APPLE TREE SYSTEM RESEARCH

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Jianlu Zhang

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CERTIFICATE OF SUPERVISION

This is to certify that the experimental work reported in this thesis was planned, executed, implemented, analyzed and described by J. Zhang under our direct joint supervision.

G.F. Thiele

Reader in

Department of Horticulture

R.N. Rowe

Professor and Head of

Department of Horticulture

Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

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by J. Zhang

This has been a co-operative research project between the Ministry of Agriculture and Fisheries, Division of Horticulture and Processing, DSIR, New Zealand Apple and Pear Marketing Board, The New Zealand Fruitgrowers Federation and the Department of Horticulture, Lincoln University commenced in the winter of 1986. The objective was to monitor 15 Royal Gala or Gala apple orchards in the three main apple producing regions of New Zealand to produce a data base for modelling biological and financial interactions. Selected trees were continuously monitored for three growing seasons. One orchard was continuously monitored for another 3 years (in the third additional year for the purpose of model validation). The orchards were 5 - 8 years old during the first monitoring season. Twelve of the orchards were on MM106 rootstock and the remainder on M793. Tree density ranged from 455 - 1102/ha. Five trees were monitored for fruit number and fruit quality in each orchard at harvest. Three branches from each monitored tree were chosen to record the number of flowers and fruits before thinning and after thinning.

To establish a fruit tree branch sampling system which can be reliably extrapolated to a whole tree basis, measurements from 204 trees, 151 parent branches and 9283 sub-branches were involved. Wood density was measured and the estimation of the volume of a branch, and the ratio of the branch to the whole tree, compared. Evidence is presented to show that the ratio of the sum of branch cross sectional area (CSA) to the trunk CSA is equal to the ratio of fruitfulness of the whole tree to fruitfulness of the sum of the branches. A relationship has been established between the sum of the CSA of branches directly arising from the central leader and the trunk CSA of central leader-trained apple trees. Ratios of 1.6 - 2.1 : 1 have been determined over 7 years of research without any major influence from pruning. The relationship of secondary branching of individual fruiting arms was investigated also, suggesting a similar relationship between branch CSA and secondary branch CSA but the influence from pruning, in this case, is relatively greater. Between orchard, tree and branch variation is explained. Recommendations on branch sampling for research and monitoring purposes are provided, based on these findings.

Climatic data from 7 meterological stations was used, incorporating temperature, sunshine hours and rainfall. For each season the orchards were monitored, climatic data was recorded for the period October in the previous growing season until harvest time (March) of the current season, a total of 18 months in each case. Correlation calculations were attempted for all monthly combinations. Contour maps of correlation coefficients between tree parameters and monthly combinations of climatic data are presented to show the major effects of climate on fruit production. The production of multiple regressions has been focused on a range of tree parameters, with relevant climatic data from the contour maps added, to refine the mathematical relationships. Higher maximum temperatures in the period of March and April produced higher initial fruit set (r = 0.54**) the following spring suggesting an effect on quality of the flower. Lower maximum temperatures in the late dormant period (August to September) produced a higher initial fruit set (r = -0.40**) as well. The natural simple regression between initial fruit set and flower number per cross sectional area (CSA) gives an r value of -0.47** indicating that the more flowers on a tree the lower the percentage initial fruit set. Introduction of the climatic effects produces a refined multiple regression with an r value at 0.76^{**}. A negative correlation for estimating fruit number/ha after thinning was determined (r = -0.78^{**}).

The estimation of fruit volume from fruit diameter was explored. Fruit growth curves based on fruit diameter or volume were plotted for 2 growing seasons. The influence of temperature on fruit growth is documented. Fruit size variation was explored and the sampling size for estimating average fruit weight is recommended. It is demonstrated how fruit number after thinning can be extrapolated to estimate total yield, fruit size and size distribution at harvest. Average fruit size was positively correlated with November to February temperatures in the previous season and also maximum temperatures in the December to January period prior to harvest. A negative correlation with fruit size was found for minimum temperatures in May. All these improved knowledge on the relationship between average fruit size and fruit number after thinning, but the maximum temperatures in December and January were critical in providing more accurate information (r = 0.81**) for harvest predictions.

For management planning it is necessary to relate yield, fruit quality and size distribution, revenue and cost data, in order to calculate annual gross margins. A set of dynamic mathematical models developed are presented, to demonstrate the interrelationship of factors influencing apple production and profitability. Based on the model, a computer program was

produced for practical orchard application. At the blossom and pre-thinning stages of fruit production, model users may specify parameters recorded from their own trees (eg flower numbers) and climatic data to predict tree behaviour for the next stage. At the post-thinning stage, model users may again specify parameters recorded from their own trees (eg fruit number) and climatic data to predict yield and fruit size distribution at harvest. These predictions can be correlated with financial data such as price realisations for the fruit and production and harvesting costs, to minimise estimated net return. The models allow annual climatic data to be balanced against biological parameters (eg fruit number) in order to minimise costs and maximise gross income and annual gross margins. For example, the required fruit number per tree after thinning can be correlated with the size grade distribution which will maximise returns, incorporating weather, cost and other key management parameters.

Carbohydrate reserves in the dormant period are of primary importance for fruit production in the following year. The storage of starch in different parts or organs of apple trees was compared. The concentration of starch in the root system is much higher than that in the above ground parts. Observations of root growth and photos provided the evidence that roots continued to grow in the dormant period in Canterbury. Non-structural young rootlets contained almost no starch. For secondary roots, on average, thin roots contained higher concentrations of starch than thicker roots. However, results indicated there is greater variation of starch concentration in thinner roots. Results also showed that the starch content in root bark is much higher than that in root wood. The sampling variation may be reduced when bark and wood are separately tested. This is because the ratio of bark to wood is different for different roots. To minimize the variation, the bark of roots above 1 cm in diameter is recommended for analysis. Under 3 different crop loads, starch content was measured using replicates of 6 roots per tree and 3 trees per treatment. Starch content under light crop load conditions was significantly higher than that of middle and high crop loads, indicating a negative correlation with crop load in the growing season. A negative relationship between the content of starch and soluble sugar was found, reflecting the vigour of root growth. For the following year's production, higher yield or fruit number was positively correlated with the stored starch level or negatively correlated with the yield or fruit number in the previous growing season.

An accurate method of estimation of fruit size distribution using average fruit weight and standard deviation of the mean is discussed.

KEYWORDS: apple (*Malus domestica*. L.), bark, climate, crop load, cross sectional area (CSA), fruitfulness, fruit number, fruit size, fruit size distribution, model, monitor, prediction, root, root growth, soluble sugar, starch, temperature, yield.

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CHAPTER 1

INTRODUCTION

Crop monitoring work was introduced by Thiele (1983) into New Zealand in the early 1980s' on a range of crops such as blackcurrants, peaches and nectarines and kiwifruit. He recognised that the fruit tree is a "system" with roots, tree structure, leaves and fruit all interacting one with the other and he questioned what biological and economic knowledge existed about the interacting relationships (Thiele, 1981). The monitoring work he initiated, incorporated the tree (or plant) as well as the interacting environment of the orchard, soil and climate (the orchard system). The system, he suggested, was operated by growers by chance. Growers made individual decisions based sometimes on a prescription supplied by advisers or on information directly or indirectly related to their orchard. The systems approach, he suggested, together with the development of a data base of information, offered the opportunity to mathematically formulate biological relationships which would allow the efficiency of the fruit tree to be studied as an economic unit (Thiele, 1987).

As the work progressed he initiated a co-operative research project to explore the system approach with the Gala group of apples. The Ministry of Agriculture and Fisheries, Division of Horticulture and Processing, DSIR, New Zealand Apple and Pear Marketing Board and the Department of Horticulture, Lincoln University cooperated in the operation which commenced during the winter of 1986. The work involved a total of 15 orchards initially in 3 districts. The comparative analysis of year 1 data and the initial relationships were summarised in a Lincoln College discussion paper by Zaprzalek and Thiele (1987). A Lincoln College dissertation by Zhang (1988) analysed the results of the second growing season. Concurrently Thiele (1990; 1992) worked for a year stationed at the University of Hannover to test the whole system approach to grower education and research with Jonagold apple growers in Germany and the Netherlands. At the same time, systems modelling experts shared their expertise with him on developments in computer modelling. The key aim of this thesis was to develop a computerised apple tree model using the initial 3 years of the Royal Gala data together with additional measurements added to the data base subsequently.

Before modelling the tree behaviour, it was essential to develop a sampling technique to allow flower and fruit numbers to be extrapolated to a whole tree basis. Sampling techniques have been developed in Chapter 3. Based on the original Gala measurements over 3 years, and additional measurements on Gala and other varieties in the subsequent 3 years, apple production models have been developed in Chapter 4. In an attempt to explain crop loading potential and alternate bearing, starch storage analysis of apple trees was conducted and summarised in Chapter 5. Chapter 6 discusses the key results, relates the work in this thesis to that of other researchers and recommends the direction of future modelling work in pomology.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews recent work on modelling research in Pomology, the climatic effects on apple production and apple production forecasting. Physiological work applicable to this thesis is also reviewed with a specific section on carbohydrate storage in apple trees.

2.1 MODELLING RESEARCH IN POMOLOGY

This section reviews some of the key modelling research in Pomology. Although it deals with some of the more detailed physiological modelling work it concentrates on biological modelling and predictive models associated with yield. Development of computer simulation models for fruit crops has been much slower than in agronomic crops because of tree size, structure and longevity (DeJong *et al.*, 1990), but recent work in fruit research modelling has been in more depth and shows potential for realistic commercial application.

2.1.1 Chilling Requirement

In natural habitats of deciduous trees, dormancy during a cold winter is necessary for the tree to resist cold injury (Lang, 1989). However, the protection of cultivated plants against winter injury may present problems not found in natural habitats. Many cultivated species were either bred for specific fruit-quality factors or have been selected and moved to climates other than that in which they evolved. Thus, many domestic forms are not completely adapted to the environment in which they are cultivated (Westwood, 1988).

If the winters become too mild and/or too short, true dormancy becomes nearly irreversible. Under these conditions, the symptoms of prolonged dormancy or delayed foliation may occur. Some flowers suffering from prolonged dormancy may show delayed and very weak leafing (Saure, 1985). The stamens are usually affected at an earlier stage than the pistils (Black, 1952). The stigma and style make no growth after the bud stage of development, but the ovary and remainder of the flower develop to normal size (Weinberger, 1950). In many cases the pistils are dwarfed and the flower primordia often abort and the flower buds absciss at various stages of development (Black, 1952).

It is widely recognized that winter chilling temperatures are required for the spring growth of dormant buds. Erez and Lavee (1971), using controlled conditions, observed that a temperature of 6°C contributed more to rest completion in peaches than any other of their test temperatures (10°C was about half as efficient in breaking rest as 6°C). When 21°C was alternated with a low temperature, it nullified the effect of the low temperature.

A specific amount of chilling is required to terminate or break rest and restore the bud's ability to expand and grow again. Weinberger (1950) proposed the term "chilling hours" for winter air temperatures less than 7°C. However, the end of rest is not predictable by a simple summation of the number of hours below 7°C because temperatures slightly above 7°C also have a rest-breaking influence (Ryugo, 1988).

Table 2.1 Chill units calculated by different models

Chill unit values	Corresponding temperature (°C)	
	Utah model (Richardson *et al.*, 1974)	North Carolina Model (Shaltout and Unrath, 1983)
0.0	< 1.4	-1.1
0.5	1.5 - 2.4	1.6
1.0	2.5 - 9.1	7.2
0.5	9.2 - 12.4	13.0
0.0	12.5 - 15.9	16.5
-0.5	16 - 18	19.0
-1.0	>18	20.7
-1.5	--	22.1
-2.0	--	23.3

Two models were developed by Richardson *et al.* (1974) and Shaltout and Unrath (1983) for estimating the end of rest, taking into consideration the relative effectiveness of a specific temperature range; that is converting temperature to chill units (Table 2.1). Both models chose the optimal temperature around 7°C marked as 1 chill unit. The North Carolina model assigned a more negative effect to the temperatures above 21°C reaching a chill unit

of -2 at a temperature of 23.3°C.

Several papers (Erez *et al.*, 1979; Anderson, *et al.*, 1986; 1990; Anderson and Richardson, 1987; Real-Laborde *et al.*, 1990) reported on testing the models. The Utah model has been criticized for inaccurate predictions of plant response, especially in areas with mild winter conditions (Erez *et al.*, 1979; Shaltout and Unrath, 1983; Ebert *et al.*, 1986; Laborde, 1987).

2.1.2 Modelling of Tree Growth

Modelling of tree growth is divided into wood and leaves, and forms the basis of most fruit tree modelling research.

2.1.2.1 Tree Growth and Trunk

The cross sectional area (CSA) and the circumference of the trunk of a tree are the most obvious tree size parameters as well as the easiest measured. Pearce (1952) cited an instance of its use in forestry in 1804. Hoblyn (1931) recommended trunk circumference as a standard recording in fruit tree research. He said "No single measure is ever sufficient to describe the vigour of a particular tree." Pearce and Davies (1954) suggested that the circumference should ordinarily be measured 12 inches (30 cm) above the graft union.

Martínez-Zaporta (1952) working with pears found that there was a close correlation between increase in trunk circumference and tree height at the end of the first season of growth. The coefficient varied slightly between years and was probably related to the system of pruning. They calculated that trunk circumference can be a useful measurement of annual wood production. Severe cutting back throughout the first season of growth had no effect on trunk diameter.

Some authors used CSA to estimate apple tree weight (Heinicke, 1921; Sudds and Anthony, 1928; Collison and Harlan, 1930; Knight and Hoblyn, 1934; Pearce, 1952; Westwood and Roberts, 1970). Heinicke (1921) found that the weight of a tree increased about 7.3 times when the trunk circumference was doubled. Pearce (1952) proposed a formula $W = AG^b$, where W is tree weight, A is a constant, G is trunk circumference, and b ranged between 1.92 and 2.76. However, Westwood and Roberts (1970) found a very good linear regression

between trunk CSA and total above-ground weight.

The increment in trunk circumference has been used to estimate shoot growth. It was found by Martínez-Zaporta (1952) that there was a close correlation between increase in circumference and the height at the end of the first season of growth. Wilcox (1937) found moderate positive correlations of about $r = 0.50$ between terminal shoot growth and increase in trunk circumference in the same and alternate years. In any one year though it is not satisfactory by itself, since on biennial bearing trees there is a decrease in the ratio in the same year that the terminal length shows an increase. Overholser *et al.* (1937) found the highest r value of 0.705 could be obtained using data over a 4-year period. Moore (1965b) found the increment in powered circumference (b^α - a^α) was correlated with total length of shoot (> 5cm) growth produced during the period. Correlations were higher when circumferences were raised to powers of between 2 and 5 before calculating the circumference increment, with the highest correlations usually obtained when circumferences are cubed.

The frequency distribution of shoot length of Ralls and Starking Delicious apple trees with a wide range of age, vigour and pruning treatments was investigated by Kikuchi (1974). A model was proposed to represent changes in the growth status and structure of the shoot system in relation to tree age and pruning practice. Baumgärtner *et al.* (1986) described a demographic model for simulating the annual growth patterns of an apple tree. A tree is assumed to consist of a perennial frame with populations of leaves, shoots, fruits and roots developing on it. The dynamics of these populations are simulated as time invariant distributed processes.

Moore (1968a), was concerned with variation of fruit tree size as measured by trunk circumference at the time of planting but he found that the variation had been virtually eliminated by the time the trees had increased their trunk circumference about fourfold.

2.1.2.2 Leaf Area

This section deals with the leaf as a site for photosynthesis and associated research.

A correlation between shoot length and shoot leaf area has been established for a number of apple cultivars (Byass, 1968; Barlow, 1980; Palmer, 1987) and peach and prune (Boynton

and Harris, 1950). Leaf area was related linearly to stem length based on 5 apple cultivars studied by Johnson and Lakso (1985). The expression was described as Y = a + bX, where Y is leaf area, X is shoot length, a is the interception and b is the slope. Different shoot types and different cultivars have different intercepts and slopes as shown in Table 2.2.

Table 2.2 The constants (a) and the slopes (b) for the relationship between leaf area and shoot length (Johnson and Lakso, 1985)

Cultivar	Shoots with terminal bud set		Growing shoots[z] (all shoots)		Growing shoots (1 - 20 cm)	
	a	b	a	b	a	b
Golden Delicious	63.5±15.6	10.0±0.54	25.5± 8.3	9.7±0.38	15.4±3.5	14.5±0.89
McIntosh	114.0±36.9	14.0±0.90	39.3±12.2	12.3±0.41	12.3±5.3	16.2±0.82
Milton	21.9± 9.7	11.2±0.29	5.3± 7.1	9.7±0.27	10.2±2.8	8.4±0.36
Jonamac	--	--	20.5± 7.8	15.3±0.37	53.8±4.2	12.4±0.60
Delicious	5.5±36.7	10.4±0.77	--	--	--	--

[z] includes all growing shoots during the season.

Table 2.3 Parameters for sour cherry leaf and shoot growth (Flore *et al.*, 1986)

Objective	Formula
spur leaf area	$= 18.57(1-e^{-0.008(\text{degree-days})})$
long-shoot leaf area	$= 30.89(1-e^{-0.0062(\text{degree-days})})$
leaf length	= (leaf area)/0.605
petiole length	= 0.256(leaf length)
shoot base diameter	= 0.05 • Sqrt((total leaf area above shoot)/30)

Both shoot length and leaf area showed strong linear relationships with accumulated growing degree-days, but the shoot length relationship showed less variability among cultivars than did leaf area. The daily leaf area increment per shoot for a 4°C base was defined as $\text{LeafArea}_{\text{increment}} = 0.00008\ \text{DegDay}_{4C}$ (Johnson and Lakso, 1985). Flore *et al.* (1986) proposed a series of formulae for sour cherry leaf and shoot calculations based on the degree

days accumulated since leaf emergence (Table 2.3).

Detailed measurement of fruit tree growth was taken by Forshey *et al.* (1983). Twenty-five 8-year-old McIntosh/MM106 apple trees were harvested 5 times during the 1980 growing season. For each harvest, the numbers of spurs, shoots, leaves on the spurs, leaves on the shoots, and fruits were counted. The surface areas of trunk, scaffold, 3, 2 and 1 year-old wood and spurs, and shoots, shoot leaves, spur leaves and fruit were also measured. This provided the basis for carbon budget research. Dry matter assessment of this work is reviewed in section 2.1.3.4.

2.1.3 Modelling of the Carbon Budget

The purpose of modelling a carbon budget is to attempt a quantitative analysis of the seasonal dry matter and carbohydrate requirements of fruit tree growth and development. A quantitative carbon budget model of fruit trees could be useful in estimating daily potential tree demands for photosynthates (DeJong and Goudriaan, 1989). The primary sink activities of the fruit would be growth and respiration and the source activity would be photosynthesis.

2.1.3.1 Respiration

The dark respiratory rate was separated into two components (McCree, 1974). The "maintenance" component was associated with providing energy for maintaining what is already present while "growth" respiration provides energy and reductant necessary for the synthesis of new plant material. The maintenance respiration is proportional to the dry weight of the plant and is strongly related to temperature.

Several papers deal with fruit tree respiration studies. Compared to the earlier models (eg Proctor *et al.*, 1976), DeJong and Walton (1989) and Lakso and Johnson (1990) proposed that the basic time step should be one day rather than one minute or one hour. Using the daily integral eliminates the complexity of the diurnal changes in radiation geometry. Lakso (1992) further developed his model to include the leaf fall to budbreak period and dealt with discontinuous canopies. Lakso and Johnson (1990) proposed a respiration submodel based on the exponential response of the respiration rate (R) to temperature in different tissues expressed by $R = ae^{kT}$, where a = R at a temperature of 0°C; k = the temperature coefficient of R; T = the temperature in °C.

Table 2.4 Estimated coefficients for respiration

	a	k	T	References
leaf	0.066	0.090	T_{time}	Watson *et al.*, 1978
leaf	--	0.025-0.090	$(T_{max}+2T_{min})/3$	Lakso & Johnson 1990
wood	0.004-0.010	0.085	T_{mean}	Lakso & Johnson 1990
fruit	0.003-0.020	0.055-0.100	T_{mean}	Lakso & Johnson 1990

The respiration rates for leaves are based on one-sided surface areas. The rates for wood are based on wood surface area since different aged wood of different volumes gives similar respiration rates when expressed on a surface area basis. Fruit respiration is based on fruit fresh weight. Individual tissue submodels for leaves, fruit and perennial structure (wood) were developed based on different a and k coefficients (Table 2.4).

Research with tart cherry (Pollack *et al.*, 1961), grape (Pandey and Farmahan, 1977; Koch and Alleweldt, 1978) and apple (Krotkov, 1941; Jones, 1981) all indicate similar patterns of fruit respiration during fruit development. Fruit usually have high initial rates of respiration per unit dry weight during early fruit growth, gradually declining during later stages of growth. For example, the work of Jones in England (1981) showed that the response of the respiration rate of apple fruit at 20°C in the dark declined from 120 ng CO_2/s•g fresh weight at 4 weeks after full bloom to less than 3 ng/s•g fresh weight by late September. Maximum rates of peach fruit respiration per unit weight at 20°C were similar for the two cultivars used during the first two stages of fruit growth but higher for the early cultivar during the final stage of fruit growth (DeJong *et al.*, 1987). At the same temperature, respiration rates were low when apple trees were dormant, rose rapidly to a peak in spring (before full bloom) and then declined steadily through the season (Butler and Landsberg, 1981).

Many papers have calculated the respiration cost. The cost of growing a kiwifruit berry with 18.5 g dry matter near Fresno, California was 25.6 g glucose per fruit per season (Walton and DeJong, 1990). This could be partitioned into 19.68, 2.73 and 3.19 g glucose per fruit per season for carbon skeletons, growth respiration and maintenance respiration, respectively. On average, respiration accounted for 22.6% of the cost of kiwifruit growth. Respiration accounted for 15 - 30% of carbohydrate required for sweet cherry fruit growth

(Loescher *et al.*, 1986) and 16.3 - 20.5% for peach fruit growth (DeJong and Walton, 1989). Lakso and Johnson (1990) working with apple trees, calculated that, of the total of 23 kg of CO_2 respired over the whole season, leaf respiration accounted for about 71%, fruit respiration about 18%, and wood respiration about 11%. Kappes and Flore (1986) estimated that respiration used 30.9% of the total carbohydrates required of sour cherry trees. During fruit development stages I, II and III the share of respiration was 32.7, 70.7 and 19.91%, respectively. The increased need for respiration during stage II is because of lignification and lipid synthesis during pit hardening and embryo development. DeJong *et al.* (1987) also reported daily peach fruit respiration rates per unit dry weight and per fruit throughout the growing season.

Sruamsiri and Lenz (1985) working with strawberries reported that, during changes from light to dark, photosynthesis and mesophyll conductance decreased sharply, but dark respiration rates reached their maximum values only 16 minutes after darkening.

2.1.3.2 Light

A model for the distribution of solar radiation incident on leaves in an isolated apple tree was presented by Thorpe *et al.* (1978). The simulated area of shadow cast by a tree compared well with measured values. Models by Charles-Edwards and Thorpe (1976), Jackson and Palmer (1980), Palmer (1988) and Wagenmakers (1990) also emphasized sunlight interception by different orchard designs and were helpful in clarifying some important interrelationships of orchard design, light interception and productivity.

Winter (1980) considered that light is a very important fruit production factor and determines the optimal tree height and planting density. The optimal tree height for apples, Winter claimed, equals half the distance between rows + 0.5 m in Northern Germany, + 1 m in Southern Germany and + 1.5 m in the Mediterranean region. A 0.5 m increase in tree height may increase the yield by 10 - 20% but would also increase the picking costs. The productivity was always greatest in the 0 - 1 m outer zone claimed by Rud' and Tanas'ev, (1974). Bella (1971) proposed a model to test mathematically the competitive interaction between individual trees. It consisted of the influence zone of each tree, which is a function of its size, and the amount and nature of interaction. The interaction depends on the distance between, and the relative size, of the competing tree and its competitors.

Palmer (1980) claimed that light interception by an orchard can be increased by reducing the spacing, increasing the height and spread of trees and increasing the leaf area index (LAI). Computer modelling of light interception by hedgerow trees has produced the following conclusions. If the LAI is low (less than 1) then, within quite wide limits, tree size and spacing have little effect on light interception. At higher LAIs, tree size and arrangement become significant factors if there are wide alleyways, but the closer an orchard approximates to a continuous cover of leaves the less important these factors become. Light interception gives an indication of potential yield; the actual yield can be reduced by serious within-tree shading. Palmer's model was also used to map the light distribution patterns within full-field, spindlebush and palmette orchards. Over a wide range of hedgerow dimensions and between-row spacings, a linear relationship was found between the maximum light interception achievable before serious shading occurs and the maximum light interception which would be achieved if the trees were solid. From this it is now possible to predict the LAI needed to maximize production of top quality apples. Any further increase in leaf area, Palmer claimed, will only lead to the production of small fruit, although total yield and dry matter production will increase with the increase in light interception. Predicting light interception and potential yield, by a range of hedgerow tree forms and spacings, was also used as a guide to the design of orchard systems for mechanical harvesting (Jackson and Palmer, 1980). Červenka (1978) investigated the orientation of the leaves in the crown of apple trees and the absorption of solar radiation in USSR. A mathematical model was produced from measurements during August/September of leaves (including inclination of the halves of the leaf blades) on shoots and spurs, in the crown of a 10-year-old Goldenspur apple tree on M9 rootstock, to quantify the absorption of photosynthetically active solar radiation on windless and cloudless days.

2.1.3.3 Photosynthesis

Proctor *et al.* (1976) presented light response curves of photosynthesis, light compensation, photosynthetic efficiency, photorespiration, dark respiration and soil respiration of young apple trees in Canada. They also calculated the carbon accumulation between 7 July to 12 August. Papers by Watson *et al.* (1978) and Thorpe *et al.* (1978) also reported photosynthetic measurements and relevant coefficients. At a saturating photon flux density, photosynthesis P_n was linearly related to internal CO_2 concentration C_i, up to $C_i \approx 250$ mg/m^3. Optimum temperatures for P_n were slightly different in the two years and were in the range 16 - 26°C (Watson *et al.*, 1978). Avery (1977) reviewed the available information

on maximum photosynthetic rates and concluded that the maximum CO_2 uptake rate for apple leaves at normal CO_2 concentrations, under saturating light, is about 1 mg $CO_2/m^2 \cdot s$.

DeJong and Doyle (1984) reported that peach leaf photosynthetic capacities changed very little during different periods of fruit growth. During the early stages of fruit growth there were no significant differences in leaf gas exchange characteristics between fruiting and defruited trees. During the early part of the last stage of fruit growth, CO_2 assimilation rates were 11 - 15% higher in fruiting trees than defruited trees. DeJong (1986) believed that the fruit effect on photosynthesis is primarily related to stomatal behaviour.

An integral model for daily gross photosynthetic rate per unit ground area was developed by Lakso and Johnson (1990) allotted on a per tree basis (in g $CO_2/m^2 \cdot day$):

$$P_{daily} = \alpha ShP_{max}(1-e^{-kL})/(\alpha kS + hP_{max})$$

where α = leaf photochemical efficiency in μg CO_2/Joule total radiation;
S = daily integral of total radiation on a horizontal surface in $MJ/m^2 \cdot day$;
h = daylength in seconds;
P_{max} = rate of light saturated leaf photosynthesis in $g/m^2 \cdot s$;
k = canopy light extinction coefficient;
L = leaf area index per total area allotted per tree.

The temperature effect on photosynthesis is included as a fractional reduction of P_{daily} estimated by the normalized equation $P_{fract} = -0.026 + 0.0436T + 0.00094T^2 - 0.000043T^3$. This relationship gives a maximum at about 28°C and zero at 0 and 44°C.

