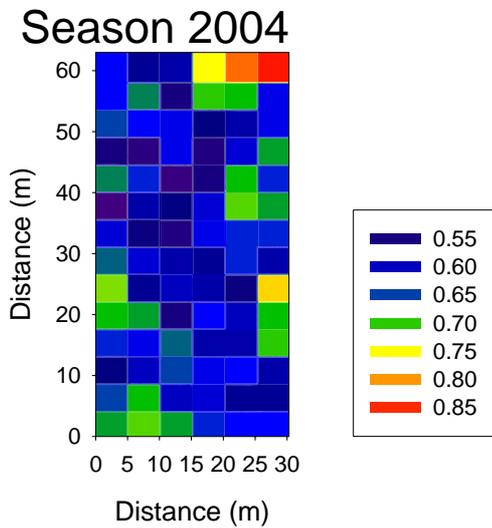
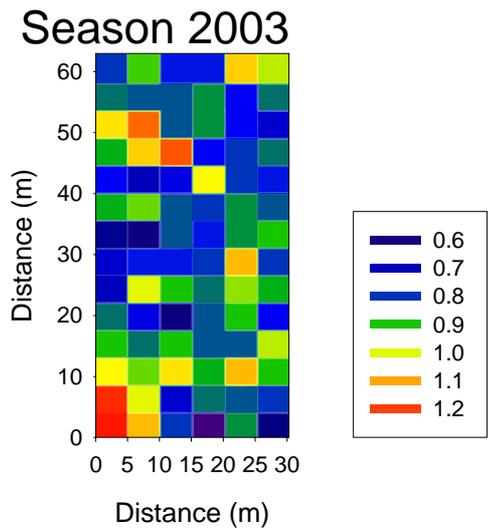


Figure 9.7. Raw variation in ‘Hayward’ kiwifruit within-vine variation in fruit dry matter content (standard deviation) per individual vine within a 0.17 ha Te Puke orchard block. Each season is mapped on its own scale to highlight between vine variation within any one season, and differences of scale between seasons.