2.1.3.4 Dry Matter Production

Some researchers (Heinicke and Childers, 1937; Forshey *et al.*, 1983; Palmer, 1988) measured the dry matter production of apple trees. Working with apples, Forshey *et al.* (1983) measured the dry matter weights of trunk, scaffold, 3, 2 and 1 year-old wood and spurs, and shoots, shoot leaves, spur leaves and fruit 5 times during the season. The total tree dry weight at harvest was 124% greater than at the beginning of the season, but slightly more than half of this increase was due to leaves and fruit. The increase in the weight of the woody tissues was 8824 g, or 59.2%, of which 1599 g/tree was removed by pruning. Thus the net increase in dry weight from the beginning of a growing season to the beginning of the

following season was 48.8%. Palmer (1988) measured the yield, leaf area and dry weight over the first 5 years of Cripsin/M27 apple trees grown in a bed system. By the third year, the population of spurs was much larger; 56% of the leaf area was from spurs. From the third to the fifth year these trees produced 78 t/ha fresh weight of fruit, and 17 t/ha of dry matter of which 65% was fruit, 23% leaves and 12% woody tissue including roots. Trani *et al.* (1981) reported the accumulation of dry matter in 20 to 120-day-old apple fruit, fruit production per tree and per ha and major and minor element accumulation.

Dry matter production can also be calculated by modelling photosynthesis and respiration. Hansen (1971) calculated that only the development of the first 5 to 6 leaves was dependent on reserves; after that, the shoots became self-sufficient by photosynthesis, that is the leaf becomes a carbohydrate exporter before attaining a quarter of its final area, about 12 - 15 days after emerging from the bud. Johnson and Lakso (1986a; 1986b) provided a similar result from a carbon balance model. The model was based on measurements of net photosynthesis and dark respiration rates and estimates of the dry weight in the different components of the shoot. Under the prevailing weather of 1981 in New York, the model indicated that a shoot growing to a final length of 50 cm became a net exporter of carbohydrates 19 days after budbreak, a time corresponding to a shoot 4 cm long with 10 unfolded leaves. Assuming the same early growth rates, a shoot with a final length of only 2 cm starts exporting at 15 days after budbreak. The total export of carbohydrates remains higher from short shoots than long shoots until 36 days after budbreak, indicating that short shoots supply greater amounts of carbohydrates to the rest of the plant during this early period. The model estimated the total import of carbohydrates from reserves of about 165 mg for a long shoot and 80 mg for a short shoot. In each instance, these reserves only accounted for about 20% of the total carbohydrates used by the shoot up to that point. The remainder was supplied by current photosynthates. Increased light reduced carbohydrate import and caused earlier and greater export. Increased temperature augmented carbohydrate import and the subsequent rate of carbohydrate export. Short shoots had a greater initial rate of carbohydrate export and continued to export more total carbohydrates than long shoots for about 30 to 50 days after budbreak. Slow leaf area development at a given temperature had little effect on carbohydrate import but delayed the beginning of export. Kappes and Flore (1986) reported that net export of carbohydrate in sour cherry started after 3, 4 and 17 days for the seventh leaf, the terminal leaf and the shoot respectively, at a leaf size of 10.6 cm^2 and 9.2 cm^2 respectively, and a shoot length of 16 cm. While the absolute size at the start of net export was similar, the percentage of full expansion was 17 for the seventh leaf and 51

for the terminal leaf. The onset of export seems to depend on the leaf position. It was also estimated that fruit produced 11.2% of their required carbohydrate. During stages I, II and III of fruit development, fruits produced 19.4, 29.7 and 1.5% of the carbohydrate used during the respective stages. This shows the importance of fruit photosynthesis during its early development when leaf area is still small.

Walton and Fowke (1992) reported specific costs of kiwifruit for a growing season (g glucose/g dry weight) ranged between 1.16 and 1.26 for leaves, 1.15 and 1.35 for shoots, and 1.17 and 1.27 for fruit. Mean specific cost for fibrous roots was 1.17 g glucose/g dry weight. The biosynthetic cost (kg glucose per vine) was approximately 25% more than the biomass. The cost of growth respiration was approximately 17% of the total cost of synthesis. In a grape growth model, Gutierrez *et al.* (1985) proposed that photosynthate is allocated first to respiration, then fruit and reserves, and lastly to vegetative growth. Buwalda and Lenz (1992), working with apples, reported that cropping significantly increased total biomass in spite of the reduction of leaf and root biomass.

Rud' *et al.* (1982) reported that Starkrimson apple trees produced 8.5 - 12.6% greater phytomass annually and made better use of photosynthetically active radiation than the cultivar Prize Wagener. Starkrimson yielded 438.6 and 433.0 centners (Russian unit)/ha in the 5th and 6th years after planting and the proportion of the yield in the annual phytomass increment, in terms of economic productivity, reached 37 - 45%. In Prize Wagener the corresponding values for a yield of 172.5 centners/ha were 19 - 19.6%, and 31 - 36% for yields of 226.6 - 317.6 centners/ha.

Heim *et al.* (1979) compared the dry matter production of young Golden Delicious apple trees in Montpellier, France and Bristol, England in 1975 - 1976. Montpellier received 18% and 24% more radiant energy than Bristol in 1975 and 1976, respectively. For the respective years, dry matter production in Montpellier was 12% and 25% greater than in Bristol.

To quantitatively describe the whole apple tree physiological process for tree growth based on carbon assimilate production, distribution and utilization, a model was developed by Seem *et al.* (1986). Three major tasks were tree-environment linkages, canopy structure and photosynthesis and assimilate distribution and utilization by the tree organ systems for their maintenance and growth.

The tree model consists primarily of organ and physiology submodels. Organ submodels represent 6 physiologically distinct organ groups: leaf biomass, current-season extension shoot biomass, stem biomass, root biomass, fruit biomass and stored reserve carbohydrate biomass. The three physiology submodels include resource production, resource allocation, and tree-environment interactions. The model can also be easily interfaced with disease or insect pest models. The model program, written in FORTRAN V, allows the user to progress through a growing season by use of a set of 16 commands. The command structure permits the user to display and/or alter 83 of the simulation variables at any time during the simulation process. Although the model program was developed on a large computer system it was modified to run on a microcomputer.

Some other programs developed include the "Stella" dynamic simulation model for an apple tree (Lakso and Johnson, 1990), models on peach fruit (DeJong *et al.*, 1990), on kiwifruit (Buwalda *et al.*, 1990), and on citrus (Harpaz *et al.*, 1990).

2.1.4 Modelling of Nitrogen

Nitrogen (N) is one of the most important factors affecting plant growth. In spring, the initial carbohydrate reserves do not determine the amount of new growth, whereas reserve N is of decisive importance for shoot growth vigour (Tromp, 1983). Spring leaf growth of a deciduous tree depends largely upon the N supply of the previous year through the remobilisaton of N stored during the winter (Habib and Millard, 1992).

Photosynthesis depends not only on climatic factors such as solar radiation and temperature, but also on the demand for dry matter. The demand for dry matter is affected by N status of the plant. An experiment by Wermelinger and Baumgärtner (1990) on grapes showed a proportional allocation of the photoassimilate to its three sinks, maintenance respiration, reproductive growth and vegetative growth, depending on the level of soil N. With increasing N deficiency, higher proportions of assimilate were incorporated into the fruit. The allocation to vegetative mass reacted conversely, whereas maintenance respiration remained at 35% of the total carbohydrate production at all levels of soil N. At a hypothetical soil N content of zero, 40% of the standard yield was produced but plant N reserves were completely depleted at the end of the growing season.

Some experimental data shows the demand for N. Belle de Boskoop apple trees on sandy

soil, were given 3 levels of N fertilization for 26 years of monitoring nutrition in an apple orchard (Gautier, 1976). The maximum yields (375 - 409 kg/tree) were obtained with 170 kg N/year for the first 18 years, followed by 250 kg/year. During the growing season, potted 2-year-old Golden Delicious apple trees were given low N (1 - 2.3 meq/litre of nutrient solution) or high N (10 meq/litre), supplemented in some cases with 0.5% or 2.0% urea sprays (Hansen, 1980). Terminal shoot growth increased with the duration of high N supply, especially with early summer application and a correlation with leaf N was established. Flower density decreased only at continuously low N supply. Fruit set is dependent to a certain extent on the N status of the tree. It is indicated by leaf values immediately after flowering when the N concentration of the spur leaves should be 2.8 - 3.0% or more to ensure a proper fruit set. Fruit growth at a defined fruit/leaf ratio increases with N supply. The N supply during the early part of the fruit growth period was the more important.

A dynamic simulation model of total N partitioning in a whole peach tree was developed by Habib *et al.* (1990). Four compartments, roots, trunk, shoots and leaves, were considered. The main assumptions of this partitioning model were:

i only certain of the flow pathways between compartments need to be considered;

ii for each compartment, the rate of N outflow depends on N content of that compartment (source capacity);

iii the rate of N outflow from a compartment is proportional to the sum of rates of dry matter increase in the compartments that can act as sinks for that compartment;

iv total outflow from a compartment is divided among the compartments that can act as sinks according to their rates of dry matter increase (sink equality).

The results of the N allocation model were compared to the N data from 1-year-old peach trees in sand culture from the beginning of the growing season until after leaf fall. It showed that the fitted data were very close to the measured values. Loisel *et al.* (1992) stated that the transport coefficients were also estimated by fitting the model to the amounts of N in each plant compartment at each measured date. These may be used for calculating N fertilization strategy to optimize various objective functions.

The withdrawal of N during leaf senescence has still not been included in a model describing the distribution of N within a plant during a growing season (Habib and Millard, 1992). This limits the use of modelling to the current season's growth. In order to be able to model

N withdrawal from senescing leaves, a negative growth rate was suggested to allocate N back from leaves to other tissue.

2.1.5 Modelling of Evapotranspiration

Blanke and Lenz (1985) reported that transpiration rates of apple fruit were low compared with leaf values and decreased during fruit development from June to October in Germany. In the early stages of fruit development, fruit stomata seemed to function similarly to those of leaves. In early June they were 20 - 30 μ in length and 10 - 25 μ in width with a frequency around 25 per mm^2, decreasing to < 1 per mm^2 when fruit reached its final size. Blanke and Lenz (1988) working with pot-grown Golden Delicious apples, measured the transpiration of attached fruit from anthesis to harvest. Fruits were enclosed in a perspex cuvette and the transpiration rate determined by dew point hygrometry. Under laboratory conditions, each fruit transpired 100 ml water during its development. Increasing temperature or light intensity increased transpiration, particularly in the early stages of growth. Under field conditions, each fruit transpired about 50 ml water, equivalent to about 8.5 litres per tree and 18700 litres per ha. Fruit accounted for about 6% of the total water transpired.

In view of the increasingly widespread application of computer technology and automatic irrigation systems, Brezhnev and Kleizit (1987) outlined a model for the moisture cycling process under irrigation. They developed a series of 8 equations, working from an initial assumption of even moisture distribution in each soil element. Here air density, atmospheric humidity and wind speed, conductivity of the root wall, moisture potential in all elements of the plant, root-system density, and balance of moisture intake were involved. The computer model was used in conjunction with standard agro-meteorological information for automatic irrigation systems. Several empirical models for predicting apple leaf conductance from environmental measurements were compared by Jones and Higgs (1989). A simple model involving air vapour pressure deficit, air temperature and a hyperbolic function of irradiance was found to explain between 32 and 62% of the variance in leaf conductances for the different data sets. The model fit could be improved by including soil moisture deficit among the independent variables. The soil moisture distribution under an apple tree irrigated by a drip source was also simulated using CSMP (Continuous System Modelling Program) by Khatri *et al.* (1984). A transpiration model (CRPSM) successfully explained tree growth and yield differences on the basis of transpiration competition between the tree crop and

grass cover (Anderson *et al.*, 1992).

"Epidermis-free parenchyma" tissue of fruit may be found in split cherries and plums or injured apples and pears (Leuschner *et al.*, 1982). This influences the behaviour of such fruit. Model studies on Golden Delicious apple were conducted in relation to pressure, temperature and humidity. Theoretical derivations concerning temperature decline and water losses in injured apple surfaces were compared with experimental findings and the results showed qualitative agreement.

2.1.6 Modelling of Physical Injuries

Some models have been developed for apple impact bruising in harvesting and packing (Sarig and Little, 1978; Holt and Schoorl, 1983; 1985; McLaughlin and Pitt, 1984; Gan-Mor and Galili, 1987a; 1987b; Siyami *et al.*, 1987; 1988) and in transport (Schoorl and Holt, 1985; Church and Peterson, 1988) and storage (Kok and Raghavan, 1984; Baumann, 1986; Sass and Lakner, 1989).

2.2 EFFECT OF CLIMATE ON FRUIT PRODUCTION

To simplify analysis of the climatic factors affecting yield, they can be classified into exogenous and endogenous variables. The effect of weather, climate, soil type and management are exogenous on the system, while the inherent genetic, hormonal and physiological behaviour of the apple tree system, acting either independently or in combination, are endogenous (Beattie and Folley, 1977).

The effect of climate on fruit production has been reviewed by Pereira (1975), Landsberg (1977), Lakso (1987), Lakso *et al.* (1989) and Lakso (1990). From the plant physiological point of view, climate influences photosynthesis, respiration and stomatal behaviour (Landsberg, 1977; 1980). Long-term shading during most of the season is detrimental to fruit size (Lakso *et al.*, 1989). Although some climatic parameters differ by 60%, Folley (1973) postulated that the potential yield of commercial apple orchards in southern Europe is less than 50% greater than on good sites in northern Europe.

For fruit production prediction, it is more important to know the direct influence of climatic factors on fruit set, thinning and fruit growth. Climatic factors can be divided into extreme

and non-extreme weather. Extreme weather factors include the chill requirement (in section 2.1.1) and spring frosts which have a clear influence on fruit production.

2.2.1 Spring Frost

The clearest relationship between yield and an exogenous climatic factor is that of severe frost causing tissue damage to spring growth and flowers resulting in loss of crop (Beattie and Folley, 1977; Fischer, 1980). Late-flowering cultivars of apples showed significantly less frost injury but a long flowering period showed no advantage (Vogl and Pätzold, 1987). Because there was a close correlation between frost hardiness evolution and phenology a frost resistance submodel was tried by Winter (1986b). This submodel computed the LT50 frost hardiness level for buds and flowers. This level was checked back every day with the minimum temperature. Using a normal distribution, the percentage of damaged organs was estimated for temperatures near the LT50 level. The results were very closely related to real observations over the past 24 years. The percentage of frost-damaged flowers of sweet cherry was negatively correlated with fruit yield per tree (Grossmann and Störtzer, 1985). They presented a multiple regression equation for the calculation of expected sweet cherry yields from the percentage of frost-damaged flowers and the number of reproductive buds.

There is extensive literature on frost control methodology which is considered outside the field of this review. For example, Davies *et al.* (1987) worked on temperature predictions in an orchard with water sprinklers and Heinemann *et al.* (1992) developed a theoretical model based on easily measured parameters such as sprinkle application rate, temperature of water applied, air temperature and wind speed. Hamer (1981) delayed flowering by 14 days in apples subjected to water sprinkling and hence evaporative cooling.

Other extreme weather conditions affecting apple yields include extremely low temperatures in winter, hail storms, excess rainfall, drought and high winds. Of more importance to the work in this thesis are the non-extreme weather conditions as reflected in daily, weekly and monthly variations in temperature, sunshine hours and rainfall.

2.2.2 Non-extreme Weather Conditions and Their Effect on Apple Production

The yield potential of a fruit tree is sensitive to the "common" weather, or non-extreme climatic variations. Even if sufficient long term weather and yield data is available for

regression analysis the interpretation of the conclusions may be complicated by other factors such as changes in technology. Beattie and Folley (1978) analysed a long-term (1949 - 1975) variation in yield of English apple orchards and of 2 main cultivars, Cox's Orange Pippin and Worcester Pearmain. The equations of yield per hectare were fitted using annual weather and alternate-bearing as variables. The regression model explained 64 - 74% of the variance in yield, of which weather contributed 9.6 - 21%. Multiple regression analysis of Cox's Orange Pippin yields, from 1949 to 1975, showed a linear upward trend of 0.254 ± 0.039 t/ha per year. Jackson and Hamer (1980) thought this was probably attributable to advances in technology rather than to weather influences. Clearly time series weather data of this nature is suspect when other variables develop such as improved technology.

Yield is not the only parameter to consider. Quality, particularly fruit size, as it affects returns, must also be taken into account when interpreting climate-plant interactions.

2.2.3 Effect of the Previous Autumn's Weather

Temperature in the period from fruit harvest to the loss of leaves was found to be positively correlated with the following year's yields (Lakso, 1987). Delaying autumn senescence in young Delicious apple trees markedly increased flowering in the following season even though no additional growth could be seen. However, the potential importance of post-harvest conditions could be seen in the growth of young trees in a cooperative study at Long Ashton, England and Montpellier, France (Heim, 1979). These researchers found that from bud-break to harvest, the total dry weight gained by trees in each location was not significantly different. Yet, after harvest, the trees in Montpellier gained about 25% of their total weight before leaf fall compared to about 5% in Long Ashton. Also, the trees grown in warmer Montpellier produced more blossom than the Long Ashton trees the following spring. Observations of biennial bearing of apples in Hungary also led to the conclusion that the crop in the "off" year depended very strongly on the warmth and length of the period after the previous "on" year harvest (Lakso, 1985). The reasons for this were not elucidated, but this period is known to be important for the development of flower buds and roots and storage of nutrient reserves for the next year. It is not surprising that weather can be important to these processes (Lakso, 1987). However, Beattie and Folley (1977) did not find a relationship between temperature the previous autumn and yield the following year.

2.2.4 Pre-blossom

There is a particularly interesting negative effect of warmer than normal temperatures in late winter on subsequent apple fruiting. This was initially observed for apples in 1927 by a statistician for the US National Weather Service who was looking for correlations between weather patterns and agricultural yields (Mattice, 1927).

Beattie and Folley (1977) reported a clear association between mild weather in the pre-bloom period and poor yields in the apple-growing areas of north west Europe. A strong negative correlation (r^2 = -0.86**) was established between the mean yield in each year and the accumulated degree-days (over 5°C) for the early spring period February to April inclusive in the same year in England. The yield of Cox's Orange Pippin apples varied greatly from year to year during the 1949 - 1975 period of analysis. A high mean maximum temperature during the February to April period was associated with low yields for all varieties studied by Jackson *et al.* (1983) in England. Lakso's (1987) data in New York also supported these findings. Four factors, time, mean daily maximum temperatures in February to April, days required to complete pollen-tube growth and mean daily maximum temperatures in June together accounted for about 80% of the total variation of apple yield according to Jackson and Hamer (1980), working with apples in England. Although high temperatures in early spring led to early blossoming, this was not associated with greater frost damage or lower temperatures at the time of pollination. Their interpretation was that the adverse effect on yield of high pre-blossom temperature is a negative effect on flower quality and fruit setting potential.

Goldwin (1982) used daily meteorological data to establish two very high correlation coefficients between apple yield per ha and climatic data in England. Mean maximum temperature over 45 days, starting 99 days after full bloom (August and September) gave an r value of 0.96. Mean minimum temperature for a 46-day period commencing 79 days before full bloom (February and March) gave an r value of -0.86. The relationships established with data for the years 1969 - 1973, proved reasonably accurate for predictions made for the 1974 - 1979 period.

To study the physiological basis of the late winter effect Abbott (1971) designed a series of experiments with Lord Lambourne apples using controlled environment chambers in England (Table 2.5).

Table 2.5 Controlled temperatures for experiments with apples

Treatment	Dormant-Bud break	Bud break-Green cluster	Green cluster -Pink bud	Pink bud-Petal fall	Petal fall-Harvest
	°C	°C	°C	°C	Glasshouse
1	8	11	14	18	at 17°C
2	8	11	14	14	"
3	8	11	11	14	"
4	8	11	11	11	"
5	8	8	11	14	"
6	8	8	11	11	"
7	8	8	8	11	"
8	8	8	8	8	"
9	4	8	11	14	"
10	4	8	11	11	"
11	4	8	8	11	"
12	4	8	8	8	"
13	4	4	8	11	"
14	4	4	8	8	"

From the 14 treatments, the primary leaves of trees in treatments 9 to 12 were of a very healthy, dark green colour and the flowers, which reached full-bloom during May, were particularly large. They set well and cropped heavily.

Trees in treatments 5 to 8 flowered throughout April, and a high initial fruit set was followed by a period of steady fruitlet abscission until about 8 weeks after full-bloom. The trees made very little vegetative growth, but cropped heavily.

Trees in treatments 1 to 4 flowered at the end of March, but the flowers were small and the primary leaves a pale green. Initial fruit set was poor and the majority of the flowers abscissed rapidly without swelling.

In treatments 13 and 14 abundant root initials grew out along the stock above soil level. The trees did not blossom until June and the flowers were small with poor anther dehiscence. The clusters, however, were well furnished with secondary leaves and many gave rise to shoot growth. Fruit set was poor.

Low temperatures during dormancy to bud break led to relatively late bloom. This was beneficial to bud development, especially to flower buds, leading to higher fruit set. It is also clear that the lower fruit set in treatments 1 to 4 was due to poor flower bud development.

Jackson *et al.* (1983) in England also simulated conditions by holding potted Cox's Orange Pippin apple trees in cold rooms at different temperatures during February-April, transferring the trees each night to rooms kept at 5 and 10°C, respectively. The results showed that the fruit set from the 5°C treatment was significantly greater than the 10°C treatment. Jackson *et al.* also used mist irrigation for evaporative bud cooling from mid-February to late-April, producing a highly significant increase in fruit set. High temperatures during this period seem to reduce the ability of the apple flowers to be effectively fertilized even with proper pollination (Lakso, 1987). It is possible that higher temperatures reduce ovule longevity. Bergh (1985) reported in South Africa that apple floral organs developed slowly during June, July and August. Carpels grew upwards, sepals and petals elongated and pollen sacs developed in the anthers during September. Ovule primordia were distinguished toward the end of this period, approximately 21 days before anthesis.

Gautier (1976) in France found that rainfall during January-April had a positive influence on yields which could be correlated with low temperatures.

2.2.5 Post-blossom

Cool post-blossom temperatures favoured vegetative rather than apple fruit growth (Williams, 1981). Barlow and Cumming (1975) reported that high temperatures immediately after full bloom (May and early June) lead to the rapid completion of pollen-tube growth and were associated with high apple yields in England. Yield was positively correlated with good weather in the first and second weeks of May; that is in the first week after full bloom. This possibly was an effect on apple fruit retention and growth as documented by Jackson and Hamer (1980) and Jackson *et al.* (1983). However, Lakso (1987) thought the climate in New York was rarely as cold after flowering as it is in England and could not duplicate the results of the English researchers. Barlow and Cumming (1975) also reported that later, in the fourth week of May, or in the third and fourth weeks after full bloom, high sunshine hours showed a negative correlation with yields. The authors recognized this as a surprising result which they could not explain. They recorded it in their paper to indicate the

difficulties that could be encountered in this type of analysis.

Abbass (1972) working with apples and pears stated that the influence of climatic factors on growth and yield varied from month to month, and that temperature was a more important factor than precipitation. Water stress before, during and just after the flowering period (the cell division period) of apples was found to affect yields by decreasing fruit number and the cell numbers of the remaining fruit (Powell, 1974; 1976).

2.2.6 Orchard Microclimate

It is necessary to know how weather conditions in orchards differ from those measured in a standard meteorological station. Observations over two years by Landsberg (1977) showed there were some small differences in air temperature and humidity between the meteorological station and in the orchards. Orchards are open-structured plant communities which normally allow free mixing of air from within and without the orchard. However, wind speeds in an orchard depend on wind speed above the orchard, the size of the trees, their spacing, the direction of the wind relative to the rows and the extent of shelter belts.

Orchard temperature can be affected also by orchard management. For example, Andrews *et al.* (1992) reported, under full irrigation, the temperature of a Royal Gala apple tree canopy was not more than 1°C higher than the air temperature while with no irrigation the differences reached 1.6°C. The temperature of shaded leaves were 0.7°C less than those of the exposed canopy.

2.2.7 Modelling of Phenology

Apple bud development and growth after dormancy was used by Landsberg (1974) to produce an empirical model of growth up to full bloom. The analysis and model were set in the framework of the physiological mechanism considered to be responsible for dormancy and subsequent bud growth.

The literature also contains attempts to predict flowering date. Jackson's (1975) data predicting full bloom, relates to total degree-days >5°C from 1st February to 15th April in England. In some years, he suggested, when the spring is mild, the autumn temperature could influence blossom time as well.

For predicting harvest dates, the period between flowering and harvest can be divided into 3 phases of differing temperature response (Kronenberg, 1988). In most cases the first month after the beginning of flowering and the period immediately before harvest showed a positive response in terms of harvest date to high temperatures with apples. During the period in between, which varied from 1 - 2 months in early cultivars to 5 - 6 months in late ones, no temperature effects were found in most cultivars. Luton and Hamer (1983) could not find a relationship between meteorological data taken from the 50% full bloom stage until the recommended harvesting date and the length of the growing season. Good correlations were established between the number of days from 31 August in England to the recommended harvest date with temperature, solar radiation and potential evaporation but accumulated temperatures from June to September were the most significant. By including the date of 50% full bloom in a multiple regression the prediction of harvest date was further improved (r^2 = 0.72). Using this regression, the differences between harvest dates predicted by 1 September each year and recommended dates were less than 3 days in all but one of the previous 21 years.

2.3 PRODUCTION FORECAST

Production in this case is defined in economic terms. Not only must yield be capable of prediction but the effect of size distribution on fruit value requires that production be recognized as a function of fruit number, fruit size and dollar value.

2.3.1 Yield and Trunk Size

Trunk circumference, as a simple measurement stated in section 2.1.2.1, can be used to correlate with yield per tree of apples (Waring, 1920; Oosten, 1976). However, the correlation is different for different varieties. Clarke (1967) found Worcester Pearmain showed a stronger correlation than Cox's Orange Pippin. The correlation may also become less as trees grow older (Waring, 1920). Sudds and Anthony (1928) also used both yield and tree growth as they related to trunk circumference, but the correlation was much better if the circumference was squared or cubed.

Wilcox (1941) studied several possible methods of adjusting apple yields for differences in tree size. The adjustment was too small when made to a constant trunk circumference, and too large when made to a constant CSA of the trunk, and about right when made to a

constant geometric mean of the circumference and the CSA. The most reliable method, however, appeared to be to use the coefficient obtained from the regression between yield and trunk size. Large differences in severity of pruning were found to lessen the reliability of the methods used for making the yield adjustments.

Increase in mean trunk circumference (in cm) of 8 to 17-year-old McIntosh apple trees was a linear function of mean crop load (in kg/cm^2) (Webster and Brown, 1980). Kecmanović (1979) obtained a similar result.

An inverse correlation was also observed between productivity and the increment in trunk circumference (Borkowska, 1974). The previous year's yield influenced the current year's yield primarily and influenced growth only indirectly. Removing the developing fruit in a year of high yields resulted in increased trunk growth compared with untreated trees (Abbass, 1972).

Crop density has been defined as the number of fruit carried on the tree per unit of trunk CSA (Lombard *et al.*, 1988). Robinson *et al.* (1991) calculated crop density based on trunk CSA, annual increase in trunk CSA, canopy volume, or on a land-area basis. The best regression fit between fruit size and crop density was obtained using trunk CSA. The land-area method gave the poorest fit.

2.3.2 Factors Affecting Fruit Size

The first 3 weeks following apple flowering are of cardinal importance in the cell division process and little cell division occurs more than 35 days after full bloom. Exceptionally heavy crops produced by the trees during the preceding years were mainly responsible for the small fruit at 42 days following bloom as well as at harvest (Bergh, 1985).

Aeppli (1983) reported that, when apple trees flowered early, perhaps in a warm season, fruit grew much larger and longer than in a cooler season. The difference in diameter was evident 2 months after full bloom. The apple fruit growth data of Welte (1990) showed a strong correlation with temperature especially during the first 50 days after bloom. Cool weather not only may retard fruit development during the early part of the season, but also will affect later fruit growth (Batjer *et al.*, 1957).

Bergh (1985) grew apple trees in 2 growth chambers. Both chambers were held at a day temperature of 22°C. One was held at a night temperature of 12°C, and the other at 18°C initially. During the third week after bloom the night temperature of the chambers was exchanged. The results clearly showed that the weekly growth rate of the fruit (increase in volume) was higher with the higher night temperatures (18°C). This is because fruit grows mainly at night. Low night temperatures could retard fruit growth even later than 6 weeks following bloom. Williams *et al.* (1969) reported that an ambient temperature between 12.8° and 23.9°C appeared to be ideal for an increase in fruit volume of Bartlett pear. Ambient temperatures above 26.7° and below 12.8°C appeared to reduce pear fruit growth. They found that volume increases on average 1.5% per day during the period from 95 to 120 days from bloom.

Webb *et al.* (1980) reported on Golden Delicious apple trees with different numbers of fruit per spur, per branch and per tree. At harvest, fruits were weighed individually and their positions on spurs and branches noted. There was no indication that a reduction in number of fruit per spur led to an increase in mean size per spur. Although mean fruit weight on branches may differ significantly from their tree means, the differences cannot be attributed to the degree of crop loading on different branches. Therefore mean fruit weight was not affected by uneven distribution on the trees, whether between spurs or branches. Seed number was not a determining factor for fruit weight but fruit number per tree does influence the fruit size.

Negative correlations were found between yield per tree and average fruit weight for apples (Preston, 1954; Forshey and Elfving, 1977; Lenz and Gross, 1979; Trani *et al.*, 1981), plums (Wells and Bukovac, 1978) and kiwifruit (Burge *et al.*, 1987; Cooper and Marshall, 1988). Thinning increased mean fruit weight and reduced total yield (Forshey and Elfving, 1977; Wells and Bukovac, 1978; Winter, 1980; Burge *et al.*, 1987). Although fruit thinning increased the percentage of larger fruit, the actual number of large fruit was either unchanged or reduced (Forshey and Elfving, 1977; Burge *et al.*, 1987). Winter (1980) pointed out that thinning increased both yield and fruit size in the following year. Crassweller *et al.* (1992) emphasised the importance of early thinning to increase fruit size. However, Stolle and Kluge (1976) measured random samples in 2 consecutive years and did not find significant correlations between average yield (kg per tree) and mean diameter (mm) of the fruit.

Other factors may affect fruit size. Hamm and Lenz (1980) reported that apple fruit on short shoots were larger than those on long ones, and fruit in the apical position were larger than in the basal crown region. Palmer *et al.* (1991) reported that mean apple fruit weight per tree at harvest was linearly dependent on leaf area per fruit and on light interception per fruit, a photosynthetic effect.

A model concept for better understanding of fruit development dependent on endogenous and exogenous factors was developed by Saure (1978). The model was based on the interaction of gibberellins and cytokinins with auxins and ethylene under different environmental conditions. The hormonal balance and interactions at 3 phases of fruit development were graphically presented and the observed hormonal effects during fruit development explained by their interactions.

2.3.3 Fruit Size Prediction

Winter (1980) stated that a 1 mm increase in apple fruit diameter at harvest corresponds to a 4% increase in yield and a 10 - 20% increase in value. Many apple fruit growth curves have been reported (Tetley, 1931; Tukey and Young, 1942; Denne, 1963).

Bergh (1982) proposed a model which emphasised number of apple fruit per cm trunk circumference during the current year, number of fruit per cm trunk circumference during the previous year and the average diameter of the fruit 40 days after full bloom. A multiple linear regression equation was fitted to the data. The independent variables included in the fitted equation accounted for approximately 95% of the variation in fruit size at harvest.

Forshey (1975, 1976) reported in New York that McIntosh apple fruit weight and fruit diameter on 1 August and at harvest were found to be closely related. Average fruit size on 1 August provided an estimate of fruit size distribution at harvest. A practical example was given of apple crop forecasting using the Forshey method by growers (Costante, 1976). The research showed that the later the prediction the greater the accuracy. Crassweller *et al.* (1992) found the accuracy of prediction better for large fruit. Although the reason was not clear, the sizing ability of the smaller fruit is subjected throughout the growing season to a greater number of factors.

Several researchers obtained significant correlations when comparing fruit size earlier in the

season with the size of the same fruit at harvest. Batjer *et al.* (1957) measured apples at 35, 55 and 75 days after full bloom over 4 years and in all cases the r values were significant at the 1% level when related to harvest size. The r values naturally were higher the longer after full bloom the initial measurements were taken. They constructed a table for the average diameter of fruits in various box-size groups at 5-day intervals, beginning at 35 days from full bloom and extending to harvest, allowing growers to predict fruit size at any stage during the season. Stolle and Schmidt (1975) also found it possible to predict final fruit size of apples from the 60 days after full bloom stage. Williams *et al.* (1969) predicted from the same stage with pears and Davis and Davis (1948) used the expression "reference date" about 40 days after full bloom to predict final fruit size of peaches at the 1% level of significance.

2.3.4 Forecasting Yield

Fukushima (1965), Jackson (1967), Vogel and Christoph (1970) and Neumann *et al.* (1975) all worked on predictive apple models but Winter made the most significant contribution on the prediction of fruit production. In 1966 he proposed a method to determine a normal, regional, expected yield in relation to fruit set and also an average fruit weight prediction. In 1971, he described a method for predicting yield from any particular growing region over a period of several years. The assessment was based on estimations of the potential yields for trees of different ages and sizes, the fruit density on the tree (which has an optimal value for any variety, below which quantity, and above which, fruit quality suffers) and the average fruit weight. The reliability of the method depends on good statistical data on tree age, variety, rootstocks and planting methods for the region. The actual annual yields varied quite closely around the predicted value according to climatic conditions. In 1977, Winter (1977) proposed the Bavendorf method of estimating yields in apple orchards. He based this on measuring the crown silhouette (height x diameter) in m^2 and the fruit density by counting the number of fruit (10 samples per tree) on 0.36 m^2 of the crown through a special viewer at a distance of 3 m from the tree. The fruit size was measured on 40 fruit samples in 10 - 20 plantations. A cultivar and fruit size correction factor was applied reducing the error to $< 5\%$. In 1983 he further developed the Bavendorf method according to three phases of yield capacity (YC) in a tree's life: increasing YC, full YC and reducing YC. The method involves calculation of the crown surface, counting the number of fruit per tree and determining mean fruit weight. Many factors affecting YC such as cultivar, rootstock, density of planting and environment were incorporated in the computer model he named

FRUPRO. The basic elements of this model have been used annually in the main apple growing areas in Western Europe for predicting the yield capacity of an observed growing unit (tree, orchard or region), by estimating fruit set density soon after the June fruit drop, and calculating the average fruit weight at harvest by regional weather data and a growth curve in each year. Subsequently Winter (1988) applied the model in Brazil to successfully forecast total apple production at about 135000 t in the Catarian region.

Lehmann *et al.* (1985) also described a method for pome fruit yield forecasting for the current and following years using 34 factors in his computer model. The first 14 factors concerned plantation data (eg cultivar, rootstock, age, and soil), and the others were mainly crop measurements and various calculation factors. The system offered diverse forecasting possibilities. A load density method was described by Liard and Rolin (1978). It assumes that 86% of the fruit is visible. The prediction is based on the crown surface area, and a knowledge of the number of fruit per unit crown surface area, the number of trees/ha, and the fruit weight for the cultivar. Studies were also carried out by Bulychev (1975) on apple trees with large-volume round crowns, small-volume round crowns, palmette crowns or spindlebush crowns. Formulae are presented for forecasting the yield, and for determining the volume of actively assimilating leaves in m^3/m^2 of soil surface, and the yield per unit of actively assimilating leaves in kg/m^3. Korn (1980) proposed that if pome fruit is to be harvested mechanically a lower weight should be taken into account than when a multi-phase hand harvest is planned and some of the fruit will have had time to grow larger. His predictions for 3 apple cultivars over a 3 year period were satisfactory. Forshey (1975; 1976) used weight of fruit/cm of branch circumference 2 months prior to harvest, to accurately predict yields at harvest on the same branches.

A mathematical model for kiwifruit cropping was developed and successfully applied by Testolin and Costa (1990; 1992) based on the percentage of fruitful buds, the number of fruit per fruitful shoot and the mean fruit mass.

A pollination model developed by Brain and Landsberg (1981) takes account of the effective pollination period (EPP) of the flowers, ovule fertility, insect visiting rate and the probability that insects will be carrying compatible pollen. The probability that a fruitlet will drop increases as the number of fertilized ovules decreases. The best strategy for ensuring adequate pollination is increasing insect visiting rate (eg hives/ha). Variations in the EPP cause relatively small differences in pollination and fruit set. The models can be used to

explore a number of facets of pollination and fruit drop in apples. Cour and Bousquet (1981) predicted crop yields from pollen counts. Yields of olives and grapes (both wind pollinated) could be accurately forecast from pollen counts obtained from a pollen trap comprising vertical gauze filters dipped in silicone oil and used in conjunction with an anemometer. Pollen counts in Montpellier, France on 15 and 20 June gave accurate forecasts of yields of olives ($r = 0.96$) and grapes ($r = 0.97$). These were not only much earlier than those made by the Department of Agriculture of France, but they were more accurate. Yields of olives varied widely from 1973 to 1978, but annual pollen counts correlated well with yield. For apples (insect pollinated) the yield forecast from pollen counts is less accurate. Cour and Villemur (1986) reported that, taking into account climatic, biotic and agronomic factors, crop yields were within 10% of estimates. With 5 years of calibration a yield estimate for a single apple orchard could be made to within 5% at the end of the flowering period. Besselat (1987) reported on another model based on grape pollen analysis of the atmosphere which gave promising results over 5 years. Forecasts made on 1 July had a margin of error not > 5%.

Kalinina (1977) also described a method of compiling tables for estimating fruit yields in wild fruit forests. The method was based on visual assessment on a 1 to 5 point scale and on tree age and number/hectare. Fucik (1984) reported forecasting Texas citrus production over 4 seasons. His method was based on counting total fruit per sample tree and rating orchards for productivity and condition. Baghel *et al.* (1988) reported on forecasting the yield of mango. The results showed that the number of fruit/m^2 of tree canopy could be considered the most effective parameter for predicting the yield or total number of fruit per tree, followed by yield or fruit number of secondary branches, number of fruit per panicle and number of panicles/m^2. The number of secondary branches is also considered an important factor for yield forecasting.

2.3.5 The Distribution of Fruit Size

Most of the fruit weight distribution curves for apples (Clarke, 1990; Webb *et al.*, 1980; Visser and Pieterse, 1977) and kiwifruit (Judd *et al.*, 1989) appear to fit a normal curve. However, some reports show the distribution being skewed (Clarke, 1990), slightly positively skewed (Visser and Pieterse, 1977; Webb *et al.*, 1980; McAneney *et al*, 1989) and negatively skewed (kiwifruit) (Burge *et al.*, 1987). Some distributions are more of the "kurtosis" type with a peaked typical bell-shaped normal distribution curve. However, the

assumption of normal distribution seems well justified and the departures from normality can be tolerated (McAneney *et al*, 1989; Judd *et al.*, 1989).

Webb *et al.* (1980) working on 8 Golden Delicious apple trees reported that, although the mean weight of apple fruit differed, there were no significant differences between the standard errors, which ranged from 23.7 to 30.4 g. They concluded that a value of 26.7 g may be accepted as a common value for the standard error. Wells and Bukovac (1978) stated that plum size distribution curves over 2 seasons were similar in shape irrespective of thinning treatment. McAneney *et al.* (1989) reported that the standard deviation of individual fruit weight of kiwifruit harvested from 2 blocks was 20.5 g. The standard deviation changed less than 2 g between seasons, despite wide variations in the mean fruit weight of 30 g, with crop loading and vine age. However, Judd *et al.* (1989) claimed that the standard deviation of kiwifruit weight ranged from 8 to 27 g. No obvious dependence on standard deviations of mean weights of kiwifruit was found (Judd *et al.*, 1989).

2.3.6 Economic Simulation

This section reviews the work on bio-economic simulation models of fruit production. Winter (1986a, 1986c) developed the simulation model FRUPRO which he used to compute biological and economic results based on 28 biological and economic input parameters. Winter calculated the capacity of a tree as a function of age and various vegetative growth parameters, such as area, cultivar and rootstock. He defined fruit set density as normal in relation to growing area and cultivar over a sequence of 2 years. The fruit size was calculated as typical for the area, cultivar and rootstock or defined to be n mm larger or smaller than normal. Other important bio-technological inputs were planting system and final tree height. Economic parameters such as costs and prices, wages, rent of land, and interest rate were other variable inputs. Annual outputs of the model were yield, hours of labour, costs, returns, gross margin and profit. The model is divided into sub-models which run separately for planting system, evolution of tree capacity, distribution of yield by quality and grading classes, mechanization, picking and pruning. The equilibrium prices and quantities can be calculated for each simulated year using an iterative procedure (Behr, 1986). The reliability of the model can be tested in an ex-post simulation using German apple market data. Simulated and observed time series of imports, quantities demanded (fresh fruit, autoconsumption, processing, market withdrawals) and new plantings were compared for the period 1973 - 1974 to 1981 - 1982.

Kiwifruit size is important in determining the profitability of an orchard with the proper management of crop load being vital to the production of fruit in the preferred market sizes. A computerised decision support aid enhances the ability of orchardists to make decisions regarding target crop loads and management strategies (Atkins, 1990). A peach thinning optimization computer model was developed by Johnson and Rasmussen (1990). The model deals with fruit size, crop loads and net revenue.

Since one of the most difficult problems in fruit growing is choosing between alternative plantings and determining the timing for optimal replanting, computer models were developed for economic orchard evaluation (Buchwald, 1986). The probability value for the useful life of trees was determined on the number of trees/stand, the required proportion of bearing trees after t years and expected losses during the period (Kramer and Friedrich, 1979; Busch and Triemer, 1980; Davis and Thiele, 1981; Goedegebure, 1986a; White, 1986; Bauer *et al.*, 1990). The models evaluate technical research results and are useful as an advisory tool for selecting investments and timing replanting. The structure of the models are briefly outlined and the results of an evaluation of planting density shown.

Models for integrated pest management of apples were developed by Russo and Seem (1980). The definition, design and evaluation of models are discussed, and a simple model for apple tree growth applicable to many areas of research, including integrated pest management, was developed. The model design was based on linear relationships between yield (dry matter accumulation) and transpiration, and between transpiration and open pan evaporation. Farm and pest management models were developed also by Hall and Lemon (1990) and Laurenson (1990).

2.3.7 Software Development Strategy

Personal computers are being used more frequently in orchards to help growers make their management decisions. Mainly younger orchardists are taking advantage of computer use. The use of personal computers will become more attractive when software verified for practical use is developed (Winter, 1990). Hobkirk (1986) suggests that the programs should include a payroll/personnel management system, an orchard record system, a general ledger system, a market analysis system and a group of economic analysis systems. The users need the capability to update the daily activities of their orchards and to compare their results with a standard model to detect weak points on their orchards. Reliable models for crop

forecasting are needed to plan labour and packing material requirements and working capital needs. Models should be developed to forecast plant diseases, phenology, and fruit development and maturity. A fax-linked, computer-operated decision support system was proposed for apple and kiwifruit production by Hodson *et al.* (1992).

Software development is not only a new business, but it may also change the direction of research. A closer cooperation between researcher and grower may lead to a much quicker acceptance of scientific results by growers and also to better transfer of growers' experience to researchers. The knowledge of growers and researchers will be jointly documented and updated in dynamic models that become closer and closer to reality (Winter, 1990).

Many management simulation models have been developed to produce cash flow analyses (White, 1986; Goedegebure, 1986b; Grob and Rais, 1986; Caggiati *et al.*, 1990; Goedegebure, 1990; Alvisi *et al.*, 1990; 1992; Sinclair, 1990; Caggiati *et al.*, 1992; Rajotte *et al.*, 1992). A policy analysis model for peaches and apples was designed in Germany (Behr, 1990) to evaluate the effects of different market policies on production, consumers and public expenditure. A chemical thinning expert system was developed by Crassweller *et al.* (1992) for a decision support incorporating climatic, cultural and application conditions. Other diverse models include, a kiwifruit nutrition management service developed by Buwalda and Smith (1990), a calculation program of growth regulator solutions by Gilbertz (1992), a fruit breeding database by Bassi *et al.* (1990), and an almond nut cross-pollination, set-simulation model (ALMOPOL) by DeGrandi-Hoffman *et al.* (1989).

2.3.8 Research on Yield Potential

Extensive research has been conducted on yield potential. Marro *et al.* (1985) reported that apple fruit number per leaf area was correlated positively with yield/ha. High-yielding orchards were characterized by high values of both leaf area index (LAI) and fruit number per leaf. Total fruit yield increased with increasing leaf area but the effect on single fruit weight was less marked. Asada (1988) reported that the apple LAI range was 1.8 - 4.0 and averaged 3.0. It was correlated with yield. Maximum yield (t/ha) was at 2.25 LAI. Fruit number per m^2 of leaf area ranged between 3.9 - 8.6 and averaged 6.7; the yield per m^2 of leaf area range was 1.1 - 2.5 kg/m^2 and averaged 1.8. Ferree (1982) stated that the efficiency of spur leaves determined by apple fruit/100 cm^2 of leaf area was highest in the upper third of the canopy and decreased in the lower levels of the tree. Makariev (1982)

reported that apple fruit yield calculated in relation to leaf area ranged from 0.52 to 0.64 kg/m^2 of leaf area in the 3rd year and was 1.63 - 1.91, 1.1 - 1.25 and 3.86 - 5.16 kg/m^2 in the 4th, 5th and 6th years, respectively. Apple yield was found to be most highly correlated with the volume of the crown and its surface area (Nesterov and Shipota, 1985). Mukhanin (1985) suggested that productivity should be considered only in relation to crown projection (m^2) and volume (m^3) but not per individual tree, which he contended leads to a reduction in accuracy.

Streitberg *et al.* (1982) reported a positive correlation between the percentage of fruit buds and apple yield per tree. The optimum yields were obtained when 30 - 55% of the buds were fruit buds. Streitberg and Handschack (1983) stated that a level of 30 - 35% fruit buds on 1, 2 or 3-year-old shoot terminals were adequate for optimal apple yields, provided no severe winter injury occurred. A random sample of 40 buds was sufficient for a rapid estimation of fruit bud numbers.

Jacoutet (1987) stated that the future of fruit production depends on the characteristics of the existing orchards, tree mortality, new plantings and trends in yields. Červenka (1983, 1984) researched the potential productivity of the apple cultivar Goldenspur using a model of fruit development in relation to photosynthetic productivity. The calculated productivity was compared with actual yields on the best fruit farms in Czechoslovakia. Over 5 years, actual yields averaged from 17 to 50% of the potential productivity. In some years yields reached 66 to 70% of the potential. Of the 17 cultivars the author tested, only 2 (Goldspur and Lord Lambourne) produced > 50% of their theoretical yield.

2.3.9 Research on Alternate Bearing

Another important topic related to yield is alternate bearing. Comprehensive reviews (Jonkers, 1979; Monselise and Goldschmidt, 1982) have dealt with this subject. This review concentrates only on related modelling work.

Various methods have been studied for the measurement of the irregular and biennial phenomena. Hoblyn *et al.* (1936) proposed a quality measurement B to test whether the phenomenon was indeed biennial, and a quantity measurement I to test the intensity of the effect expressed as $I = (\Sigma(Y_{i+1} - Y_i)/(Y_{i+1} + Y_i))/n$, where n is the total years and i is the ith year. Another quantity measurement K, to emphasize larger differences and minimize

smaller ones was proposed by Pearce *et al.*(1967) expressed as $K = (\Sigma(Y_{i+1} - Y_i)^2/(Y_{i+1} + Y_i)^2)/n$. A computer was used to simulate data with a known basic pattern (whether biennial or not), trend (tendency to increase or decrease at a steady rate) and random variation. The conclusion was reached that I, the established method of measuring bienniality, and a related quantity, K, were the most useful. Szczepański (1980) thought that the quantities I and K were found suitable for determining the cropping pattern of trees only in the case of a uniform rhythm of biennial bearing. They were found unsuitable in the case of a constant rise or decline in tree productivity over a number of consecutive years. He proposed a quantity L to cope with this variability. For correct evaluation of biennial bearing a sample of at least 15 trees is required. Based on a χ^2 technique, Marchetti and Ughini (1984) used a decrease in yield in the low-bearing year, against the high-bearing year, arbitrarily fixed at 25%, as the threshold value in determining the 'expected' value. Application of the method to 98 apple cultivars of 4 different types (yellow or red fruited, standard or spur) showed that it gave rapid and clear indications of individual varietal tendencies.

Schmidt *et al.* (1987) incorporated a biennial bearing factor in their mathematical model for predicting apple yield but Beattie and Folley (1978) did not prove a significant effect of biennial bearing in their model.

A method of reducing crop variation in apple trials was proposed by Moore (1976) over a period of 16 years during which the trees received no differential treatments. Crops for a varying number of years were accumulated in order to determine how long a period was needed to obtain a low coefficient of variation. Four year's recordings were better than two, but six years gave little advantage over four. Covariance of previous crops was useful, two years being as good as four. Adjustment by trunk circumference was less successful but could be recommended in conjunction with the previous crop. Number of fruit was a more reliable parameter than crop weight. Removing positional variation by analysis of variance did not have a major effect in reducing variation. Hinz (1989) reported that fruit number and yield per tree were negatively correlated with shoot growth ($r = -0.71$) and stem diameter growth ($r = -0.67$). Fruit number had a negative influence on flower and fruit numbers in the following season, and also affected fruit size, fruit growth and yield. Roversi *et al.* (1979) recorded yield data on 14 apple cultivars collected over 5 years from 15 environments in northern Italy. Analysis revealed a negative correlation between yield stability and productivity.

Many researchers have attempted to define or measure the ability of a fruit tree to carry a particular crop load and to determine if it is possible to quantify bearing potential. Although not directly related to the modelling emphases in this thesis it was decided to investigate the energy potential of a tree in terms of carbohydrate levels to relate this to yield. Hence the next section reviews work on carbohydrate reserves in fruit trees, in non bearing compared with bearing trees and where the crop is alternating.

2.4 CARBOHYDRATE RESERVES IN POMOLOGY

Carbohydrates constitute the major part, about three quarters of the dry weight of woody plants. In the young apple tree as a whole, approximately one-third of the dry weight is extractable in the form of soluble sugars, starch and hemicellulose. In the bark and root, where the percentage of living cells is higher, as much as 50 - 60% of the dry weight may be extractable at certain times of the year (Oliveira and Priestley, 1988). This subject has been reviewed by Murneek (1942), Kozlowski and Keller (1966), Priestley (1962; 1970), Oliveira and Priestley (1988), Loescher *et al.* (1990) and Kozlowski 1992).

"Reserves" may be defined as materials produced in excess of current assimilation and respiration requirements (Glerum, 1980) which may be removed later from storage to support metabolism and growth (Priestley, 1960). The initial spring growth of deciduous fruit trees is wholly dependent upon food reserves stored in the trees from the previous season, until the new leaves can carry out active photosynthesis (Priestley, 1960; Tromp, 1983). Food reserves for the growth and development of an apple tree are primarily carbohydrates (Murneek, 1933; Priestley, 1981). They accumulate during the growing season and are made available in the following spring.

2.4.1 Carbohydrates in Various Organs

Storage of reserves is a function only of the living cell (Priestley, 1964b) mainly in the parenchyma. Specialized cells such as sieve-tubes do not store reserve nutrients, as it would disturb their physiological function of transport. Since it is essential for the storage parenchyma in the phloem and the xylem to be in direct contact with vascular tissue, a special function in the transport of reserve compounds is attributed to radially-running ray tissue containing the parenchyma with the main conducting elements in the phloem and xylem (Ziegler, 1964).

2.4.1.1 Above Ground

The starch and sugar content of the bark and wood of apical and middle portions of long 1-year-old apple shoots were measured by Naumann and Faby (1987) from the beginning of dormancy in late October until early April in Germany. Glucose, fructose and sucrose are mainly stored in the bark. Starch accumulation is more intensive in the pith, medullary rays and wood parenchyma (Schimpf and Stösser, 1984; Naumann and Faby, 1987) than in the bark and phloem tissues. Woody tissues may play a role in keeping the carbohydrate demand and supply in balance (Yoshioka *et al.*, 1988). All live cells apart from those of the cambium, phelloderm and sieve tubes, contain starch, the content of which is highest in the nodal areas (Schimpf and Stösser, 1984). During the winter and spring the small amount of starch was found to disappear from all tissues except the pith.

2.4.1.2 Roots

More than half the reserves of dormant trees may be located in the roots (Murneek, 1942). He found a ratio between starch and the soluble sugar fraction of between 3 and 4 for apple roots according to age (Table 2.6).

Table 2.6 Quantitative distribution of carbohydrates in 18-year-old Jonathan apple trees in Mid-October (calculated from Murneek, 1942)

Materials	Dry weight (kg)	% of dry weight			
		Total carbohydrate	Starch	Hemicel-lulose	Sugars
Total above ground	203.7	30.8	4.4	23.1	3.4
Root stump	21.9	37.0	11.0	23.0	2.7
18 - 14 year old roots	28.2	39.0	11.4	24.7	2.9
13 - 7 year old roots	16.3	43.8	12.3	26.4	5.1
6 - 1 year old roots	2.6	42.0	11.5	25.0	4.7
Total below ground	69.0	39.6	11.5	24.6	3.5

Sugar constitutes a small proportion of the carbohydrate fraction accumulated mainly in the roots prior to bud break. Starch continues to accumulate in the roots, and to a lesser extent in the woody parts of stems, until final leaf fall (Stassen, 1984). Root starch concentration in fruit trees does not appear to varying significantly with air temperature during dormancy, possibly due to winter soil temperatures being higher than air temperatures (Tromp, 1983).

2.4.1.3 Flowers

The changes in starch and sugar levels in the styles of a sweet cherry cultivar Büttners Rote Knorpel and a sour cherry cultivar, Schattenmorelle, were investigated by Stösser and Neubeller (1980). They found that starch accumulated in the conducting tissue of the style, reaching a maximum at anthesis, before being gradually broken down. In Büttners Rote Knorpel no starch remained 4 - 6 days after anthesis and in Schattenmorelle, all the starch disappeared 1 - 2 days after anthesis. The maximum sugar content occurred 2 days after anthesis for Büttners Rote Knorpel and at anthesis for Schattenmorelle.

2.4.2 Seasonal Changes

Seasonal studies of carbohydrate reserves in trees have been conducted for more than 100 years (Oliveira and Priestley, 1988) and specifically in fruit trees by many authors (Kandiah, 1979a and b; Smith *et al.*, 1986).

Dolgova (1974) in the USSR determined the starch and soluble sugar content in 1-year-old shoots of 3 apple cultivars at 15-day intervals throughout the year. Maximum starch accumulation occurred in September and maximum soluble sugar accumulation occurred in November. In 1-year-old shoots the starch content decreased and sugar content increased as the season moved from autumn into winter. With decreasing temperature starch was almost completely hydrolysed by February in Germany (Schimpf and Stösser, 1984). After re-synthesis, due to the increasing temperature, a second starch maximum occurred in early April. With the start of bud swelling and cambial activity starch content decreased rapidly, showing a second minimum at full bloom. This confirmed the importance of stored starch as a source of energy for bud development and initial growth during early spring (Stassen, 1984). Arutyunyan (1977) found that flower bud initiation and differentiation coincided with high leaf carbohydrate content, especially starch.

In peach buds the carbohydrate content was associated with morphogenesis, whereas in the shoots, carbohydrate metabolism was correlated with air temperature (Elmanova, 1974). In studies with the winter-hardy grape cultivars Rhine Riesling and Muscat Ottonel, Kirillov *et al.* (1976) found the greatest changes in shoot sugar, starch and hemicellulose content occurred in the temperature range 0° to -10°C. Maximum sugar content (7.8 -8.4% of dry matter) in the current year's grape shoots was observed during flowering (Khatshevich, 1977). The level declined to 3.1 - 3.5% at the end of the growing period. Shoot starch content was lowest during flowering and highest at the end of the growing period.

2.4.2.1 Dormant Period and Early Spring

Hansen (1967b) used ^{14}C to trace the movement of carbohydrates in apple trees. After exposure to ^{14}C during October in Denmark, the majority of the ^{14}C absorbed was found in the root. During the winter, and in particular the spring, the amounts of ^{14}C in both the above-ground part of the tree and the root are reduced to approximately 40% of the autumn values (Hansen and Grauslund, 1973).

From studies with ^{14}C, at least some utilization of reserves from apple roots took place during spring (Hansen and Grauslund, 1973). However, only in the very earliest phases of development does the growth of flowers and shoots appear to be based to a greater extent on materials supplied from reserves than from current photosynthesis (Hansen, 1971). He found that the fixation of ^{14}C by growth in the exposed leaves is high in the earliest phases of growth. The fixation of ^{14}C is considerable in the flowers, including the petals, immediately prior to flowering, in intensely growing fruit, and in the woody parts of the current year's shoots. A decrease of 4 - 5% of dry matter in spring was calculated. The total amount of carbohydrate and of structural materials in the non-leafy part of the tree for each stage remained very similar up to the end of shoot extension (Priestley, 1973). After this, carbohydrates accumulated faster than structural material, especially with higher light radiation (Priestley, 1963).

A few days after bud burst, starch was detected in grape shoot cortical parenchyma and pith and, to a lesser degree, in the leaf midribs and in cells of the lower epidermis (Bernard, 1985). Starch was later detected mainly in the interfascicular rays, xylem and, to a lesser extent, in the phloem. During the period from veraison to maturation, starch disappeared progressively from the mesophyll of leaves at the basal part of shoots.

2.4.2.2 Diurnal Changes

Diurnal changes in carbohydrate content of leaves were studied during rapid growth, fruit ripening and after harvest in 3 apple cultivars noted for irregular bearing. In bearing trees, maximum carbohydrate accumulation occurred during the night and in non-bearing trees in the evening (Arutyunyan, 1977).

2.4.2.3 Quantitative Description

One to 3 year old apple branches were analyzed on 6 dates between January and April in Yugoslavia by Bulatovic *et al.* (1974). The water content increased during that period and the dry matter content decreased; the highest dry matter content was found in 3-year-old branches (56.80%). Total sugars increased in January - February and then decreased; their content was highest in 1-year-old branches (4.78%). Starch accumulated until February and then started to decrease. Dobreva (1983) in the USSR found that the magnitude of changes in soluble sugar and starch content in maturing grape shoots during the autumn-winter period amounted to 6.5 - 7%. Greatest changes occurred in mid-November to mid-December and in mid-February to the end of March. The most rapid change recorded for soluble sugars was 0.16% per day and for reducing sugars 0.13% per day.

For a 2 year old apple tree with a dry matter weight of about 300 g, the utilization of reserves from the tree in the spring was calculated to be at least 13 g of dry matter (Hansen and Grauslund, 1973). However, only a minor part (< 25%) appeared to serve as structural material for new growth. Priestley (1970) found that plants grown in complete darkness only needed to lose one third of their extractable carbohydrates before they died.

2.4.3 Influence of Alternate Bearing on Carbohydrate Reserves

In bearing trees the contents of soluble and insoluble carbohydrates decreased during fruit development and ripening but increased after harvest (Arutyunyan, 1977). In non-bearing trees, carbohydrate content remained unchanged during the same phases but was appreciably higher than in bearing trees. The effect of fruit has an influence on carbohydrates according to several researchers. The content of ^{14}C in the leaves is reduced more rapidly in shoots bearing fruit than in those without (Hansen, 1967a). Every year a dramatic fall in the starch content was observed in the fruit-bearing spurs at the end of June between the 5th and 6th

week after full bloom in Poland (Grochowska, 1973). Apple leaf samples collected on 10 September in Germany from non-fruiting trees had a much higher total carbohydrate content (20.1% dry weight) than those from trees cropping heavily (13.9%) (Siebertz and Lenz, 1982). The leaves of non-bearing apple trees had considerably higher starch content (Grochowska, 1973; Lenz and Engel, 1984). Three year old bearing Golden Delicious apple trees had a smaller root system with a lower starch content in the autumn than non-bearing trees (Lenz and Siebertz, 1980).

For Pistachio, characteristically a biennial bearer, non-bearing 1-year-old branches gave rise to heavy crops the next year and, because of greater quantities of nutrient reserves, also produced extensive shoot growth (Crane and Al-Shalan, 1977). Levels of total sugars in bark and wood of bearing and non-bearing branches were similar throughout the year but starch levels were generally higher in non-bearing branches. For citrus, the starch content of non-bearing trees was always higher than that of bearing trees (Lenz and Küntzel, 1974; Shimizu *et al.*, 1978). Total sugar, starch and acid hydrolysable polysaccharide content increased rapidly in the main organs on non-bearing trees after fruit thinning, while that of bearing trees increased rapidly after harvest.

Shimizu *et al.* (1978) found that annual accumulation of reserve carbohydrate in each bearing citrus tree before thinning was approximately 38 g, of which 58% was in the fruit. In contrast, annual accumulation of reserve carbohydrate in a "non-bearing" tree before thinning was approximately 28 g, 11% of which was distributed in the leaves, 22% in the stems, 11% in the trunk, 47% in the underground parts and 9% in the fruit.

Two 15-year-old alternate bearing Wilking mandarin trees, one in the "on" year and the other in the "off" year, were uprooted and dissected into 11 organ types by Goldschmidt and Golomb (1982). Starch and soluble sugar concentrations were determined for each organ (Table 2.7).

The off:on ratio for starch was very high in the root system (7 to 17), lower in leaves and branches (3 to 5) and in the trunk it did not exceed a ratio of 2. The levels of starch in the trunk remained relatively high during the "on" year, suggesting that starch deposited in the trunk is not easily mobilized and recycled. The off:on ratio is much lower for soluble sugars than for starch. Starch seems to behave as a true reserve material, which may accumulate in high concentrations and then be almost completely depleted. A total dry matter, starch and

soluble sugar balance was compiled for each tree. The "off" tree contained 13.26 kg starch and 10.66 kg soluble sugars, compared with 2.95 kg starch and 6.75 kg soluble sugars in the "on" tree (excluding the fruit).

Table 2.7 Starch and soluble sugar concentration (mg/g dry matter) in organs in off and on year trees of Wilking mandarin (Goldschmidt and Golomb, 1982)

Organ	Starch			Soluble sugar		
	Off year	On year	Off:on ratio	Off year	On year	Off:on ratio
Fruit	--	38.2	--	--	407.0	--
Leaves	122.6	33.8	3.6	178.2	121.6	1.5
Twigs (d^z < 1 cm)	97.0	25.7	3.8	102.6	83.6	1.2
Branches (d = 1 - 3 cm)	73.9	20.4	3.6	70.4	47.0	1.5
Branches (d = 3 - 5 cm)	78.2	17.0	4.6	55.8	40.2	1.4
Branches (d > 5 cm)	76.6	19.0	4.0	70.6	47.8	1.5
Trunk above graft union	80.2	38.4	2.1	50.4	43.2	1.2
Trunk beneath graft union and main root	96.1	46.7	2.0	47.2	58.4	0.8
Major roots	124.6	17.5	7.1	56.0	47.8	1.2
Roots (d > 0.5 cm)	163.2	9.4	17.4	77.2	40.0	1.9
Minor roots (d < 0.5 cm)	179.8	19.2	9.4	67.8	52.0	1.3

[z] d = diameter.

Xia *et al.* (1983) found that the starch content in roots, leaves and shoots of apple trees (about 20 years old) was lower in the "on" year than in the "off" year, especially in the roots. Working with lemons Jones *et al.* (1975) found there was no difference in root system size between the "on" and "off" condition, as measured by density of feeder roots. However, the starch content of both the feeder roots and small roots was very low during an "on" year (when the average crop load was 300 kg per tree) compared with that during an "off" year (crop load 0 - 1 kg per tree). They suggest that this typical reduction in content is

associated with prolonged bud dormancy, delayed spring growth and an "off" crop the following year. Xia *et al.* (1983) also noted that the number of flower buds was significantly correlated to root starch content.

2.4.4 Other Factors Affecting Carbohydrate Reserves

A range of other factors have been researched. These include tree age, interruption of movement of nutrients in the phloem by mechanical treatment such as ring barking, pruning effects, and the effect on photosynthetic activity by defoliation. Environmental effects are also briefly reviewed.

2.4.4.1 Age

Sixty-year-old Boskoop apple seedlings grown as standard trees and 16-year-old bush trees of Boskoop grafted on M9 were assayed for starch by Dietz and Held (1974) in Germany. Wood samples were taken from the trunks for assay. The starch content between April and October for the older trees was lowest in mid-May, rose to a peak in late July, showed a sharp decrease in mid-August in the pre-bearing year whilst the flower initials were laid down, and then increased to a maximum by mid-September. Variations on this pattern, caused by age differences within the crown but not by the presence of fruit, were demonstrated in the older trees which had received rejuvenation pruning. In the younger grafted trees the starch content decreased between April and June, rose to a peak at the beginning of September, dropped during flower initiation and rose to a second peak in late October. These trends were very similar in trees with 3 different crop loads.

Autumn planted spur Delicious apple trees showed significantly greater shoot extension growth and a lesser tendency to become spurbound than spring planted ones (Young, 1989). Higher starch reserves were found following the growing season after autumn planting than after spring planting.

The carbohydrate content of grape wood of different ages was studied by Rjabtschun (1974). As the annual rings aged there was at first a gradual increase in the carbohydrate content of the sapwood and later, as the heartwood formed, a continuous decrease in the starch and total carbohydrate content. The sugar content was highest in the youngest wood. The region of heartwood formation was characterized by an increase in the content of soluble sugar

resulting from hydrolysis of insoluble carbohydrates. Changes in carbohydrate content during the vegetative period were most marked in the young sapwood and in the phloem fibres, whereas in the heartwood there were only negligible seasonal variations in carbohydrate content. This change in carbohydrate metabolism with age occurred earliest in branches; rootstocks and secondary roots aged much more slowly.

2.4.4.2 Ringing

Wallerstein *et al.* (1978) reported that ringed one-year-old sour orange seedlings had decreased starch level and respiration in the roots. One month after ringing the decrease in starch level stopped and respiration rates returned to the level of non-ringed seedlings. Ringing seedlings inhibited the translocation of ^{14}C-sucrose from leaves to roots, yet starch accumulation was observed in all parts of the seedlings including the roots (Wallerstein *et al.*, 1974). Ringing appeared to encourage starch accumulation in the roots independent of carbohydrate transport from the leaves. Ringing also raised the fresh weight in all parts of the seedling and lowered the percentage dry weight of rootlets. Priestley (1964a) reported similar results for apples. Priestley (1976) also reported that dry matter per unit area of associated leaf was higher on ringed apple branches which enhanced fruit set. On unringed branches the dry matter content was lower due to uninterrupted translocation to the rootstock.

2.4.4.3 Pruning

Dormant pruning of apple trees decreased the starch content of the trunk as measured in the following September in New York (Reich, 1985). Mature Reinette de Champagne apple trees were pruned in late November, January or early March in western Georgia by Abramishvili and Gvetadze (1976). Removal of stored substances from the tree was lowest with January pruning. Trees pruned in January also yielded best followed by those pruned in November. March pruning gave the poorest results.

Grochowska *et al.* (1977) planted Red McIntosh, Red Melba and Cortland apples on A2 rootstocks in containers in Poland. The trees were pruned by 2/3, and disbudded by 2/3 leaving only the apical and basal buds. Carbohydrate metabolism was studied on 5 successive dates during the growing season in the shoots of pruned and unpruned maiden trees of the cultivar Cortland. The trees were analyzed for bark soluble sugars and starch contents in November, for the cultivars Red McIntosh and Red Melba. The treatments had

little effect on the distribution of soluble sugars in the aerial parts of the trees. The bulk of carbohydrates was found in the roots of both pruned and unpruned trees. Root starch content was twice that of the shoots. Disbudded Red McIntosh trees accumulated starch mainly in the disbudded part of the trunk.

One-year-old shoots and roots were sampled for analysis, up to sap rise, from plants pruned to leave 40, 50, 60, 70, 80 or 90 buds per vine of grape. Maximum monosaccharide and sucrose content and highest total sugar content occurred in the shoots and roots of plants with 80 buds (Melkonyan, 1984).

2.4.4.4 Defoliation

One-year-old Delicious apple nursery stocks were hand defoliated on 1, 15 or 30 October in Washington State by Abusrewil *et al* (1983). Starch levels increased in roots and stems as hand defoliation was delayed. The amount of shoot growth produced on the trees during the summer following storage and replanting displayed a pattern somewhat like that of the levels of starch in the trees. Golden Delicious/M9 apple trees were defoliated immediately after harvest by Faby and Naumann (1986) in Germany over a 3 year period. Defoliation reduced the content of sucrose in the bark and starch in the wood, while glucose and fructose levels were higher than in control trees. Control trees in December (winter) had twice as much sucrose in the bark, and starch in the bark and wood, than defoliated trees (Naumann and Faby, 1987). Carbohydrate levels in flowers were unaffected by defoliation, but the flowers opened later in the following spring. Fruit set was lower by 6.2 - 9.0% and yield was reduced.

Worley (1979) worked with pecans in the USA. Autumn defoliation of the trees was followed by a depletion of carbohydrate reserves and a reduction or prevention of yield if defoliation occurred prior to 1 November. Refoliation of August-defoliated trees restored the depleted reserves in the current season's wood by 1 December but either prevented or greatly reduced yield the next year. September defoliation caused the greatest depletion of reserves and prevented flower production the next year. However, defoliation on 1 November had no significant effect on carbohydrate reserves.

2.4.4.5 Environmental Factors

Tromp (1983) claimed that environmental factors such as light intensity and temperature affect the root level of carbohydrates. However, apple rootstocks treated under 4° and $16^{\circ}C$ for 1500 hours by Young and Werner (1985) did not show an effect on starch, soluble sugars or sorbitol levels in the scion, shank or roots of the trees. Irrigation stress enhanced the ringing-induced decrease in starch level in the main root of sour orange seedlings (Wallerstein *et al.*, 1978). Starch content was higher in apple leaf lamina of trees well supplied with water than in low-water treatments (Fuhrt and Lenz, 1989). There was a significant correlation between the carbohydrate content of various tissues (twigs, scaffold wood, trunk wood and trunk bark) of 4 - 5 year old Southland peach trees and the mean maximum temperature for the preceding 15 days (Dowler and King, 1966). The correlation was positive for starch and negative for sugar.

2.4.5 Crop Load Adjustment

Renet Simirenko, Golden Winter Pearmain and Papirovka apple trees bearing normally 10 - 14 thousand flower buds per tree were pruned to remove 50 - 75% of the flower buds (Kurennoi and Apolokhov, 1973). The treatment increased by 1.8 to 3.0 times the supply of carbohydrates to the remaining flower buds. This resulted in better shoot growth, larger leaves, better fruit set, greater average fruit weight and regular bearing. The effect of both vegetative and reproductive growth on starch content was shown by using apple trees with many fruits and short 1-year-old shoots compared with few fruits and longer 1-year-old shoots (Dietz and Held, 1974). The data showed that both crop load and vegetative growth affected alternate bearing. The starch content tended to remain at a relatively low level and the fall in starch levels characteristic of flower initiation was not evident. It was especially so in trees with vigourous shoot growth producing no flowers in the following season.

Goldschmidt and Golomb (1982) working with citrus, suggested that the carbohydrate reserve built up in the "off" season would be recycled and used for next year's crop. Removal of fruit by mid-summer permitted reasonable flower bud differentiation the following year, owing to the build-up of the starch reserve levels. Changes in the location and movement of ^{14}C-labelled carbohydrates in pecan leaves and shoots were monitored with an autoradiograph from bud break until after fruit maturity (Sparks and Davis, 1974). The direction of carbohydrate translocation is shown in a schematic diagram by the authors for each of 9

leaves on a shoot during 8 stages of plant development. Alternate bearing was shown to be closely related to the carbohydrate stress occurring during kernel development. In experiments when leaves but not fruit were removed from the trees at full bloom, severe alternate bearing was induced. Removing the fruit but retaining the leaves minimized alternate bearing.

2.5 SAMPLING TECHNIQUES IN POMOLOGY

Sampling is the technique for obtaining data from experiments. Correct sampling is needed to produce reliable results but reliable sampling procedures for fruit tree research have not been investigated to the extent that they should have been (Jacob, 1953; Marini, 1985). This section reviews the sampling size, control of error and branch sampling in fruit tree research.

2.5.1 Sampling Size

Some researchers use a small sample size of only a few trees but others used 100 trees per treatment (eg Dozier *et al.*, 1983). Marini (1985) noted that data collection is expensive and that it is important to use the minimum sample size which provides a satisfactory level of precision. The information should be obtained from the minimum number of replications which will yield the desired precision (Schultz et al., 1955). Any number of replications less than this number will not yield the desired precision (on the average) even if all the fruit or branches on the trees are observed.

Apart from treatments, variability can be classified into two groups, sampling and environmental variability (Ferguson, 1962). An erroneous conclusion that treatment means do not differ may result from a sample size insufficient to detect the difference (Marini, 1985). Precision is often specified by the maximum error which will be tolerable or allowable in estimating a treatment mean difference (Schultz *et al.*, 1955). The next section deals with decisions on precision.

2.5.1.1 The Level of Probability

It is often difficult with fruit trees to obtain the commonly accepted precision at 95% probability. The great number of trees per treatment needed to detect growth and yield differences at the 5% level of significance is unacceptable in most instances because it limits

severely the number of treatments which can be evaluated in an experiment. Pomologists may want to consider using a different probability level than the traditionally accepted 5% level. Testing equality of means at the 10 or 15% level would still provide reasonable protection against a Type I error. Otherwise, researchers may have to be satisfied with detecting only large (>30%) differences in treatment means (Marini, 1985). As an example, Marini and Trout (1984) claimed that the differences in fruit colour of peach detectable at the 5% level decreased only slightly as trees per treatment were increased. For practical purposes, researchers usually want to detect differences of about 10 to 15% fruit colour. This level of sensitivity, they suggested, can be achieved by sampling 12 or more fruit from 4 or more trees per treatment. A wide range of sampling methods and acceptable confidence levels are suggested in papers summarised in Appendix 1.

It is not feasible or useful to review all these papers as the sampling techniques vary according to the research and the situation. What is important to recognise is that fruit tree researchers often have to settle for an accuracy level of > 5%. The level of accuracy is sometimes stipulated as part of the objective.

2.5.1.2 Fixed Differences

Two examples are quoted here dealing with fixed differences. Burroughs and May (1953) required an accuracy of $\pm 5^{\circ}$ when testing the specific gravity of cider apple juice and found they needed at least 50 fruit per sample.

Elkner and Coston (1989) measuring net photosynthesis in peaches required the detection of 5 mg $CO_2/dm^2 \cdot$hour difference between 2 treatments and needed 5 replicates. When they applied more stringent difference levels at 2 mg $CO_2/dm^2 \cdot$hour they required 18 replicates. Clearly the expense and the accuracy acceptable must be weighed one against the other. This is illustrated in the next section with a cross section of other standards in the literature.

2.5.1.3 Accuracy Limits

Several authors found very little improvement in accuracy with a large increase in sample size. Marini and Trout (1984) found that smaller differences in fruit colour were detectable when up to 16 fruit per tree were sampled but thereafter the minimal improvements in detectable differences were unwarranted. Habeeb and Ismail (1969) working on ascorbic

acid levels in oranges, also suggested that increase in accuracy was seldom significant over 10 fruit per tree although they tested up to a sample of 40 per tree.

Distribution of fruit size may need a different approach. To obtain a normal distribution of cherry size groups, Davidson and George (1959) found they needed 200 fruit but the degree of accuracy of the distribution curve with fewer samples was not documented. Accuracy in sampling for leaf chemical analysis is discussed by Sharpe (1951) working with pecans, assessment of leaf area per tree by Freeman (1957) and measurement of shoot growth by Jolly and Holland (1957).

Clearly level and control of error are the key factors in sampling technique.

2.5.2 Control of Error

After specification of the precision required, the size of the experiment is determined by the magnitude of the variation from (A) tree to tree (replication to replication) in a given treatment, (B) samples from a given tree (plot), and (C) determinations on a given sample. The variability of A, B, and C generally are determined experimentally and are expressed as components of variance (Schultz *et al.*, 1955). The work on fruit tree experimental error is extensive (Sharpe and Middelem, 1955; Schultz, 1955; Hanson, 1955; Cain and Andersen, 1976; Marini and Trout; 1984; Trout and Marini; 1984). Working on components of variance, Marini and Trout (1984) proposed that increasing the number of fruit per tree was more effective in decreasing detectable differences in fruit firmness than increasing the number of trees per treatment, because the magnitude of variation due to fruit was much greater than that due to trees. The number of samples taken per tree is usually limited by cost rather than availability of material.

The valid application of tests of significance in analysis of variance requires that the experimental errors be independently and normally distributed with a common variance (Steel and Torrie, 1980). Many methods for normalizing populations and equalizing variances have been suggested to utilize the analysis of variance technique. Logarithmic transformation is used on populations whose means are proportional to their standard deviations. After logarithmic transformation, the long right tail of a distribution is pulled closer towards the centre and the short left tail is pushed further away from the centre (Li, 1964). Kikuchi (1966) found measurements of the total leaf area gave nearly normal distribution after

logarithmic transformation. Jolly and Holland (1957) made the assumption that, when the data were approximately log-normally distributed, the logarithmic transformation could be used for the measurement of extension growth of apple trees. Pearce and Davies (1954) found the logarithm of the weight of an apple tree had a good relationship with the logarithm of the trunk circumference. Llewelyn (1968) used a logarithmic transformation to analyze fruit retention records.

Complete random sampling does not always have an advantage for large fruit trees with complicated structures. Johnson *et al.* (1967) sampled apple loads for fruit inspection. They concluded that, with field crate loads, strictly random, stratified random and systematic sampling methods are equally effective, provided that at least 13 crates per load are included in the samples. Jolly and Holland (1957) thought that systematic shoot sampling could be used on any form of tree whatever its condition, and, where sample number averages 20 - 25 measured shoots per tree, there is usually little loss of accuracy. Random branch sampling may be used on any set of trees on which the necessary branch measurements can be made but will generally be less accurate than systematic shoot sampling. Davidson and George (1959) measured cherry fruit size, sampling fruit from the three levels, top, centre and bottom and the four quarters, north, east, south and west of the tree. It was suggested that the centre level be chosen because samples in this area were generally intermediate in size and weight between top and bottom samples. Examples for systematic sampling are given by Kikuchi (1966) and Forshey and Elfving (1979a).

2.5.3 Branch Sampling

Accurate estimation of yield or fruit number per tree is a common problem. Winter (1976) proposed a method to measure fruit density by viewing the number of fruit on the outside of the tree in a hand held window of 0.36 m^2 at a distance of 3 m using an average of 10 random counts. Results were verified to $\pm 5\%$. However, for apple trees on non-dwarfing rootstocks, the error of volume estimation will be increased. Gaps created in the trees by pruning for tier placement will create difficulties. This sampling method is also difficult to manage at the flowering stage and when fruit number is high before thinning.

Branch sampling has been generally accepted as representative of the entire tree for comparison of flowering, fruit set and in fruit thinning studies (Forshey and Elfving, 1979a). Some studies have been conducted on the translation of information from branches to whole

trees.

One of the earliest reported studies on branch sampling was on open centred citrus (Jessen, 1955). He "ordered" the whole branching system and compared three different methods for working out the relationship between sampled branches and the whole tree. The relationship, based on CSA, was much better than either that based on equal proportion (for each branch) or that based on "order" proportion. His CSA method measured the area of all primary, secondary, tertiary etc branches but found the work time consuming. Pearce and Holland (1957) criticized the large error in Jessen's work, but Jolly and Holland (1957) thought that the method gave a moderately accurate estimation of extension growth. Kumar *et al.* (1985) confirmed and modified Jessen's scheme, proposing a branch magnitude method. This assumed each shoot was equal and the percentage of a branch to the whole tree could be based on shoot number.

There is some sampling work reported for fruit trees with central leader trained systems. Chaplin and Westwood (1972) sampled 10 limbs from each of 27 Royal Ann sweet cherry trees, using the average crop load multiplied by trunk CSA, to correlate tree yield. He achieved an r^2 value of 0.85. Forshey and Elfving (1979a) sampled 2 or 3 branches per tree to estimate the whole tree yield and fruit number using a regression method achieving reasonable results. They were still concerned with the precision of their work because of the variability between the branch samples and cultivars and the relationship between tree size and bearing surface. Forshey and Elfving (1979b) thought crop load cannot always be translated directly to yield per tree claiming it is an accurate indicator of differences in yield per tree only when the trees are of comparable size. Volz (1988) compared the branch sampling method and the fruit density sampling method. He concluded that the results were quite similar, and suggested multiple regression of the two methods for best results.

CHAPTER 3

BRANCH SAMPLING

3.1 INTRODUCTION

Many fruit researchers have worked on crop loading (Westwood and Roberts, 1970; Forshey and Elfving, 1977; 1979a; 1979b; Rowe, 1985). Kiwifruit bears fruit usually on a surface frame where crop load research can be based on fruit/m^2 of bearing surface. The optimum crop load method (fruit/m^2) was proposed by Mills and Atkins (1992) and executed in commercial orchards. Apple trees on dwarfing rootstock in Europe carry 150 - 200 fruit per tree, and it is not difficult to calculate the optimum crop load. Beyond Europe, most apple production regions still use vigorous or semi-vigorous rootstocks with 500 - 2000 fruit per tree. Accurate estimation of fruit on a large tree is difficult for research work on crop loading and the application by growers of optimum crop loading methods is time consuming.

Some attempts were made to express yield or fruit number per unit cross sectional area (CSA) by using branch samples and trunk measurements on apples (Forshey and Elfving, 1979) and cherry (Chaplin and Westwood, 1972). However, the fruit number and yield per CSA of branches are different from those per CSA of the trunk for the same tree (Zhang, 1988). Although ratios between branches and trunks were proposed based on these authors' regression results, the consistency of the regression equations still needs more investigation. Understanding the nature of the relationship between branches and trunk is the key requirement. In this chapter, research on the measurement of branch size is documented in an attempt to extrapolate branch sampling to the whole tree.

3.2 MATERIALS AND METHODS

3.2.1 Measurement of Wood Volume and Density of Branches

Three branches of a 9 year-old Gala apple tree were removed in the winter of 1989. A total of 86 sub-branches were measured, originating from the three initial branches, with the diameter of each sub-branch recorded 10 cm (except for very small shoots) from the base.

The measurements made were:

i the base diameter (and hence CSA);

ii the length of the main axis: measured along the axis;

iii weight;

iv wood volume: this was determined by measuring each shoot in a sugar solution and determining the weight of the displaced solution (Mohsenin, 1986). The liquid density was determined by hydrometer as 1.15 g/cm^3 (Volume = weight of displaced liquid ÷ density of liquid by weight).

3.2.2 Measurements of Length, Diameter and Weight of Branches and Trees

Thirty six representative branches (not subjected previously to severe pruning) were removed from 9 year-old Gala apple trees during the winter of 1989. All branches and shoots directly arising from the main axis of each of these 36 parent branches were separately measured for length, diameter and weight providing a total of 802 sub-branches or shoots. The measurements were collectively related to the 36 respective parent branches.

In the following year, thirteen 16 year-old Granny Smith trees were to be removed from the orchard and the opportunity was taken to conduct similar weight, length and CSA recordings using whole trees. In this case a total of 98 primary branches directly arising from the main leader were recorded and related to the whole tree.

3.2.3 CSA of Branches and Trunks

The details of trees and branches measured for CSA are listed in Table 3.1. A total of 30 nursery trees, 30 young trees, 144 mature trees, 151 parent branches and 9283 sub-branches were measured for CSA.

3.2.4 Fruit Recording Using Branch Sampling

All Royal Gala trees which were part of the monitoring program (Sources 15 - 29 in Table 3.1) had fruit recordings taken from 3 selected branches on each monitored tree with one sample branch at each of 3 levels.

Table 3.1 Trees and branches measured for CSA

Source	Cultivar	Age	Sample No	Year measured	Orchard	Order[z]
Nursery trees						
1	Braeburn	0[y]	10	1989	LU[x]	tree
2	Braeburn	0	10	1991	LU	tree
3	Royal Gala	0	10	1991	LU	tree
Young trees not in commercial production						
4	Braeburn	1	10	1989	LU	tree
5	Royal Gala	2	10	1989	LU	tree
6	apple seedling	3	10	1989	LU	tree
Mature trees in production						
7	Gala	9	10	1989	LU	tree
8	Gala	10	10	1990	LU	tree
9	Gala	11	5	1991	LU	tree
10	Gala	12	5	1992	LU	tree
11	Royal Gala	4	9	1990	MSRO[w]	tree
12	Cox etc.[v]	15	10	1989	LU	tree
13	Granny Smith	16	13	1990	LU	tree
14	Granny Smith	17	7	1991	LU	tree
Trees used in modelling work in Chapter 4						
15-29	Royal Gala	5-8	75	1986	Model[u]	tree
Primary, secondary and tertiary branches						
30	Gala	(9)[t]	12	1989	LU	1
31	Gala	(9)	13	1989	LU	2
32	Gala	(9)	11	1989	LU	3
33	Gala	(10)	10[s]	1990	LU	1
34	Gala	(10)	10[r]	1990	LU	1
35	Gala	(10)	10	1990	LU	2
36	Gala	(10)	10	1990	LU	3
37	Royal Gala	(4)	9	1990	MSRO	1
38	Granny Smith	(17)	46	1991	LU	1
pruned						
39	Royal Gala	(2)	10	1989	LU	1
not pruned						
40	Royal Gala	(2)	10	1989	LU	1

z trunk and central leader are in order 0 listed as "tree";
the branches directly arising from the central leader are order 1 (primary);
the branches directly arising from order 1 branches are order 2 (secondary);
the branches directly arising from order 2 branches are order 3 (tertiary);
y first winter young trees without heading in the nursery;
x Horticultural research area of Lincoln University;
w Main south road orchard, Canterbury;
v 4 Cox's Orange Pippin, 4 Royal Gala and 2 Granny Smith on M9;
u all 75 modelling trees detailed in Chapter 4. These trees were originally measured in 1986 by Zaprzalek and Thiele (1987).
t the ages in brackets are tree age not branch age;
s thick branches with a support function;
r relatively thin branches without much frame function;

A more detailed branch sampling program for fruit recording was conducted on seven, 17 year-old Granny Smith trees (sources 14 and 38 in Table 3.1). In this case, fruit was recorded at the second order of branching and related to the CSA of each second order branch. Subsequently, recordings from second order branches were summed to provide parent or first order branch data and related to the CSA of these parent branches. These same trees were part of the starch analysis in Chapter 5.

3.3 VALIDATION OF WOOD DENSITY

There are two ways that the aerial parts of a large apple tree might be measured.

i. **The effective bearing volume of a tree.** This includes the wood of the branches and trunk as well as the leaves and some space for bearing. Although this measurement is useful for assessment of potential production, the effective bearing volume is difficult to measure accurately, especially for large trees with gaps between the fruiting tiers.

ii. **The wood volume of branches and trunk.** This can be measured accurately. Under normal conditions and without severe pruning, wood volume should correlate with effective bearing volume. In this study, trees not severely pruned have been used.

3.3.1 Relationships Between Branch Volume and Other Factors

Table 3.2 shows the relationship of branch volume to the other measurements grouped according to branch diameters. Branch weight shows the highest correlation with volume in all size groups. This is because weight ÷ volume = density, which should be a constant. Detailed measurements are listed in Appendix 2.

For shoots with a diameter < 0.9 cm, the CSA : volume relationship was poor. This is because some of these small shoots were bourse shoots (Figure 3.1) which usually have large diameters and short length and volume. The density of bourse shoots is clearly less than that of normal shoots.

The ratio of shoot or branch length to diameter affects the volume estimation. For small diameter shoots, the ratio tends to increase with increase in length (Figure 3.2). For shoots or branches with a diameter of 2 - 4 cm, the ratio becomes concentrated in the range of 60 - 80. As the diameter increases relative to length the ratio decreases. For branches with a diameter > 10 cm, the ratio becomes concentrated around 30.

Table 3.2 Relationships of branch volume to length, CSA and weight

Branch diameter (cm)	Sample No	density (g/cm^3)	r value of volume versus		
			length	CSA	weight
<0.5	21	1.08	0.88**	0.42	1.00**
0.5-0.59	11	1.10	0.88**	0.13	1.00**
0.6-0.69	14	1.05	0.97**	-0.42	1.00**
0.7-0.79	14	1.08	0.83**	0.17	1.00**
0.8-0.89	13	1.08	0.97**	-0.04	1.00**
>0.9	16	1.10	0.83**	0.99**	1.00**
all	89	1.08	0.76**	0.99**	1.00**

** significant at 1% level;

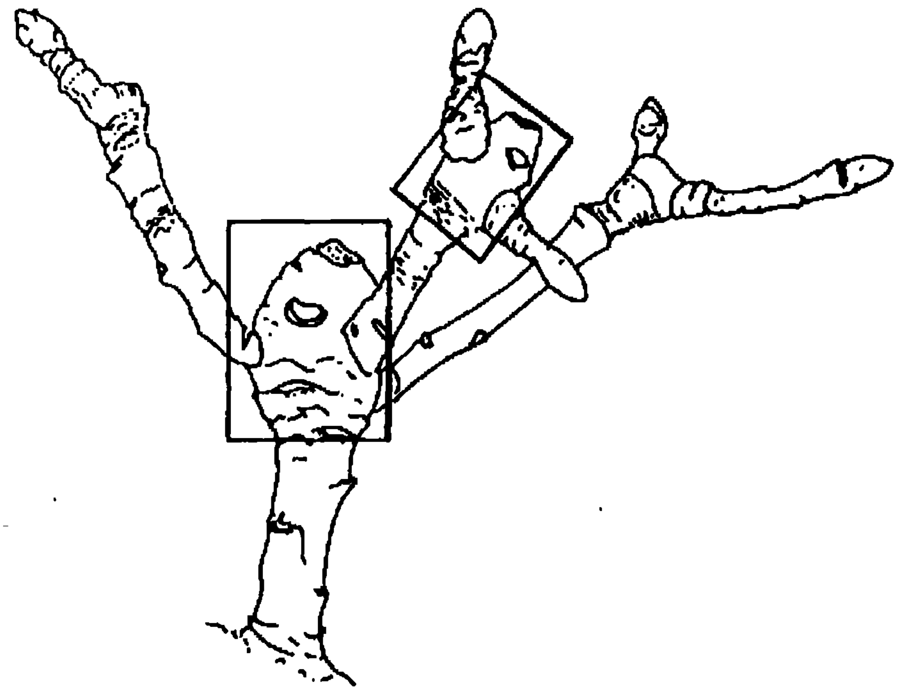

Figure 3.1 Bourse shoots (in box)

To summarise, the weight is shown to be more reliable for larger shoots with a diameter of 0.9 cm or greater and when pruning has not been severe. When the wood density of apple trees is accurately measured, branch volume may be easily obtained by weight ÷ density.

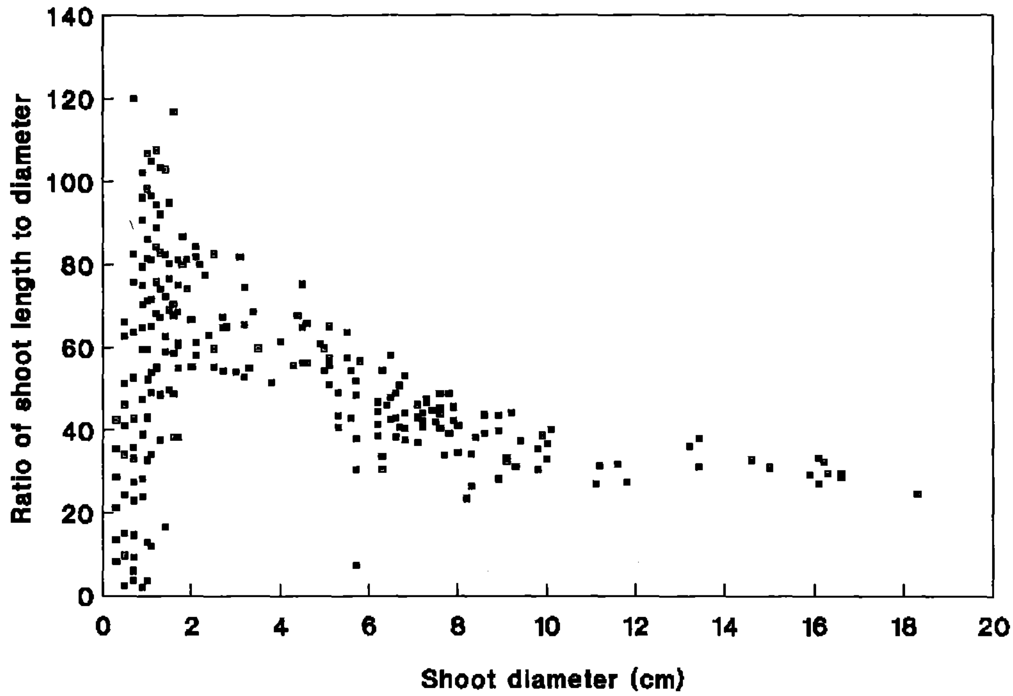

Figure 3.2 Relationship between the ratio and the shoot diameter

3.3.2 Wood Density

Measurements from 86 shoots and 3 main branches (Appendix 2) indicate the density is relatively consistent with 82% within the range 1.04-1.16 g/cm^3 (Figure 3.3).

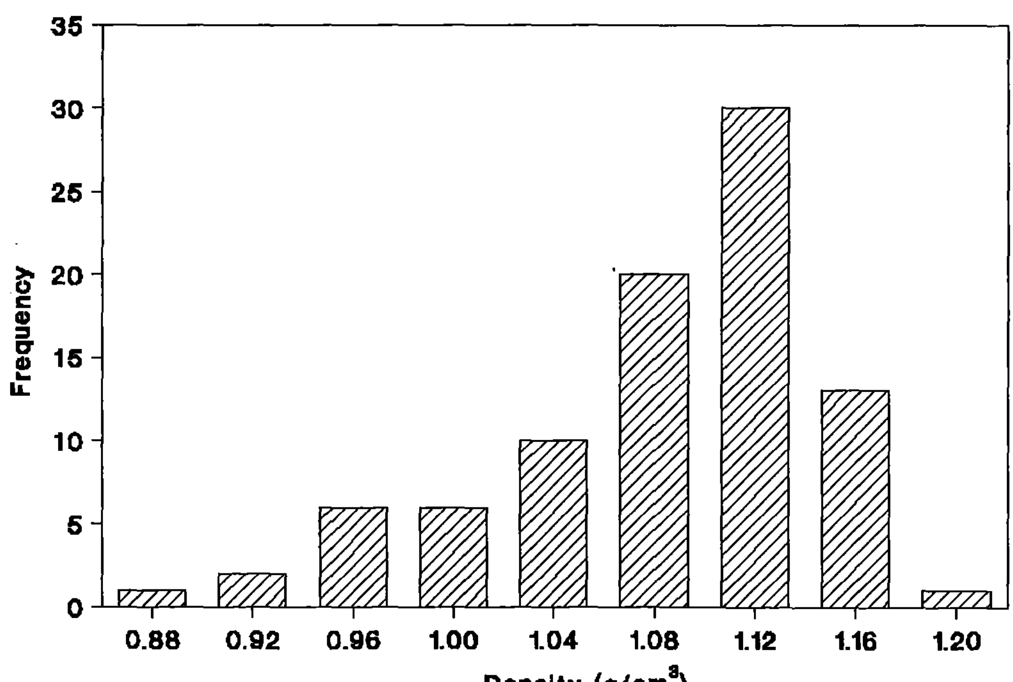

Figure 3.3 Distribution of wood density of an apple tree (N=89)

The average density of branches in different size groups is listed in Table 3.2. The distribution of the average density is calculated in the range 1.05 - 1.14 g/cm^3. As the scale used to measure weight and volume was accurate to 0.1 g, the density used in the calculations is corrected to the first decimal point.

Figure 3.4 indicates that the density of a "branch" does not vary significantly with length, except where bourse shoots are involved. The bourse shoots usually have a short length but a larger than expected diameter with a density < 1 g/cm^3 (Appendix 2). In the figure, bourse shoots are usually in the < 15 cm length category showing a wide range of density. In practice bourse shoots would not be selected and therefore can be ignored.

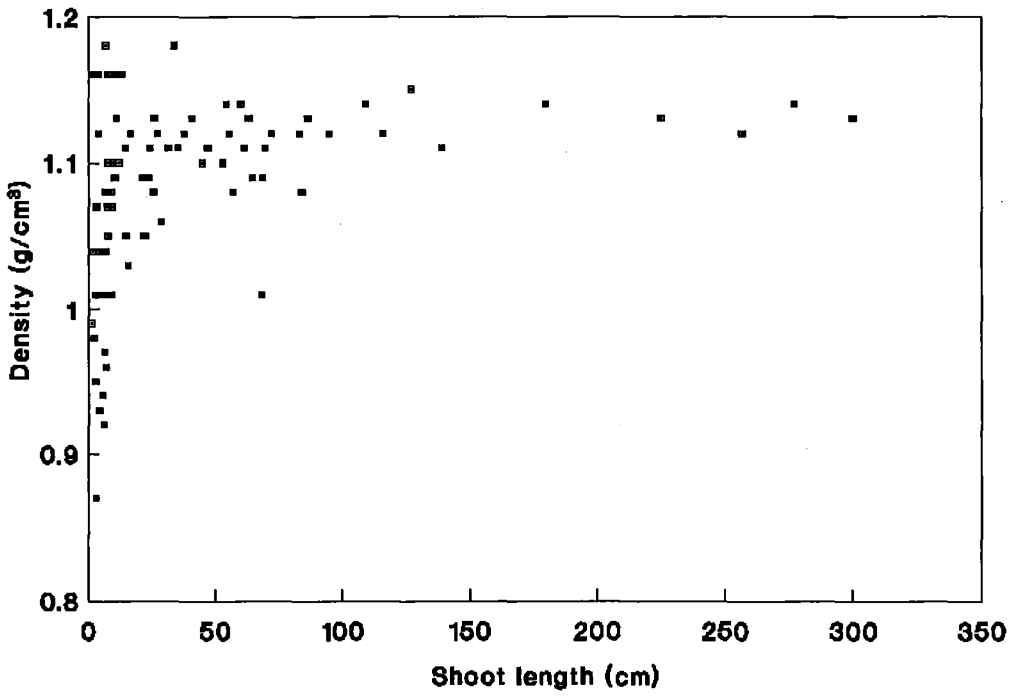

Figure 3.4 Relationship between shoot length and density

3.4 ESTIMATION OF BRANCH VOLUME FROM DENSITY

Having proved that volume can be obtained from weight divided by density, it is necessary to investigate branch weight. Although some branches may be cut off and weighed accurately, it is impossible to do that in practice and therefore it is necessary to determine a method for estimating branch weight.

One-dimensional measurements (the length of the main axis and the base diameter) and two-dimensional measurements (base CSA) were used in the study. A three-dimensional

measurement can be calculated from the base CSA x length of the main axis. This lacks actual meaning but it may be useful in practice. A similar calculation was used by Johnson and Lakso (1985). This arbitrary calculation will be termed C3D.

Table 3.3 Relationships between branch weight and other measurements (r values)

Samples	Sample No	Length	Diameter	CSA	C3D
Branches of Gala	838	0.69**	0.82**	0.97**	0.99**
Trees of Granny Smith	111	0.76**	0.90**	0.95**	0.97**

** significant at 1% level;

Table 3.3 shows that C3D has the highest correlation with weight for both the Gala and Granny Smith samples, indicating the potential use of three-dimensional measurements.

3.5 ESTIMATION OF THE RATIO OF THE SAMPLED BRANCH TO ALL BRANCHES

Branch sampling is used for estimation of fruit number for large trees. In order to translate the information from sampled branches, the relationship of that branch to the whole tree must be known. This is the key point about branch sampling.

Assume that branch 3 in Figure 3.5 is sampled. It is necessary to extrapolate accurately from the sampled branch to the whole tree (6 branches). It is not practical for orchardists to count all fruit on the tree and hence a practical sampling method must be found to provide a ratio of the sampled branch to all branches (Holland, 1968b).

According to section 3.4, the ratio of the sampled branch to all branches may be expressed in weight by weighing cut branches. The ratio of the weight of branch 3 to the "whole tree" must be determined (Figure 3.5). The main axis, that is the trunk and central leader below branch 6, is much heavier than any of the branches, but this main axis is an unproductive part of the tree and should not be included in the calculation of overall tree weight. The sum of the weight of all 6 branches will henceforth be referred to as "sum" representing the *operative* weight of the whole tree. The extrapolation of measurements of the sampled branch to a whole tree basis will be in proportion to the equivalent summed measurements of all the productive primary branches.

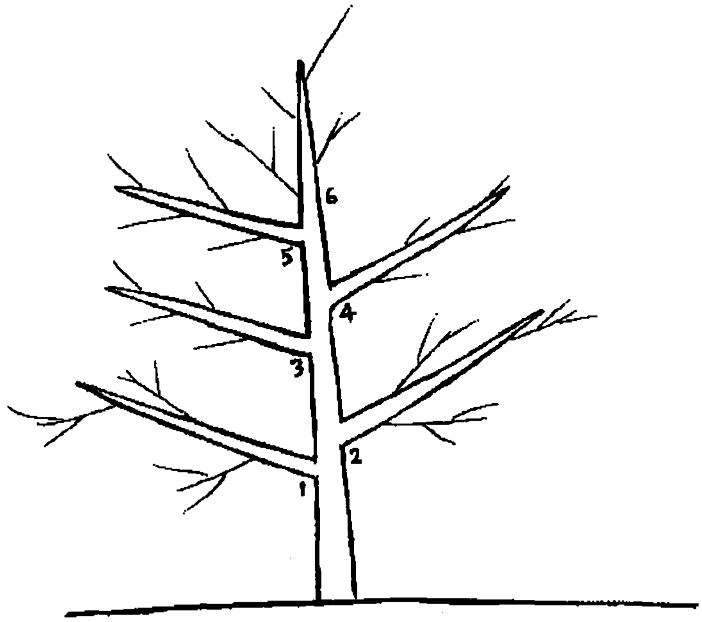

Figure 3.5 Branches of an apple tree

The lengths, diameters, CSA and C3D of the branches sampled were used to test the hypothesis that extrapolation to a whole tree basis is valid.

3.5.1 Extrapolation from Branch Weight

From 36 branches of Gala apple trees 802 sub-branches were removed, weighed and measured. The ratio of each sampled branch to the sum of all branches arising on that parent branch was studied. This means that the weight ratio of each of the 802 sampled branches to its parent summed weight was calculated in 36 cases. On the same basis, ratios were calculated for base diameter, CSA and C3D measurements for each of the 802 sample branches. Ninety-eight branches from 13 Granny Smith apple trees were measured and extrapolated in the same way. Table 3.4 shows the correlation coefficients of the various measurements grouped according to size of the sub branches. In each case the correlations are of the sub branch to parent weight ratio with the equivalent ratios of the other measurements.

Table 3.4 shows that C3D is the best measurement to estimate the ratio of weight of branches to the sum of all branch weight in any size group. These correlations were studied in different size groups of branches to determine any exception. For branches with a diameter between 2 - 3 cm, there was a high correlation with CSA. Even with 18 year-old Granny Smith trees subjected to severe pruning the correlation was still relatively high. For

smaller branches (diameter 0.5 - 2 cm) branch length showed a better correlation than CSA because length in this case is proportionally larger than the CSA would indicate. For small branches (<0.5 cm in diameter), the correlation is not very high but branches of this size would not be sampled in practice.

Table 3.4 Correlations between the ratio of weight of the individual sub-branches to the sum of the weight of all branches on the parent branch with the equivalent ratios of other measurements (according to size groups)

Branch		Weight ratio correlated with			
diameter (cm)	Sample No	Length ratio	Diameter ratio	CSA ratio	C3D ratio
Branches of Gala apple trees					
<0.5	208	0.86**	0.65**	0.73**	0.89**
0.5-1	453	0.94**	0.81**	0.89**	0.98**
1-1.5	110	0.92**	0.81**	0.90**	0.98**
1.5-2	20	0.94**	0.80**	0.85**	0.96**
2-3	11	0.76**	0.78**	0.91**	0.95**
all	802	0.89**	0.75**	0.91**	0.98**
Granny Smith apple trees					
4-12	98	0.65**	0.72**	0.75**	0.84**

** significant at 1% level;

It is necessary now to consider if there is a scientifically accurate method of estimating the "sum" of all the branches.

3.5.2 Estimation of the "Sum" of All Branches

The trunk can provide information for the whole tree and is used here for estimation of the "sum" of all the branches. Correlations and simple regressions were executed for each Gala (N = 36) and Granny Smith (N=13) tree as follows:

i Length of the main axis of the parent branches correlated to the sum of the lengths of

the main axis of all the sub-branches arising from each respective parent (N = 36).

ii Base diameter of the parent branches correlated to the sum of the base diameters of all the sub-branches arising from each respective parent (N = 36).

iii Base CSA of the parent branches correlated to the sum of the base CSA of all the sub-branches arising from each respective parent (N = 36).

iv C3D of the parent branches correlated to the sum of the C3D's of all the sub-branches arising from each respective parent (N = 36).

Constants, slopes and r values from the regressions are given in Table 3.5. The average ratios of each correlated pair are also listed in the table.

Table 3.5 Relationship between the sum of branches and their main axis

Measurement	Length	Diameter	CSA	C3D
Branches of Gala apple trees				
r value	0.89**	0.96**	0.98**	0.94**
constant	-842	-11.4	0^z	0
slope	8.36	8.95	1.34	0.39
average ratio^y	3.57	4.76	1.31	0.41
standard error of the ratios	1.86	1.78	0.29	0.17
CV of the ratios (%)	52.0	37.4	22.0	42.6
Granny Smith apple trees				
r value	0.49	0.82**	0.85**	0.84**
constant	0	0	0	0
slope	4.76	3.55	1.72	1.13
average ratio^y	4.74	3.53	1.75	1.14
standard error of the ratios	0.84	0.34	0.20	0.16
CV of the ratios (%)	17.6	9.6	11.4	13.7

^{z} Recorded as zero if the constant is not significantly different from zero in the simple regression calculation.
^{y} the ratio of the sum of all branches to the main axis.
** significant at 1% level;

Sampling branches based on branch diameter, circumference or CSA is common (Forshey and Elfving, 1979; Chaplin and Westwood, 1972; Zhang, 1988). In Table 3.5, CSA shows the highest r values for estimation from the trunk (or parent branch) to the sum of all branches for both cultivars. CSA has slightly higher r values than C3D and the diameter relationship is better than length. This implies that the thickness of a branch is more important than the length of the main axis of the branch even for severely pruned trees.

In most of the regressions, the constants are not significant as there should be no "sum" if the trunk measurement is zero. In these cases the slopes are very similar to the ratios of the "sum" to the trunk (or main axis).

Comparing consistency of the average ratios, CSA and diameter have the lower coefficients of variation, with CSA showing the higher r values and more consistent ratios.

In this section the CSA measurement has an advantage. Section 3.4 indicated that C3D was the best predictor but CSA was still suitable for relatively large branches not severely pruned. CSA can be more readily measured and is favoured as the best form of measurement for branch sampling.

3.5.3 Examination of CSA Relationships According to Different Branch Order

When CSA is chosen for tree measurements, sometimes the primary branches are too large to be sampled. It is necessary to consider the relationship of branches of different orders (secondary and tertiary positions).

Figure 3.6 shows the relationship between the trunk CSA and the sum of CSA of the branches directly arising from the central leader.

According to Figure 3.6, for the trunk CSA to be used to predict the sum of CSA of all the branches in the first order the formula is $\Sigma A = a + bT$

where A = CSA of primary branches;

T = Trunk CSA;

a = the constant of the regression;

b = the slope of the regression.

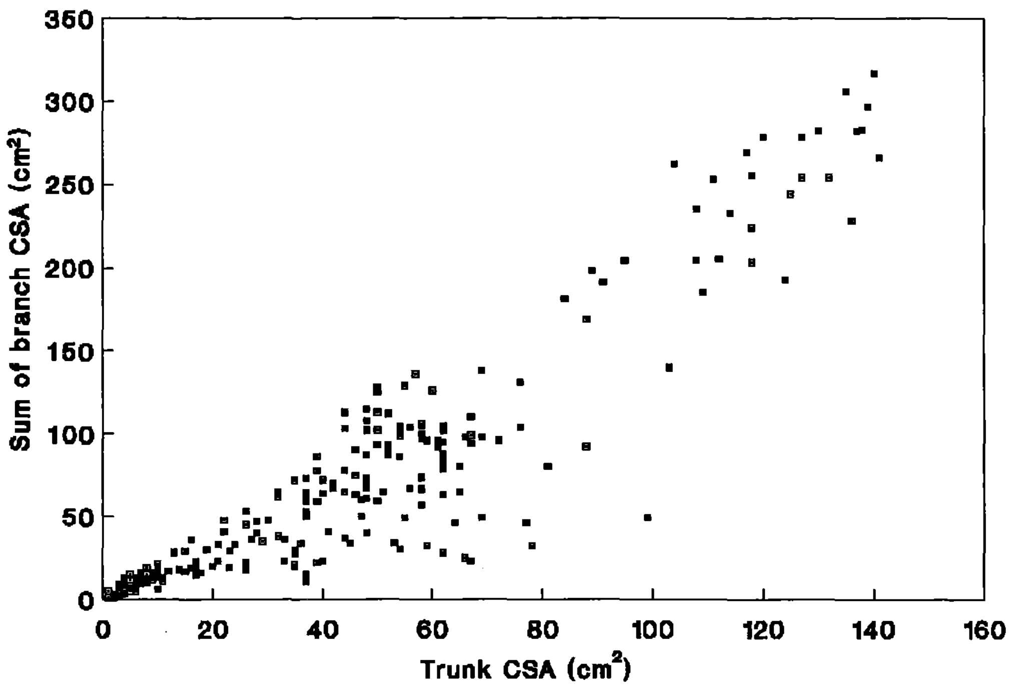

Figure 3.6 Relationship between trunk CSA and the sum of branch CSA

It is necessary to establish a relationship between the branches of the various orders. Figure 3.7 clarifies the classification of branches into primary (A), secondary (B), tertiary (C), etc. For predicting the sum of CSA of B branches the CSA of the parent branch A_1 may be used and similarly the parent B may be used for the sum of CSA of C branches. The expression now becomes:

$$\Sigma A = a_A + b_A T \qquad (3.1)$$

$$\Sigma B = a_B + b_B A \qquad (3.2)$$

$$\Sigma C = a_C + b_C B \qquad (3.3)$$

and so on.

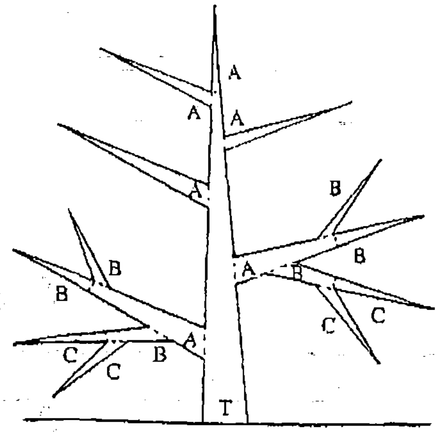

Figure 3.7 Tree branches in different orders

It is essential for investigators to know the relationship of the sampled branch to the whole tree. For the primary order (A) the ratio of branch A_1 to the whole tree is $A_1/\Sigma A$ where

$$\frac{A_1}{\Sigma A} = \frac{A_1}{a_A + b_A T} \tag{3.4}$$

Similarly, if B_1 is a branch from A_1

$$\frac{B_1}{\Sigma B} = \frac{B_1}{a_B + b_B A_1} \tag{3.5}$$

and

$$\frac{C_1}{\Sigma C} = \frac{C_1}{a_C + b_C B_1} \tag{3.6}$$

To calculate the relationship of C_1 to the whole tree

$$\frac{C_1}{\Sigma A} = \frac{A_1}{\Sigma A}\cdot\frac{B_1}{\Sigma B}\cdot\frac{C_1}{\Sigma C} = \frac{A_1}{a_A+b_A T}\cdot\frac{B_1}{a_B+b_B A_1}\cdot\frac{C_1}{a_C+b_C B_1} \tag{3.7}$$

To obtain the relationship between C_1 and T (the whole tree) it is necessary to measure A_1 and B_1 to apply formula (3.7). If the constants a_A, a_B and $a_C = 0$, the formula becomes

$$\frac{C_1}{\Sigma A} = \frac{A_1}{\Sigma A}\cdot\frac{B_1}{\Sigma B}\cdot\frac{C_1}{\Sigma C} = \frac{A_1}{b_A T}\cdot\frac{B_1}{b_B A_1}\cdot\frac{C_1}{b_C B_1} = \frac{C_1}{T}\cdot\frac{1}{b_A b_B b_C} \tag{3.8}$$

Inserting N and n for the Nth order the relationship can be summarised as

$$\frac{N_1}{\Sigma A} = \frac{N_1}{T}\cdot\frac{1}{b_A b_B b_C \cdots b_N} \tag{3.9}$$

To effectively apply the simplified formulae 3.8 and 3.9 it is necessary to prove that the constants are zero and to study the variation of the slope or ratio.

3.5.4 CSA Ratio

Regressions were separately calculated according to different source groups. Table 3.6 shows that all the constants (a), except sources 1 and 8, are zero as would be expected. Sampling error may be responsible for the exception of sources 1 and 8.

Table 3.6 Comparison of a series of coefficients (refer Table 3.1 for tree details)

Source	Order	Sample No	r value	constant (a)	Slope (b)	Ratio[z]	std[y] of ratio	CV[x] of ratio (%)
nursery trees								
1	tree	10	0.96**	-0.85	1.64	1.08	0.13	3.8
2	tree	10	0.86**	0[w]	0.86	0.93	0.18	6.1
3	tree	10	0.67*	0	1.18	1.17	0.23	6.2
young trees not in commercial production								
4	tree	10	0.80**	0	1.41	1.40	0.13	2.9
5	tree	10	0.77**	0	1.47	1.46	0.19	4.1
6	tree	10	0.92**	0	1.51	1.58	0.31	6.2
mature trees								
7	tree	10	0.93**	0	2.07	2.08	0.14	2.1
8	tree	10	0.87**	97.7	1.34	2.12	0.21	3.1
9	tree	5	0.97**	0	2.19	2.19	0.06	1.2
10	tree	5	0.82	0	1.98	1.98	0.06	2.9
11	tree	9	0.80**	0	2.34	2.34	0.15	2.1
12	tree	10	0.94**	0	1.60	1.64	0.20	3.9
13	tree	13	0.85**	0	1.72	1.75	0.20	3.2
14	tree	7	0.93**	0	1.61	1.61	0.09	2.1
Systems trees								
15	tree	5	--	--	--	1.61	0.12	5.8
16	tree	5	--	--	--	1.65	0.16	4.3
17	tree	5	--	--	--	1.63	0.10	2.7
18	tree	5	--	--	--	1.29	0.19	6.6
19	tree	5	--	--	--	1.67	0.32	8.6
20	tree	5	--	--	--	1.30	0.20	6.9
21	tree	5	0.92**	0	1.80	1.79	0.13	3.2
22	tree	5	--	--	--	1.45	0.14	4.3
23	tree	5	--	--	--	2.14	0.29	6.1
24	tree	5	--	--	--	1.63	0.25	6.9
25	tree	5	--	--	--	1.25	0.14	5.0
26	tree	5	0.89**	0	2.07	2.07	0.10	2.2
27	tree	5	0.95**	0	1.30	1.29	0.09	3.1
28	tree	5	--	--	--	1.63	0.18	4.9
29	tree	5	0.92**	0	1.86	1.85	0.07	1.7
branches in different orders								
30	1	13	0.98**	0	1.27	1.31	0.20	4.2
33	1	10	0.92**	0	1.68	1.78	0.35	6.2
34	1	10	--	--	--	1.89	0.51	8.5
37	1	9	0.87**	0	2.00	2.07	0.55	8.9
38	1	46	0.69*	0	0.74	0.80	0.27	5.0
31	2	12	0.98**	0	1.42	1.49	0.20	3.9
35	2	10	0.86**	0	2.25	2.31	0.51	7.0
32	3	11	0.82**	0	1.09	1.10	0.32	8.8
36	3	10	0.68*	0	2.06	2.41	0.98	12.9
pruned								
39	1	10	0.92**	0	1.06	1.07	0.11	3.3
not pruned								
40	1	10	0.90**	0	1.26	1.25	0.22	5.6

[z] the ratio of the sum of CSA of all branches to the trunk CSA.
[y] std here means standard error.
[x] CV means coefficient of variation.
[w] Recorded as zero if the constant is not significantly different from zero in the simple regression calculation;
-- means not significant in simple regression.
* significant at 5% level; ** significant at 1% level;

For all the cases when the constants are zero, the slopes are very similar to the ratio of the sum of CSA of all branches to the trunk CSA. This is also reasonable. When the constant is zero, the regression equation is $y = bx$. Thus, the slope $b = x \div y$ which is the ratio between the two variables. Hence consideration of the ratio(s) will be of most importance.

3.5.5 Fruitfulness (FFN) Ratio

Fruitfulness (FFN) is fruit number divided by CSA. Although Forshey and Elfving (1979) and Chaplin and Westwood (1972) discussed the relationship of crop load on branches to that of the whole tree, their work was based on empirical formulae and the nature of the relationship was not discussed. This section explores the nature of that relationship.

Seven 18 year-old Granny Smith apple trees were harvested according to secondary branches (Table 3.7 and Appendix 3).

Hereafter, the ratio of the sum of CSA of the branches to trunk CSA is referred to as CSA ratio and the ratio of FFN of the tree to FFN of the sum of CSA is called FFN ratio.

Table 3.7 Comparison of CSA and FFN ratios

tree No	1	2	3	4	5	6	7
fruit number	1420	1081	1522	1575	1067	835	868
trunk CSA (cm^2)	243	193	282	244	222	220	191
FFN of tree^z	5.84	5.61	5.40	6.45	4.81	3.79	4.54
sum CSA (cm^2)	385	314	468	373	334	393	304
FFN of sum CSA^y	3.69	3.44	3.23	4.22	3.19	2.13	2.82
CSA ratio^x	1.58	1.63	1.67	1.53	1.51	1.78	1.61
FFN ratio^w	1.58	1.63	1.66	1.53	1.53	1.78	1.59

^{z} FFN of a tree is fruit number of that tree divided by trunk CSA;
^{y} FFN of a branch is fruit number of that branch divided by branch CSA; FFN of the sum of the branches is fruit number of that tree divided by the sum of CSA of all branches;
^{x} ratio of the sum of CSA to trunk CSA is described in section 3.5.4;
^{w} FFN ratio is FFN of a tree divided by FFN of the sum of CSA of all branches.

Table 3.7 show that the CSA and FFN ratios are almost identical.

The CSA ratio is $$\frac{\Sigma CSA_{branches}}{CSA_{trunk}} \tag{3.10}$$

The FFN ratio is $$\frac{\dfrac{fruit\ number}{CSA_{trunk}}}{\dfrac{fruit\ number}{\Sigma CSA_{branches}}} \tag{3.11}$$

Clearly, fruit number for the tree is the same as fruit number for the sum of all the branches in the same tree. Hence:

$$\frac{\dfrac{fruit\ number}{CSA_{trunk}}}{\dfrac{fruit\ number}{\Sigma CSA_{branches}}} = \frac{fruit\ number}{CSA_{trunk}} \cdot \frac{\Sigma CSA_{branches}}{fruit\ number} = \frac{\Sigma CSA_{branches}}{CSA_{trunk}} \tag{3.12}$$

If the CSA ratio is known and the FFN of the sum of the branches is also known, the FFN for the tree can be calculated. Potential variation of the ratios between various types of trees and branches now needs to be considered.

3.6 VARIATION OF THE CSA RATIOS

It is possible that the CSA ratio for trees and branches will vary between young and mature trees and between orchards.

3.6.1 Mature Trees

The 144 mature trees investigated were from different orchards and districts and the cultivars and age also varied. The average CSA ratios for each group were found to be in the range 1.25 - 2.34 concentrated mainly in the 1.6 - 2.1 range (Table 3.6). Even with 18 year-old Granny Smith trees (source 13), severely pruned to less than 10 branches per tree, the CSA ratio fell within the range indicated. There was no clear difference found between the Royal Gala and Granny Smith cultivars measured.

A similar result is seen in Forshey and Elfving's work (1979). Using the apple cultivars McIntosh, Empire and Delicious, the regression equation for fruit number per tree (Y) was

based on the product of (fruit number/cm of branch circumference x the geometric mean of trunk circumference) and trunk CSA (X). Their equation was Y = 274.7 + 2.36X. Although fruit number per CSA can be quite different from that on a per circumference basis, they are similar when the circumference is in the range of 10 - 15 cm, which is the sampling range used by Forshey and Elfving. In this range of selected branches, geometric means are not very different from arithmetical means and CSA may be considered a substitute for circumference. For the range they used of 500 to 3500 fruit per tree, the constant 274.7 may not be significantly different from zero and could be omitted. Therefore the formula becomes

$$fruit\ number = 2.36 \frac{fruit\ number}{CSA_{branch}} \cdot CSA_{trunk} \quad \text{or} \quad \frac{CSA_{branch}}{CSA_{trunk}} = 2.36$$

Although the addition of the constant may make a little difference, the CSA ratio at 2.36 from Forshey and Elfving's measurements is similar to the ratios obtained in this work.

Chaplin and Westwood (1972) obtained the relationship between yield index (X) (average of yield per branch CSA x trunk CSA) and actual yield (Y) for sweet cherry as X=-2.40+2.04Y. If actual yield is used as the dependant variable, that is Y=1.18+0.49X, the slope should be about 0.5 which implies that the CSA ratio is about 0.5. Branches on cherry trees are much fewer than those on apple trees and it is possible that the sum of the CSA of branches of cherry trees is smaller than that of the trunk. This indicates that different species may have different CSA ratios but, within species, the ratio appears to be similar. A relatively consistent ratio will be useful for practical sampling work.

3.6.2 Branches of Different Orders

With sampling sometimes conducted on branches remote from the main trunk in secondary and tertiary positions, it is necessary to investigate variation of the CSA in these higher orders. In Table 3.6 the CSA ratio for higher order branches is usually smaller than that for lower orders. The ratio standard errors are usually higher indicating a greater variation. No difference between frame branches and smaller primary branches was found (sources 33 and 34).

The average ratio of branches of the old Granny Smith trees (source 38) is < 1 due to severe pruning. This indicates that severe pruning can have a greater influence on the CSA ratio for higher order branches making it difficult to formulate a firm recommendation for sampling these higher order branches.

When the sum of the CSA of branches becomes larger, the ratio increases; whereas when the sum of the CSA of branches becomes smaller, perhaps due to pruning or increasing age, the ratio decreases. If the estimation of FFN is less than it should be, it may be due to the sampling of higher order branches. In contrast, if the estimation of FFN is greater than it should be, it could be due to the larger ratio resulting from very light pruning of the monitored branches over a period of time.

3.6.3 Variation of Ratios between Orchards

Planting system and source of tree varies between orchards. Although trunk circumferences were measured at 30 cm above the point of scion/stock union according to Pearce and Davies (1954), the distances from the union to the ground are quite different from orchard to orchard and still influence the measurement of trunk circumferences.

In the calculation of the CSA ratio, the sum of branch CSA is calculated from the addition of individual CSA's. A slight error in the measurement of a branch diameter does not influence the final result very much. However, any small inaccuracy in taking the single trunk CSA measurement (diameter or circumference) can lead to a wide variation in the calculation of the CSA ratio, as indicated in the ratios calculated for the monitored orchards (sources 15 - 29 in Table 3.6).

Most of the coefficients of variation (Table 3.6) with 5-tree sampling per orchard were below 5%. The small standard error of the ratios within each orchard is the key factor. The variation in the CSA ratios between orchards indicates that each orchard should have a unique narrow range of CSA ratios established.

3.6.4 Branch Number

The CSA ratio increases with the number of branches on the tree (Figure 3.8), especially above 60 branches emanating from the central leader. Young trees usually have fewer

branches. Older trees also have fewer branches but in this case it is usually due to pruning. Because of this it is not easy to obtain a very good correlation between tree age and the size of the CSA ratio (r=0.58**).

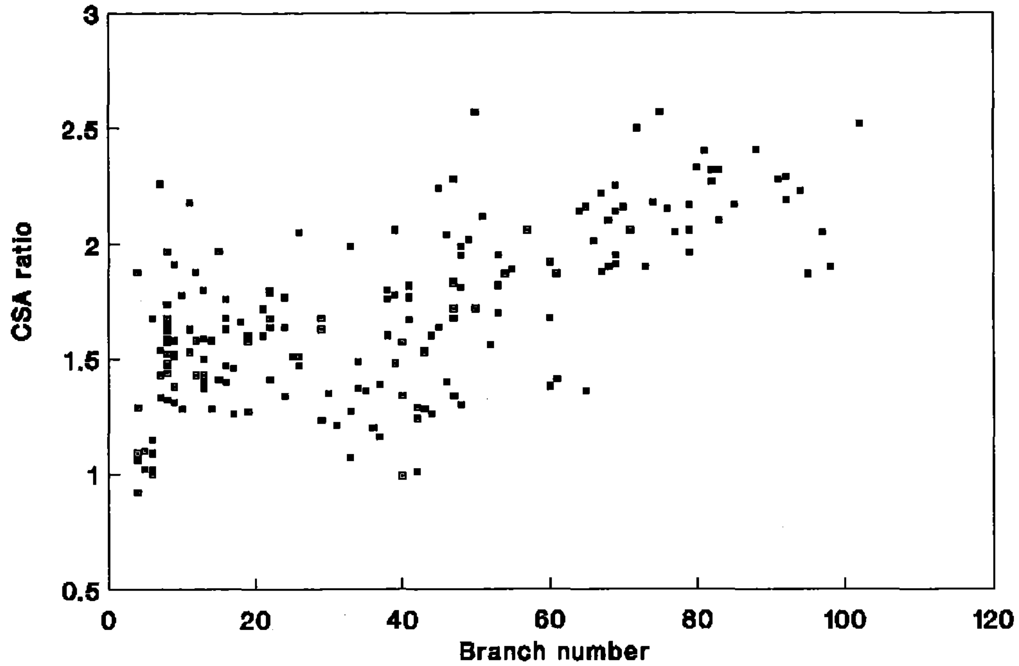

Figure 3.8 Relationship between the CSA ratio and the number of branches

The difference in the CSA ratio means for pruned branches (source 39) and unpruned branches (source 40) was significant (F=5.13*) due to the branch number reduction (Table 3.6).

3.6.5 Age

For unheaded nursery trees, the ratios are near 1 (Table 3.6). This means that in the first year the sum of the CSA of primary branches is almost equal to the trunk CSA.

At a tree age of 2 - 3 years, the ratios are clearly > 1, in the range 1.4 - 1.6 (Table 3.6) indicating an increasing ratio with increasing age.

For maturing trees, the only records kept were for the 5 Gala apple trees monitored from 1986 - 1992 inclusive in the Lincoln University Research Area. The CSA of trunks was recorded for all 7 years. The CSA of the sum of branches was recorded for 1986, and the years 1989 - 1992 and an average estimation was determined for the 1987 and 1988 years not recorded.

The change in the CSA ratio is plotted in Figure 3.9. Up until year 9 the number of branches on the trees were increasing as the trees continued to grow and then declined slightly with pruning. The sum of the CSA of branches was increasing at a greater rate than the trunk CSA until year 8. Then there could be a tendency for a slight decrease in the sum of CSA of the branches due to some structural pruning of the trees. The CSA ratio increased initially, stabilised at about 2.2 from age 8 to 11, and then declined to 2.0 at the age of 12. There is a need to repeat these measurements on a range of orchards to establish clear relationships in individual situations and according to management practices on each orchard.

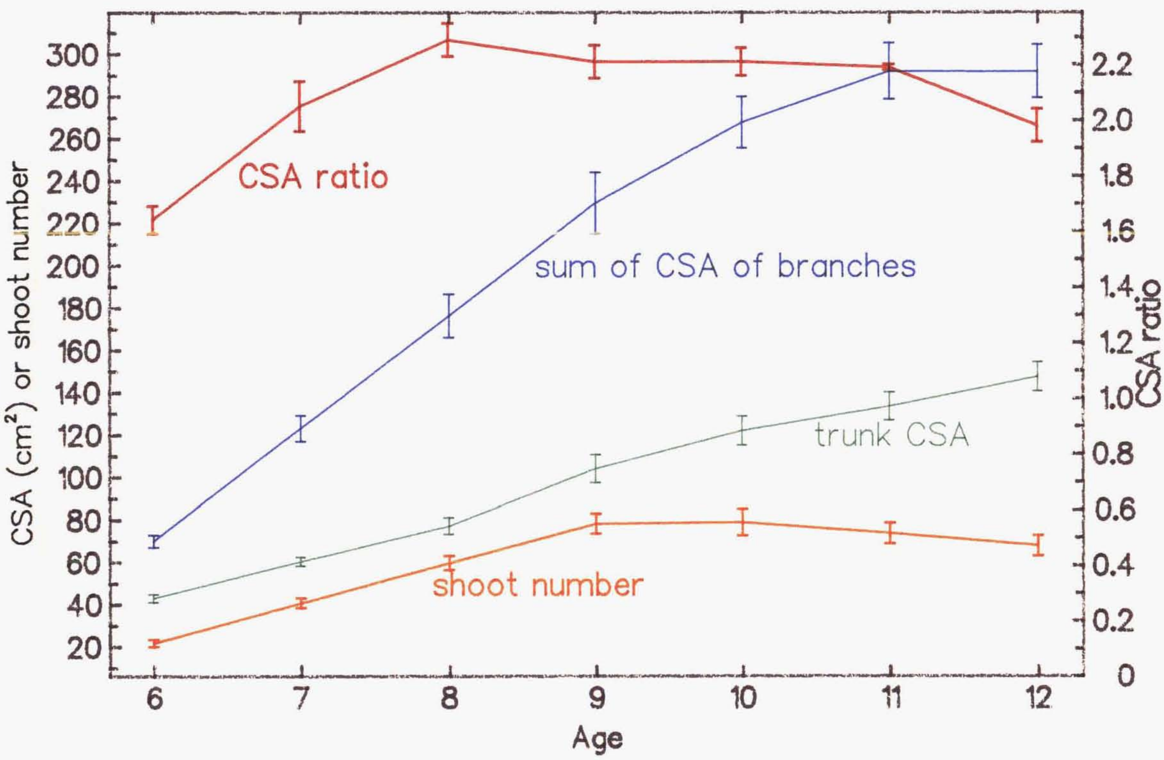

Figure 3.9 CSA ratios in consecutive years

3.6.6 Variation of Branch Fruitfulness (FFN)

FFN of the sum of the branches is total fruit number of a tree divided by the sum of CSA's of all the branches,

$$FFN_{\Sigma branch} = \frac{FN_1 + FN_2 + \ldots + FN_n}{CSA_1 + CSA_2 + \ldots + CSA_n} \tag{3.13}$$

However, in order to solve this equation, all of the branches for a tree must be measured.

This is time consuming and difficult in practice. Mathematically averaging the fruitfulness of each branch and obtaining the average fruitfulness of the total branches will provide a slightly different answer from that in equation 3.13:

$$FFN_{branch\ average} = \frac{1}{n}\left(\frac{FN_1}{CSA_1} + \frac{FN_2}{CSA_2} + \ldots + \frac{FN_n}{CSA_n}\right) \tag{3.14}$$

Equation 3.14 can be used in practice especially when sample branches are used. The accuracy in obtaining $FFN_{\Sigma branches}$ from $FFN_{branch\ average}$ will depend on the variation of FFN between branches (Table 3.8).

Table 3.8 Variation of FFN of branches

	Tree No						
Source	1	2	3	4	5	6	7
primary branches							
average FFN	4.65	4.35	4.40	5.25	3.52	2.29	4.16
standard deviation	2.88	2.69	2.29	2.86	1.22	1.23	2.70
secondary branches							
average FFN	5.74	4.69	5.27	5.77	4.55	3.45	3.03
standard deviation	3.37	3.10	3.60	4.07	2.57	3.77	1.73

The ratio, of course, cannot be constant for every branch. Sometimes a relatively small number of fruit (the numerator) will lead to a small ratio. For the average FFN of about 3 - 5 the smaller value will not be too far away from the average, but when the CSA (the denominator) is small, sometimes quite a large ratio will be created. Hence the distribution obtained. The branch FFN ratios exhibited a skew distribution (Figures 3.10 and 3.11) with a peak to the left and a long tail to the right. Under this skew distribution, the arithmetic mean will be large.

In order to obtain a more representative sample, data transformation and trimming of extreme points (outliers) in the distribution were tested.

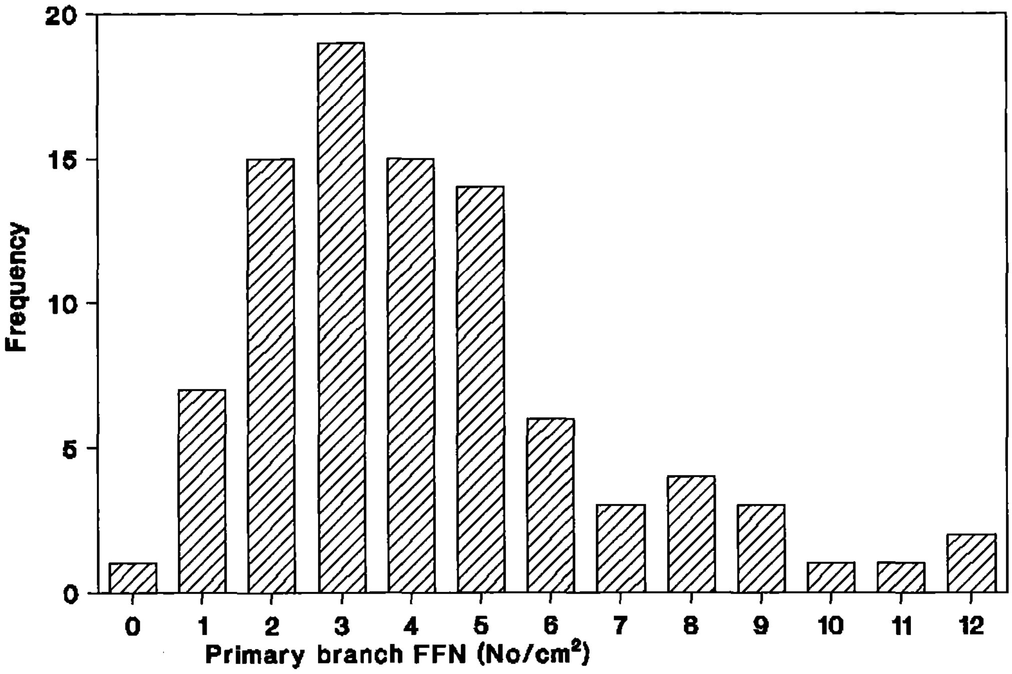

Figure 3.10 Histogram of fruit number per CSA of primary branches (N=91)

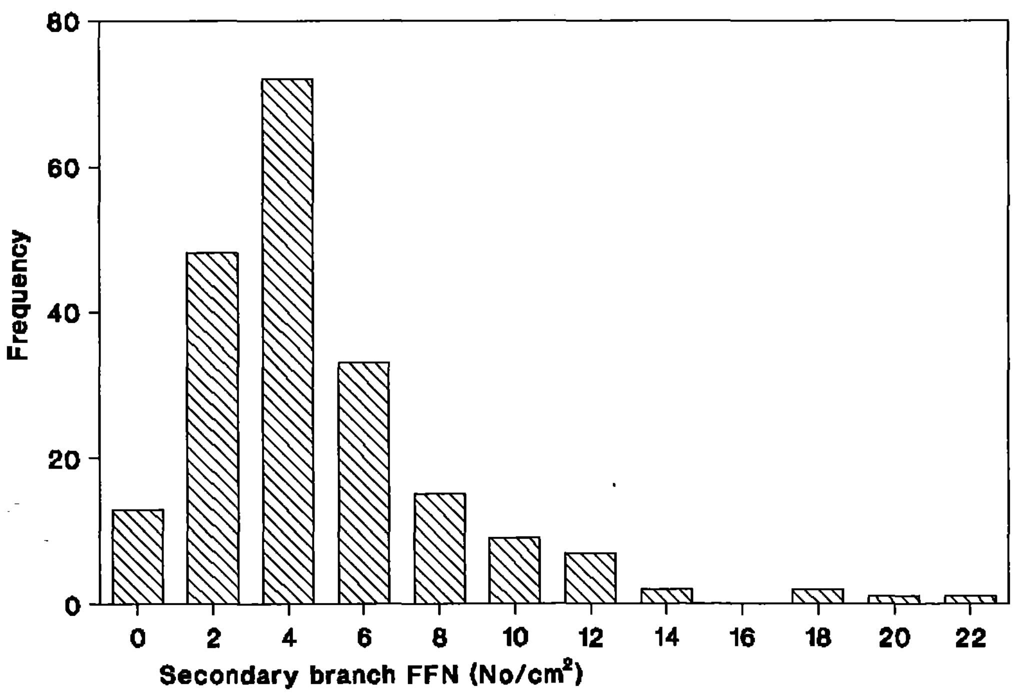

Figure 3.11 Histogram of fruit number per CSA of secondary branches (N=203)

Draper and Smith (1981) considered that an outlier should be submitted to very careful examination to see if the reason for its extremity can be determined. Anscombe (1960) emphasized that in sufficiently extreme cases, no one hesitates about such rejections. Even

writers who have expressed total disapproval of the rejection of outliers may insert a remark: "except for obviously incorrect readings". Anscombe thought that a routine rejection rule should be made. Hoaglin *et al.* (1983) described the method for exploratory data analysis claiming "resistance methods are little affected by a small fraction of unusual data values and are an important part of exploratory data analysis. It is unwise for the scale of a stem-and-leaf display to depend on the largest and smallest data values. Instead, we often begin by setting aside any unusual data values, and we then base the choice of scale for the display on the rest of the data."

Different estimation methods were compared with the real FFN of the sum of the branches (Table 3.9). Based on standard errors, the sample sizes required for a 15% error limit are given below the ratios.

Table 3.9 Comparison of different estimation methods with real FFN of the sum of branches

	Tree number						
Estimation treatment	1	2	3	4	5	6	7
FFN of the sum of branches	3.69	3.44	3.23	4.22	3.19	2.13	2.82
primary branches							
arithmetic average of branch FFN	4.65	4.35	4.40	5.25	3.52	2.29	4.16
	(17)[z]	(17)	(12)	(13)	(5)	(13)	(19)
log transformation of branch FFN	3.80	3.87	3.89	4.73	3.29	2.00	3.05
	(12)	(5)	(6)	(4)	(5)	(30)	(33)
trim 5% of branch FFN	4.02	3.59	3.79	4.55	3.52	2.29	3.77
	(14)	(4)	(7)	(7)	(6)	(13)	(19)
secondary branches							
arithmetic average of branch FFN	5.74	4.69	5.27	5.77	4.55	3.45	3.03
	(15)	(19)	(21)	(22)	(14)	(53)	(15)
log transformation of branch FFN	4.76	3.87	4.20	4.58	3.86	2.34	2.43
	(8)	(10)	(12)	(11)	(10)	(55)	(36)
trim 5% of branch FFN	4.74	3.87	3.99	4.30	4.11	2.90	3.03
	(12)	(11)	(8)	(9)	(11)	(18)	(15)

[z] number of samples to be taken for a standard error < 15% of the mean.

Figure 3.12 shows a normal distribution resulting from the trim at the 5% level. Table 3.9 shows that the log transformation and trim have quite a clear advantage compared with the arithmetical average. In some cases the log transformation produced quite large sample numbers and appears to be less reliable than the "trimming" method.

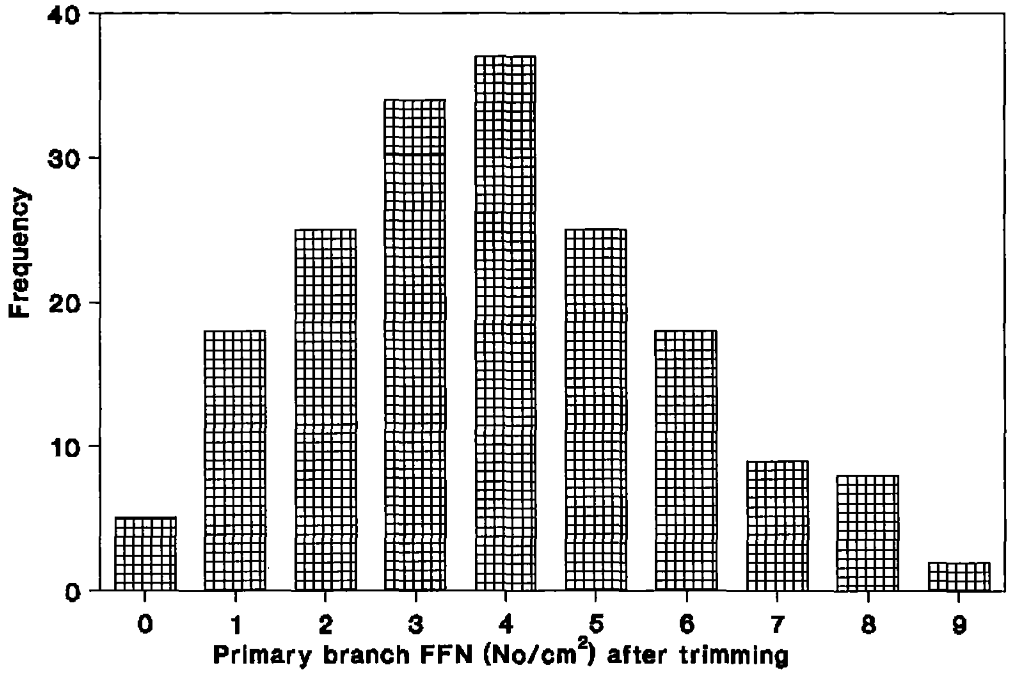

Figure 3.12 Histogram of fruit number per CSA of primary branches after deleting outliers at the 5% level (N=181, outliers=22, ie 10.8%)

For studies involving FFN ratios, use of the "trimming" method to eliminate absolute outliers is a sound choice where a very small branch with many fruits or vice versa has been sampled. This method has been applied in Chapter 4.

Seven trees were used as an example for sampling a plot. They had an average of 5.206 for FFN of the trees with a standard error from the mean of 0.337 (CV = 6.47%). For an even orchard, these samples would be enough to represent the plot. The analysis indicated in this case that 12 first order branches would provide acceptable results at a 15% error level using the trimming method and 27 branches at a 10% error level. The FFN ratio was 1.41, which is quite close to the CSA ratio of 1.61.

The variation of FFN between branches within one tree was greater than the average of the 7 trees (Table 3.8 and Appendix 3) indicating that more branches should be sampled to obtain greater accuracy.

For practical work it is not necessary to estimate crop loads for a single tree but rather the block or orchard basis will be more useful.

3.6.7 Recommendations on Branch Selection

In order to avoid extreme outlier sampling very small branches are not recommended. For example, a twig with a circumference of 1 cm may bear 6 fruits (75 fruits per cm^2 of branch CSA). This may be possible although unusual and will be quite different from the average on that tree.

Unusually high fruit number per CSA of monitored branches do not appear when the CSA is greater than about 6 cm^2, to the right of the line in Figure 3.13. This would be represented by a diameter of 2.8 cm or a circumference of 8.7 cm. This conforms with the suggestion by Forshey and Elfving (1979) about sampling branches with a circumference between 10 - 15 cm. Fruit number on branches with a CSA of about 6 cm^2 are usually less than 100 and hence feasible to record accurately (Figure 3.14). When fruit number per branch is increased the stability of the FFN ratio is not enhanced further (Figure 3.15).

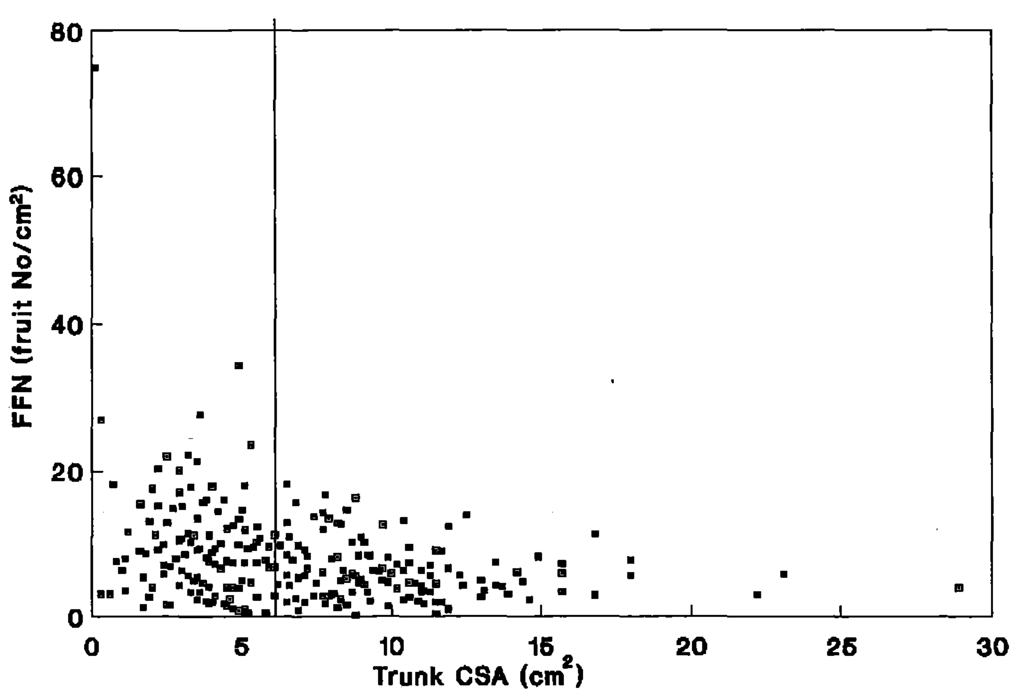

Figure 3.13 Relationship between fruit number per CSA of the monitored branch and its CSA

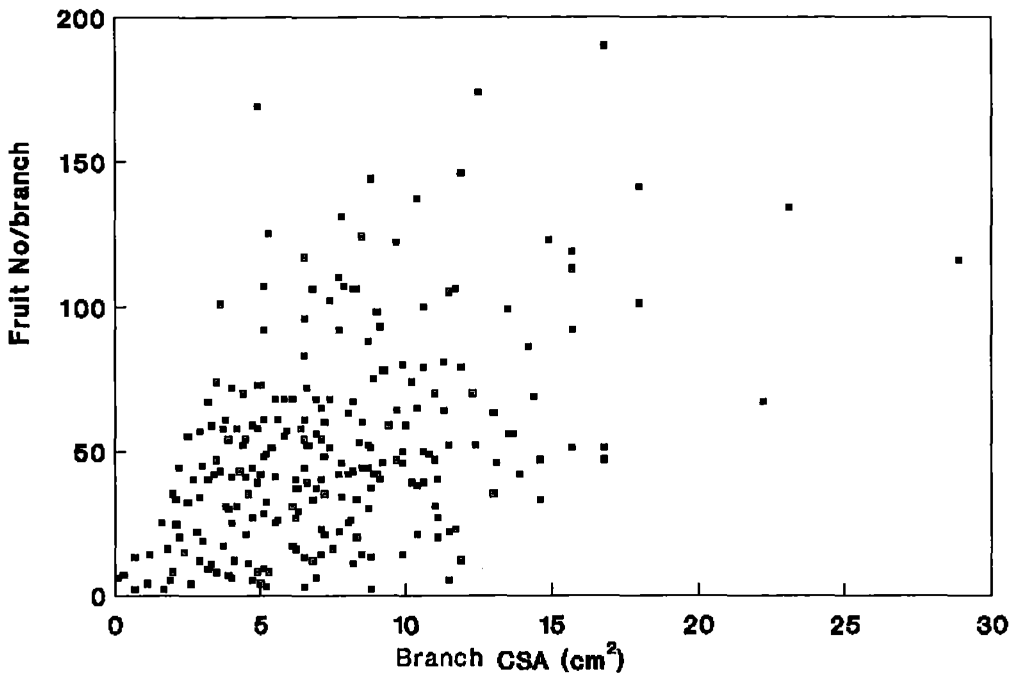

Figure 3.14 Relationship between fruit number on the monitored branch and its CSA

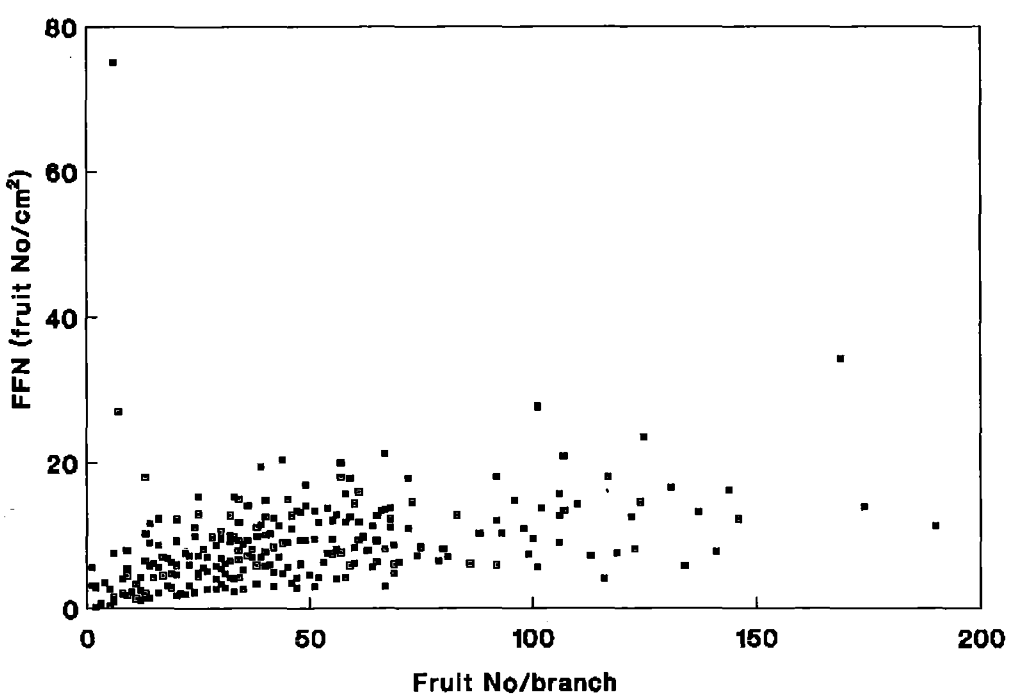

Figure 3.15 Relationship between fruit number per branch and per CSA of branch

3.7 PRACTICAL WORK

There are two methods by which the facts elicited in this chapter can be applied practically.

Because of some differences between cultivars, ages, orchard location and management, it would be preferable for ratios to be determined uniquely for each orchard where long term sampling is envisaged. Measuring the CSA of all branches on sampled trees may require excessive time in some circumstances. The research on the probability of only measuring larger branches is shown in Table 3.10 where mature trees and primary branches were used.

Table 3.10 Percentage of the sum of branch CSA remaining if small branches are omitted

		Branch diameter			
Source	Tree age	0.5 cm	1 cm	1.5 cm	2 cm
7	9	99.2	92.1	87.5	82.8
8	10	99.4	93.8	89.1	83.3
9	11	99.5	95.7	91.4	86.8
10	12	99.6	95.7	92.1	89.1
11	4	97.8	87.8	79.3	67.0
12	15	99.9	97.6	92.1	83.5
13	16	100.0	100.0	100.0	100.0
14	17	100.0	100.0	99.7	99.1
15	6	99.8	96.5	87.0	71.2
16	5	100.0	87.9	80.8	69.6
17	7	100.0	95.7	92.5	87.7
18	5	99.1	77.9	73.6	68.1
19	8	99.7	89.9	83.1	72.9
20	6	99.6	90.7	81.0	67.1
21	6	99.9	93.6	83.9	72.8
22	8	100.0	88.3	83.4	76.6
23	6	100.0	89.0	78.7	69.0
24	5	100.0	85.6	65.8	36.1
25	6	99.7	87.4	76.2	58.5
26	5	99.4	84.9	75.5	60.1
27	7	99.8	87.2	79.5	71.3
28	8	100.0	95.0	90.7	85.4
29	7	99.9	86.0	74.2	61.4
mean		99.6	92.0	85.5	76.7

Omitting measurement of branches with a diameter < 1 cm will not lose too much accuracy (Table 3.10). However if branches in the range of 1.5 - 2 cm diameter are omitted the sum of branch CSA will become inaccurate, especially when tree age is < 8.

Another way is to measure the FFN ratio by means of random sampling of branches. This ratio may be kept for a number of years with only small adjustments according to management, branching and yield records. The estimation is likely to become more and more accurate.

For some orchards, which neither have long term yield records, nor want to measure CSA ratios, the monitoring work can be started based on CSA ratios of 1.6 - 2.1 as established in this research work. However, this will not be very accurate and should be adjusted in subsequent years.

CHAPTER 4

APPLE TREE SYSTEM MODELLING

4.1 INTRODUCTION

Modelling fruit production has reached practical application with the development of the FRUPRO program (Winter 1980; 1983; 1988). Winter predicted yield and fruit size based on after thinning counts using correction factors for different climatic regions.

Although climatic data may provide reliable prediction within a region, the response can differ from year to year within the same orchard. To predict more accurately, further research is needed on the climatic influence on fruit physiology and production.

The effect of extreme weather conditions such as cold injury to fruit trees and frost injury to flowers and fruit is well understood. The effect of normal weather conditions is not so clear. Two approaches may be used to research the weather influence.

i Based on plant physiological knowledge a selected hypothesis may be proved statistically. For example "autumn temperature and/or sunshine hours positively affect the yield in the following year" (Lakso, 1987; Beattie and Folley, 1977). This method only proves what has been previously recognised.

ii New relationships, not previously known, can be identified from statistical analysis. Subsequently these must be proved and explained by designed experiments. When Beattie and Folley (1977), Jackson and Hamer (1980) and Goldwin (1982) all reported that high temperatures in the February to April period in England were associated with low yields in the following growing season, Jackson *et al.* (1983) designed an experiment using Cox's Orange Pippin apple trees and proved this "late winter effect".

The second method is difficult without extensive data over a number of years. Even using long-term records, improvement in technology can counteract the effect of weather (Beattie and Folley, 1977).

In this study, 15 orchards were monitored for 3 to 6 years. A total of 47 points were

available for analyses. The advantage was a large number of points within a short period. The disadvantage was variability between orchards in tree density and management, although the cultivar and training method were constant.

Factors affecting yields, can be classified into exogenous and endogenous variables. The inherent genetic characteristics, physiological behaviour, production in the previous season, flowering and fruit setting, acting either independently or in combination, are endogenous. The effect of climate, soil type and management are exogenous to the system.

In this paper, climatic factors and tree parameters have been combined into a model to predict fruit production.

4.2 ABBREVIATION OF VARIABLES

Abbreviation of variables used in this paper are listed below:

i **Tree parameters:**

%AA+A	percentage of fruit in grades AA and A;
%B	percentage of fruit in grade B;
%C+D	percentage of fruit in grades C and D;
%FReAD	percentage of fruit remaining after the natural drop;
%FReAT	percentage of fruit remaining after thinning;
%FBL	percentage of lateral flower buds;
$\%_{grade}$	percentage of fruit in each grade;
%R	percentage of rejected fruit;
%SET	percentage initial fruit set;
/ha	per hectare;
/tr	per tree;
/x	per cross sectional area;
_LY	in the previous growing season;
AGE	tree age;
CSA	cross sectional area of trunks;
FB	flower bud number;
FN	fruit number at harvest;
FNN	fruitfulness;
FNAT	fruit number after thinning;

FNBT	fruit number before thinning;
FrWt	average individual fruit weight;
Ln( )	logarithm to the base e;
$Price_{grade}$	price for each grade;
Y	yield;

ii **Climatic parameters:**

T	monthly average temperature (°C);
MaxT	monthly average maximum temperature (°C);
MinT	monthly average minimum temperature (°C);
S	monthly sunshine hours;
R	monthly rainfall (mm);
RD	monthly rain days;

Numbers attached to climatic parameters represent the months:

-10 ~ -12	October to December in the previous growing season;
1 ~ 7	January to July in the previous growing season;
8 ~ 12	August to December in the current season;
13 ~ 15	January to March just before or during harvest time.

eg:

T_2	monthly average temperature (°C) for February in the previous season.
$MaxT_{12\sim14}$	monthly maximum average temperature for December - February in the current season.

4.3 MATERIALS AND METHODS

Apple monitoring work commenced in the 1986/87 season. The three main New Zealand pip fruit districts Canterbury, Nelson and Hawkes Bay were included. In each district, five orchards were monitored. Fourteen orchards were monitored for the three growing seasons, 1986/87, 1987/88 and 1988/89. However, one orchard in Hawkes Bay was monitored for only one-season (1986/87) and another orchard substituted for the next two seasons 1987/88 and 1988/89. After the initial three-year monitoring period, one orchard in Canterbury was monitored for another two growing seasons, 1989/90 and 1990/91. The model developed was validated on this orchard during the season 1991/92.

Table 4.1 Basic orchard structure

District	Orchard Code	Year of Planting	Variety	Rootstock	Planting	Trees /ha
Canterbury	I	1982 R	Gala	MM106	CL	571
	II	1982 DB	Royal Gala	MM106	CL	741
	III	1981 R	Royal Gala	MM106	CL	625
	IV	1982 DB	Royal Gala	MM106	CL	741
	V	1980 R	Royal Gala	M793	MA	635
Nelson	I	1982 R	Royal Gala	MM106	MA	667
	II	1981 DB	Royal Gala	MM106	MA	588
	III	1980 R	Royal Gala	M793	CL	455
	IV	1982 R	Royal Gala	MM106	CL	667
	V	1983 R	Royal Gala	M793	CL	952
Hawkes Bay	I	1982 R	Royal Gala	MM106	MA	1102
	II*	1983 R	Regal Gala	MM106	CL	571
	II**	1982 R	Regal Gala	MM106	CL	548
	III	1981 R	Royal Gala	MM106	CL	741
	IV	1980 R	Royal Gala	MM106	MA	566
	V	1981 R	Royal Gala	MM106	MA	687

Hawkes Bay II* = the orchard monitored in the 1986/87 season;
Hawkes Bay II** = the orchard monitored in the 1987/88 and 1988/89 seasons;
R = planted as a rod (one year old from budding);
DB = planted as a dormant bud;
MA = modified axis;
CL = central leader.

Details of the monitored orchards are given in Table 4.1. Fourteen orchards had the cultivar Royal Gala and the fifteenth orchard was Gala. Twelve orchards had trees on MM106 rootstock and three orchards had Royal Gala on M793.

Trees were all trained on the central leader or the axis method and were monitored in the

initial year at an age of 5 - 8 years from dormant buds. Although five trees on each of the 15 orchards were selected at random, some degree of standardization was sought to allow reasonable comparison.

4.3.1 Measurements on the Monitored Branches

It was not feasible to count the numbers of buds, flowers, and fruits on each whole apple tree. Instead, the branch sampling technique, described in Chapter 3, was used to measure three branches on each of the five trees for each orchard.

Each tree was divided into three levels according to the height of the central leader:

Level I < 1.2 m (from the ground)

Level II 1.2 - 2.6 m

Level III > 2.6 m

Uniform branches of similar circumference from the three different levels of each tree were chosen. In selecting the branches an attempt was made to provide variation in vertical distribution and horizontal orientation to the sun. The following data was recorded on the monitored branches:

i Branch circumference or diameter at about 10 cm above the junction during the dormant period.

ii Number of flower buds. From the second season, number of terminal and lateral flower buds were recorded separately.

iii Number of fruits before and after thinning. From the second season, number of fruit from terminal and lateral flower buds before and after thinning were recorded separately. The percentages of initial fruit set, the remaining fruit on the trees after thinning and the remaining fruit after pre-harvest drop were calculated as follows:

$\%SET$ = fruit number before thinning / (5 · flower bud number) · 100

$\%FReAT$ = fruit number after thinning / fruit number before thinning · 100

$\%FReAD$ = fruit number at harvest / fruit number after thinning · 100

iv Fruit weight, colour and defects were recorded for every individual fruit from all the monitored branches at harvest time, providing fruit number and yield records. In Hawkes Bay, in the second season and for all orchards in the third season, the fruit from terminal and lateral flower buds were differentiated at harvest. Fruit weight records allowed grade classifications according to the standards given in Table 4.2 (18.5 kg = 1

carton). Rejects were classfied as less than D grade in weight, less than 60% colour, or with any defect such as black spot, russet, sunburn etc.

Table 4.2 NZ Apple and Pear Marketing Board grade classifications

Grade	AA	A	B	C	D
Fruit number per carton	80-88	100-113	125-138	150-163	175-198
Fruit Weight (g)	> 197	154-197	126-154	107-126	88-107

4.3.2 Measurements on the Whole Trees

In addition to the measurements on the monitored branches, the trees were measured also as follows:

i Tree height (m) from the ground to the terminal tip of the leader.

ii Tree width (m) across the row.

iii Tree length (m) along the row.

iv Trunk circumference (cm) at about 30 cm above the bud union during each winter.

v Number of all branches arising from the central leader and circumference of the branches 10 cm from the trunk in August 1986.

vi For each pick, the yield and the fruit number harvested were recorded on the three levels separately. Growers varied in the frequency of apples harvested from one to four picks. Maturity levels for harvesting were determined by the NZAPMB field staff in each district.

vii For each pick at each level, 20 fruits were sampled to record individual fruit weight, colour and defects for grade classification according to Table 4.2. The percentages of fruit in each grade were calculated for each level and each harvest separately. Subsequently, when all the harvests had been completed, the percentage in each grade for each harvest was calculated in relation to the total yield. Similarly, for each harvest, percentages were calculated in relation to the whole tree for size grades in each of the three tree levels and for the monitored branches. Finally, the percentage in each grade for the complete harvest was calculated.

viii Additional recordings included labour input, chemical programs and any other relevant management information.

ix The following items were calculated:

$$\text{trunk CSA} = (\text{trunk circumference})^2 / 4\pi$$

crop load (Y/x) = yield per tree / trunk CSA

fruitfulness (FFN) = fruit number per tree / trunk CSA

4.3.3 Statistical Validation for Tree Parameters

This section deals with the calculation and the validation of the averages of tree parameters.

4.3.3.1 Tree Parameter Averages

Theoretically a total of 47 samples is possible for calculation of the various means, 3 seasons x 15 orchards (5 trees/orchard) = 45, plus 2 additional seasons x 1 orchard = 47. Because some recordings were not made for some orchards in some years, the actual number of sample means available for analysis is slightly smaller than 47 (Table 4.3).

Table 4.3 Statistical validation of sampling: distribution of CVs (%)

Variable	Number of sample	Minimum	First quartile	Mean	Third quartile	Maximum	Standard error
CSA	44	1.42	3.17	4.35	5.66	7.72	1.62
FN/tr	45	0.00	6.27	8.48	9.48	26.11	4.68
FNN	42	2.71	5.37	8.88	11.36	25.61	4.70
Y/tr	45	0.00	4.47	7.08	8.87	22.86	4.56
Y/x	42	2.41	4.27	7.30	9.18	22.12	4.06
FrWt	40	0.00	2.40	3.37	3.79	8.86	1.83

The statistical validation of sample averages is expressed as coefficients of variation (CV), namely the standard error of means divided by the averages. Table 4.3 shows that the means and third quartile of the CVs are all < 10% except the third quartile of FFN which is just above 10%. Most CVs of the tree parameter averages are within the biologically acceptable range.

4.3.3.2 Monitored Branch Parameter Averages

Because of changes in the personnel collecting data in the various districts and seasons and because of natural and management variations there were some complications in the monitored branch recordings.

i Fruit number before or after thinning or at harvest time was not recorded on some orchards in a particular year;

ii In some instances no fruit remained on the monitored branches at harvest time due to fruit drop;

iii In two instances the monitored branches were broken before harvest;

iv When fruit number at harvest exceeded an earlier count, human counting error was assumed and the recording was deleted from the analyses.

v Recordings showing obvious extremes, hereafter referred to as outliers, created a particular problem in this modelling research. Where, for example, percentage initial fruit set calculations indicated an extreme in the distribution range, evidence is presented for omitting some of these "outliers" at a 5% level.

Table 4.4 lists all variations from the norm and the actual number of recordings for each parameter used in the analysis.

Parameter averages estimated by season and by orchard (15 orchards in 3 seasons and one orchard in another 2 seasons) should produce 47 means altogether. Table 4.5 shows the reduced sample number due to problems listed in Table 4.4. Each mean is normally calculated from 15 monitored branches although missing values and outlier elimination reduces the number slightly. Table 4.5 shows that the means of the CVs for the percentages are below or about 10%. At least 75% of the CVs are < 10% for fruits remaining after thinning and pre-drop, and < 15% for initial fruit set. This is still an acceptable range for biological results.

Table 4.4 Sample details for tree parameters

Variable	Number of samples				Orchard (C,N or H), year (y), tree (T) and level (L) for missing records[t]
	Missed records	Actual records	Unreliable records[w]	Outliers	
FB	0	705	-	-	-
FNBT	76	629	-	-	H1-5y3[z]; N4y2T1L3[w]
FNAT	31	674	-	-	C5y1[z]; N3y2[z]; N4y2T5L1[w]
FN	41	664	-	-	H2y1[z]; C4y3[z]; N3y2T2,3,5[y]; N2y1T3L3[x]; N5y2T4L3[x]
%SET	76	610	4	15[u]	H1-5y3[z]; N4y2T1L3[w]
%FReAT	107	598	-	-	H1-5y3[z]; C5y1[z]; N3y2[z]; N4y2T1L3[w]; N4y2T5L1[w]
%FReAD	67	537	73	28	C5y1[z]; N3y2[z]; H2y1[z]; C4y3[z]; N2y1T3L3[x]; N5y2T4L3[x]; N4y2T5L1[w]; C2y1L3T2,4[v]; N4y1T4L2[v]; H1y1T2L3[v]

z not recorded for the orchard;
y these trees were involved in a plant protection experiment and seriously affecting yield;
x the monitored branches were broken before harvest;
w unreliable records due to counting errors;
v zero fruit after thinning.
u the average of initial fruit set in H2 in the first season was 99.6%, which is an outlier from the average and hence deleted. There was no record of fruit number at harvest for this orchard. Recordings were discontinued after the first season.
t eg H1y1T2L3 = Hawkes Bay, orchard 1, year 1, tree 2, level 3.

Table 4.5 Statistical validation of sampling on monitored branches: distribution of CVs (%)

Variable	Number of samples	Minimum	First quartile	Mean	Third quartile	Maximum	Standard error
%SET	41	4.49	7.53	10.72	12.52	21.28	4.08
%FReAT	40	2.82	4.95	6.81	7.83	17.76	3.07
%FReAD	43	1.69	3.48	4.90	5.56	12.24	1.93

4.3.3.3 Tree Information Extrapolated from Monitored Branches

The commonly accepted method of handling extrapolation from monitored branch information to a tree basis is to use percentages (Forshey and Elfving, 1979).

FNAT = FN / %FReAD

FNBT = FNAT / %FReAT

FB = FNBT / (5 · %SET)

4.3.4 Data for the Previous Growing Season

The situation in the previous growing season may influence the production in the following year. Alternate bearing is a good example. In this investigation, one orchard (C1) has a 5-year record providing 4-years of recording for the "previous" growing season. Twelve orchards have a 3-year record providing 2-years of recording for the "previous" growing season. As the HB2 orchard changed in the second year there is only one "previous" season in this case. The N3 orchard had the recorded trees changed in the third year following the abortive second year recording and has no reliable "previous" season.

4.3.5 Fruit Growth

A series of fruit growth measurements were taken in the 1989/90 and 1990/91 seasons in order to have additional basic data for the predictive model.

i **Royal Gala apple fruit in the growing season 1989/90:**
Nine 4-year-old Royal Gala apple trees were chosen in Applefields Main South Road Orchard. Five axillary fruit and 5 terminal fruit from each of the 9 trees were tagged on 9 December 1989. The diameter of these fruits was measured once a week until harvest.

ii **Golden Delicious apple fruit in the growing season 1989/90:**
Seventy-two Golden Delicious apple fruits on Lincoln Canopy in the Horticulture Research Area at Lincoln University were tagged on 6 December 1989. The diameter of these fruits was measured once a week until harvest.

iii **Fruit clusters of Gala apple trees in the growing season 1990/91:**
Three 10-year-old Gala trees were chosen in the Horticulture Research Area at Lincoln University. Each fruit in four axillary fruit clusters and 4 terminal fruit clusters on each of the 3 trees was tagged on 2 November. The diameter of these tagged fruits was

measured once a week before Christmas and then once every 2 weeks until harvest. No hand thinning was executed on these clusters and chemical thinning did not occur.

iv **Volume and density measurements in the growing season 1990/91:**

Ten axillary and 10 terminal Gala apple fruits were randomly sampled and harvested once every 2 weeks from 9 November 1990 in the Horticulture Research Area at Lincoln University. Each fruit was measured at the time of harvest for diameter, height, weight and volume. Volumetric measurement was according to Mohsenin's (1986) platform scale method (see Chapter 3 for details), using distilled water. The density of each fruit was calculated from weight ÷ volume and the ratio of fruit height to diameter was also calculated.

4.3.6 Meterological Data Collection

Climatic data from 7 meteorological stations near the monitored orchards was used. These were:

Christchurch Airport, for Canterbury orchards 2 and 5;
Lincoln, for Canterbury orchards 1 and 3;
Timaru Airport, for Canterbury orchard 5;
DSIR Riwaka, for Nelson orchards 1 and 2;
DSIR Appleby, for Nelson orchards 3 and 4;
Nelson Airport, for Nelson orchard 5;
DSIR Havelock North, for all the Hawkes Bay orchards.

DSIR Appleby weather station does not record sunshine hours. For some of the other stations used records of sunshine hours were missing. In all these cases, the data used were from the nearest station where these records were complete.

The climatic parameters included in the model were daily and monthly mean temperature, daily and monthly mean maximum temperature, daily and monthly mean minimum temperature, monthly sunshine hours, monthly rainfall and monthly rain days.

In order to research the climatic effect from the bud formation period, the data covered the period October of the previous season to March (harvest time) in the current season. The end of the previous season is considered to be the end of July.

4.3.7 Multiple Regression

Multiple regression is an effective technique commonly used for exploratory research. However, when any independent variable is correlated with another independent variable, or with a linear combination of other independent variables, multicollinearity will exist, particularly with large datasets. A high degree of multicollinearity may lead to imprecision in the estimation of regression parameters (Wesolowsky, 1976).

Before executing multiple regression, preliminary analysis was carried out. For the tree parameters, one or two variable candidates were selected based on husbandry knowledge and the results of correlation with dependent variables. Log transformations were executed based on husbandry knowledge and scatter plots.

For each of the climatic parameters, 171 combinations may be produced from the 18 months of data. Trianglar contour maps of r values for each of the relationships between dependent tree parameters and climatic items were produced (see section 4.5.3). Not more than six variable candidates were selected based on plant physiological knowledge and the contour maps. According to the resulting scatter plots, no data transformations were required for the climatic parameters.

According to Wesolowsky (1976) the number of data points should be > 10 times the number of variables before selection. In this study there were 47 points altogether. Not more than five independent variable candidates were selected for final use in the model. In the SAS (SAS/STAT User's Guide, 1989) package, the model-selection methods include full model fitted, forward selection, backward elimination, stepwise, maximum R^2 improvement, minimum R^2 improvement, R^2 selection, adjusted R^2 selection and Mallows' C_p selection. In this study, R^2 selection was used for finally selecting the candidates. More than one regression equation for each dependent variable was calculated based on the results of the top subsets from the R^2 selection. These calculations also provided a chance to compare the consistency for coefficients of each independent variable in the various equations. The more consistent the coefficients, the lower the possibility of multicollinearity (Weisberg, 1985). The number of independent variables involved and the final equations were decided based on the R^2 values, the standard error and physiological and husbandry knowledge.

Asymptotic curve regressions were calculated also for the relationships between tree

parameters based on the scatter plots.

4.4 EVALUATION OF PREDICTING YIELD BASED ON TRUNK CSA

Waring (1920) was one of the first to correlate yield of apple trees with CSA. Some authors believed that tree size should be expressed as bearing surface and used this to predict future crops (Sudds and Anthony, 1928; Wilcox, 1941; Pearce, 1949). Others postulated that yield per unit of trunk CSA provided a better measure of productive efficiency (Westwood and Roberts, 1970; Rowe, 1985). Individual growers may compare their crop load with others based on a CSA basis. Waring (1920) suggested that the crop load method would not be accurate enough over time and between orchards particularly as the trees grow older.

These hypothesis were checked using the data from 12 of the monitored orchards. Figure 4.1 shows the change in the average trunk CSA of the 12 orchards over 3 continuous years with the colours showing tree age in the first year of monitoring. Generally, the increase in trunk CSA was similar for all orchards with the parallel lines depicting a similar growth rate.

Figure 4.2 shows the change in average yield per tree of the 12 orchards over the same 3 years. Increase in yield fluctuated markedly between orchards indicating that yield per trunk CSA cannot be a very useful consistent indicator of tree performance. There is also some clear indication of biennial bearing and one orchard showed a decrease in yield due to severe restructuring of the tree through pruning.

Figure 4.3 shows the change in crop load (yield per trunk CSA) for the 12 orchards. Because the increase in tree yield is slower than that of trunk CSA, the general trend in crop load is a decreasing one for all orchards except one.

The conclusion is that it would not be reliable to predict yield based solely on trunk CSA. It may provide comparisons on the efficiency of crop loading between growers but tree age must still be considered.

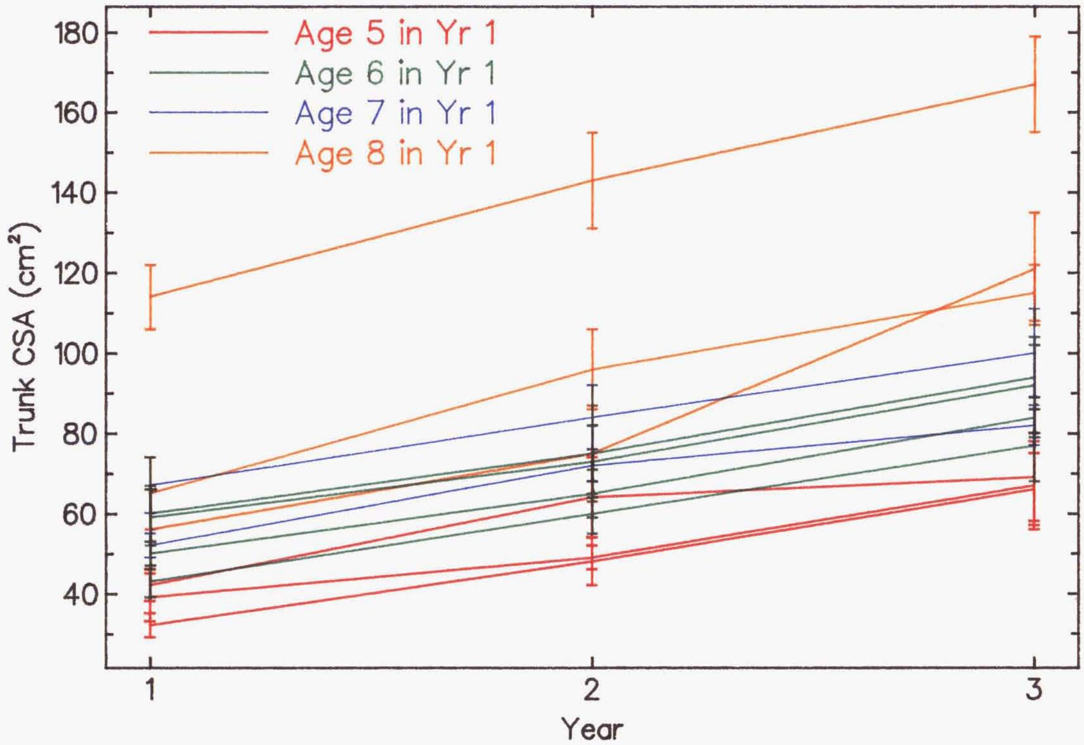

Figure 4.1 Trunk CSA by years on each of 12 orchards

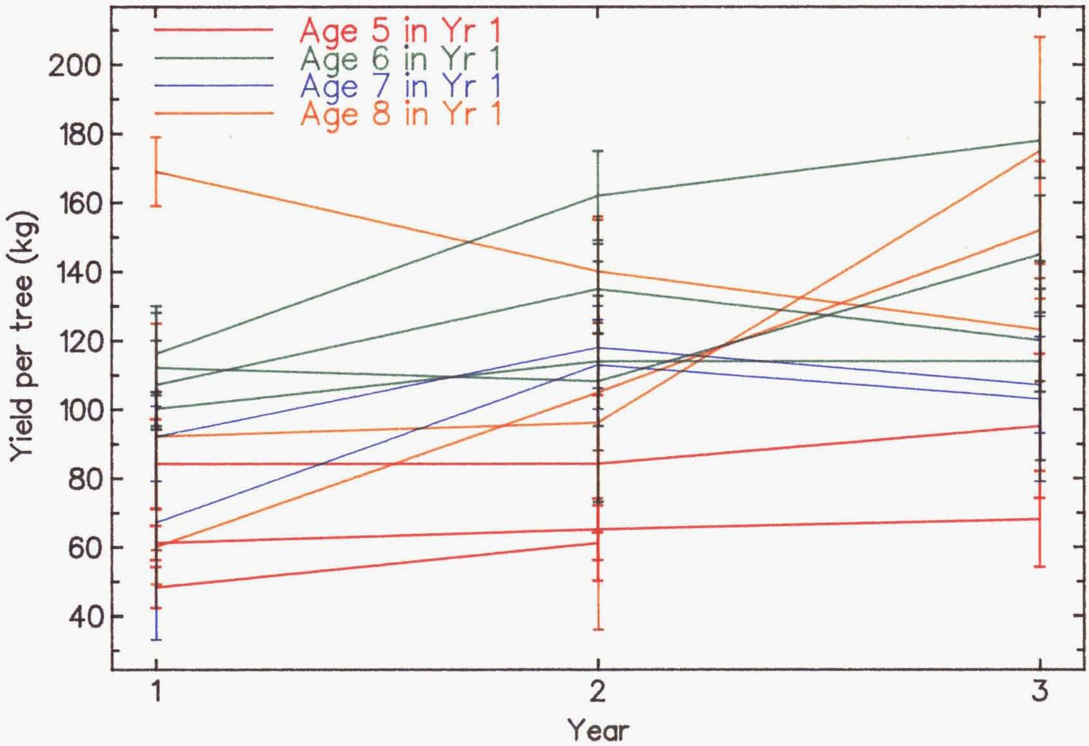

Figure 4.2 Yield by years on each of 12 orchards

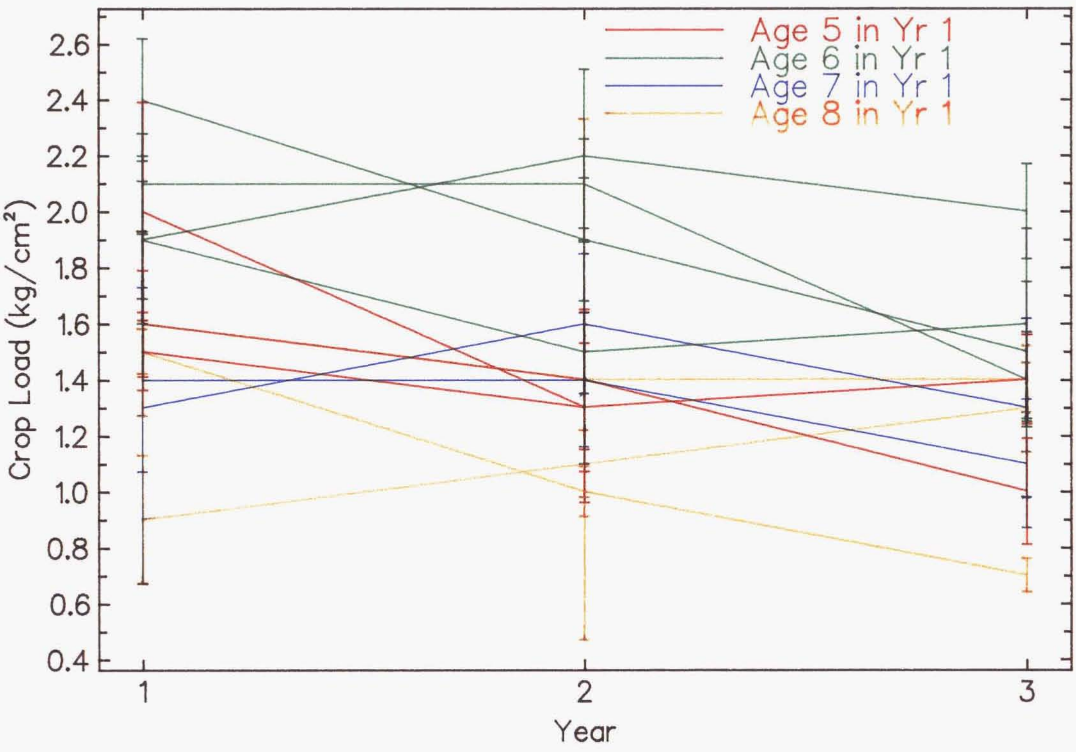

Figure 4.3 Crop load by years on each of 12 orchards

4.5 INITIAL FRUIT SET

4.5.1 Fruit Set Investigation

Fruitlets in 12 terminal and 12 axillary fruit clusters were individually tagged just after petal fall to determine initial fruit set and subsequent fruit drop. Figures 4.4 and 4.5 show initial fruit set and subsequent fruit drop in each fruit cluster for axillary and terminal fruits, respectively. The different colours represent fruit number remaining in each individual cluster with the red line showing the average and the standard error.

The fruitlets dropping before December can be interpreted as those not setting naturally but some fruits continued to drop up until the end of February. For terminal fruit clusters, 3 or 4 fruits remained on average but, for clusters in the axillary position, only one fruit on average remained at harvest time.

Two thirds of the "king" fruits remained at harvest time for the terminal clusters (Table 4.6) and only a quarter for the axillary clusters. Overall the fruit at harvest on terminal clusters was 58% while that for lateral clusters was 18%.

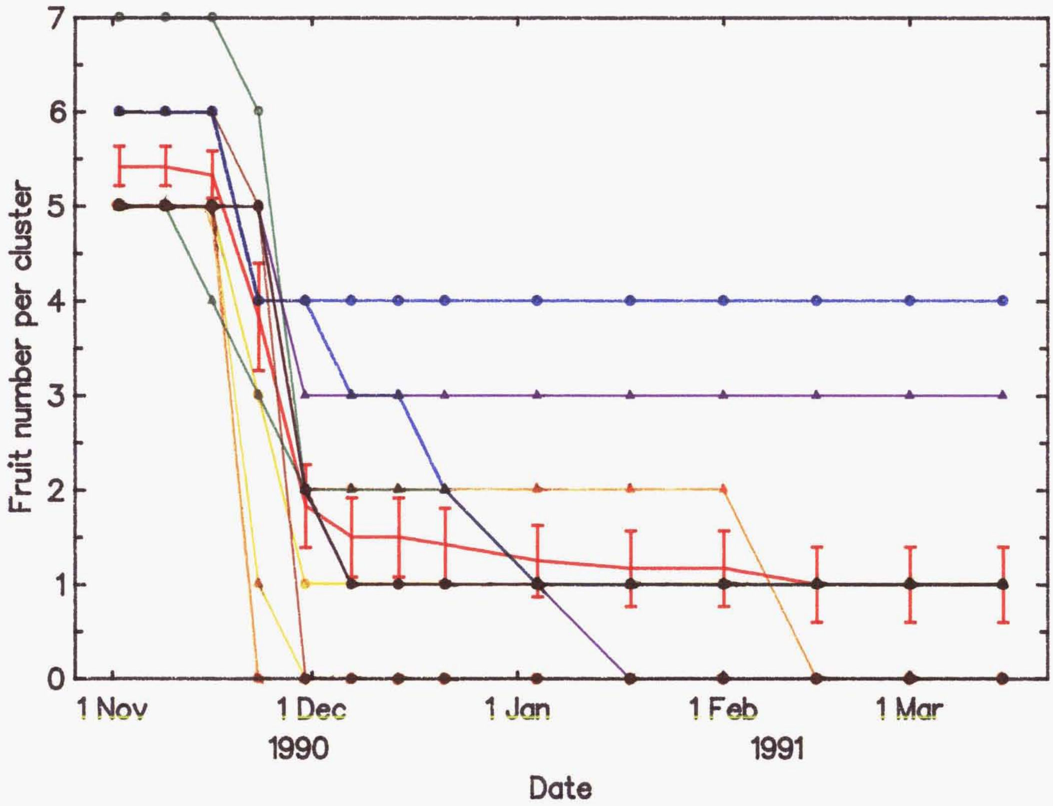

Figure 4.4 Axillary fruit set per cluster

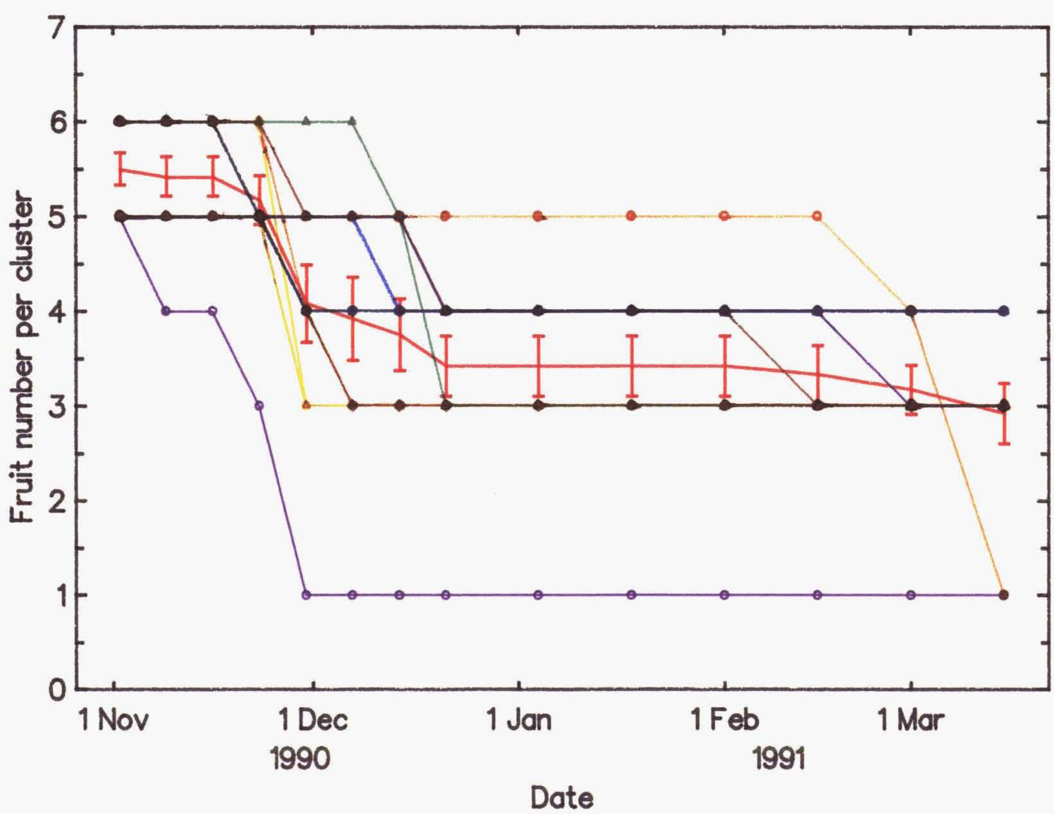

Figure 4.5 Terminal fruit set per cluster

Table 4.6 Fruit set of king fruit and other fruit

Fruit type	Terminal fruit			Lateral Fruit		
	Fruit Number		% Set[z]	Fruit Number		% Set
	Week 1	Harvest		Week 1	Harvest	
King fruit	12	8	67	12	3	25
Other fruit	54	30	56	53	9	17
Total	66	38	58	65	12	18

z %Set = fruit remaining at harvest in relation to fruit recorded at week 1.

It is usually considered that king fruits have a higher percentage set and fruit growth dominance but the evidence for this was not strong. When king fruits drop off, other fruits will relocate into the centre of the fruit clusters. Without tagging, they can look like king fruits. When fruits were tagged, the drop of king fruit could be recorded accurately.

4.5.2 The Influence of Tree Parameters on Initial Fruit Set

Several tree parameters were tested for influence on initial fruit set (Table 4.7).

Table 4.7 Relationship of selected parameters on percentage initial fruit set

Parameter	r^z value	No for regression
Percentage of lateral flower buds	-0.52**	27
Yield per tree in previous year	0.48**	26
Flower bud number per CSA	-0.47**	34
Ln(Flower bud number per CSA)	-0.49**	34
Flower bud number per ha	-0.32*	38

* significant at 5% level;
** significant at 1% level;
z r value for simple regression.

Percentage initial fruit set increased significantly (P =< 1%) with a decrease in flower bud

number and a decrease in percentage lateral flower buds. Yield per tree in the previous year has a positive effect on initial fruit set (P = <1%). This is due possibly to lower flower bud numbers (and hence a higher percentage initial fruit set) as a result of bienniality.

Table 4.8 Regressions of percentage initial fruit set to percentage lateral flower buds using asymptotic curve regression or log transformation

Formulae	No for regression	r value	Standard error
%SET = 47.3 - 0.33 %FBL	27	-0.52**	12.36
%SET = 77.2 - 12.4 Ln(%FBL)	27	-0.60**	11.57
%SET = 25.2 + 44.6 · $0.9461^{\%FBL}$	27	0.58**	11.52
%SET = 56.9 - 1.21 FB/x	34	-0.47**	15.96
%SET = 80.5 - 16.2 Ln(FB/x)	34	-0.49**	15.80
%SET = 20.2 + 49.2 · $0.9294^{FB/x}$	34	0.44**	16.02

** significant at 1% level;

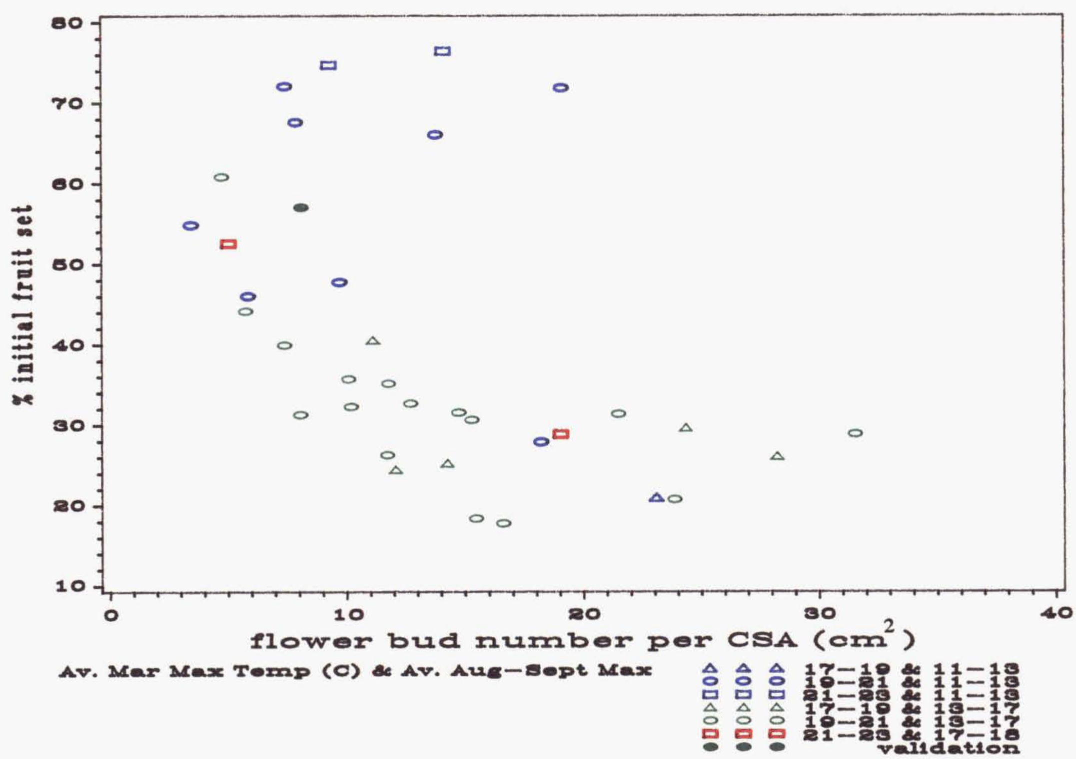

Figure 4.6 % Initial fruit set : flower buds per CSA
Av. Mar Max Temp (C) & Av. Aug-Sept Max temp (C)

Asymptotic curve regression was tested for percentage lateral flower buds and also flower bud number per CSA but there was no improvement in the regression coefficient. Log transformation provided a slight improvement in the r value for FB/x from -0.47 to -0.49 (Table 4.8).

Although Figure 4.6 clearly shows negative relationships, some unusual points still need to be explored to elicit the reasons for initial fruit set being above 60% (see 4.5.3 and 4.5.5).

4.5.3 The Influence of Climatic Parameters on Initial Fruit Set

Goldwin (1982) used daily meteorological recordings to explore a range of time-periods varying both in length and starting-date. He found that the average maximum daily temperature over 45 days starting 99 days after full bloom and the average minimum daily temperature over 46 days starting 79 days before full bloom have a major influence on yield.

It appears Goldwin commenced his analysis during the dormant period but the climate during the flower initiation period of the previous season could have an influence on set and yield in the current season. In this research, the period covered was from October in the previous season until harvesting during March with 18 months and 171 month-combinations being used. In order to avoid the effect of large numbers resulting from summing several months data, all the combinations used represent averages for the period. For example, the temperature from June to September is the average of the monthly temperatures for June, July, August and September. The correlation coefficients for each start and stop month combination are presented in triangular contour map format (Figure 4.7). It is suggested that this two dimensional approach using "r" values is more valuable for interpretation than Goldwin's three dimensional graph without "r" values. The third dimension is provided by the use of colours. The choice of colour has been based on the common usage in geographical maps. For example, lower non-significant r values are coloured green in line with lower altitudes in mapping, progressing through yellow (indicating a 5% significant level of positive correlation) to brown (indicating a 1% significant level of positive correlation) equivalent to high level altitudes in mapping. Blue colouring indicates negative r values with light blue being the 5% significant level of negative correlation and dark blue being the 1% significant level of negative correlation.

The correlation coefficients between maximum temperatures and initial fruit set (Figure 4.7b)

show 31 significant r values (P =< 5% in the yellow box) and 8 highly significant (P =< 1% with an asterisk * in the brown box) during the period between the previous October and the previous June. The key period is March and April represented by the highest r value (r=0.54**) and this is designated the function centre. The inclusion of March and April in, for example, the period of December to April, appears to be the reason for the significance established for this longer period. Hence, the real effects are focused on March and April. This does not mean that the significant r values from single months, for example December and January lose their meaning. For the purpose of selecting variables for multiple regression, the important one at the function centre should be chosen.

From Figure 4.7a and b, two groups of climatic factors emerge with important roles. The first group shows the effect of the previous growing season, during the October to April period. During this period, flower bud quality is enhanced resulting in higher initial fruit set in the following October. Higher temperatures and more sunshine hours during this period positively correlate with higher percentage set in the following season, whereas the number of rain days throughout the October - April period has a negative influence on initial fruit set, possibly reflecting lower temperatures throughout this period. The maximum temperatures in March and April provided the highest correlation coefficient (r = 0.54**).

It is possible to identify two sub-groups in this first group.

i previous December and January;

ii previous March and April.

In the first sub-group, higher temperatures benefit flower initiation and fruit growth. In the second sub-group, higher temperatures and more sunshine hours in the autumn, during and after harvest, enhances flower bud quality, which increases initial fruit set in the following growing season (Lakso, 1985; 1987). Climatic factors at this time are considered to have an important influence on the following crop.

There is a second high correlation grouping in the months of August and September immediately prior to flowering. In this case, higher maximum temperatures have a negative correlation on initial fruit set (blue box, Figure 4.7b), confirming the results of Beattie and Folley (1977), Jackson and Hamer (1980), Goldwin (1982), Jackson, Hamer and Wickenden (1983) and Lakso (1987). The French researcher Gautier (1976) also reported that higher rainfall during the equivalent northern hemisphere, January - April, had a positive influence

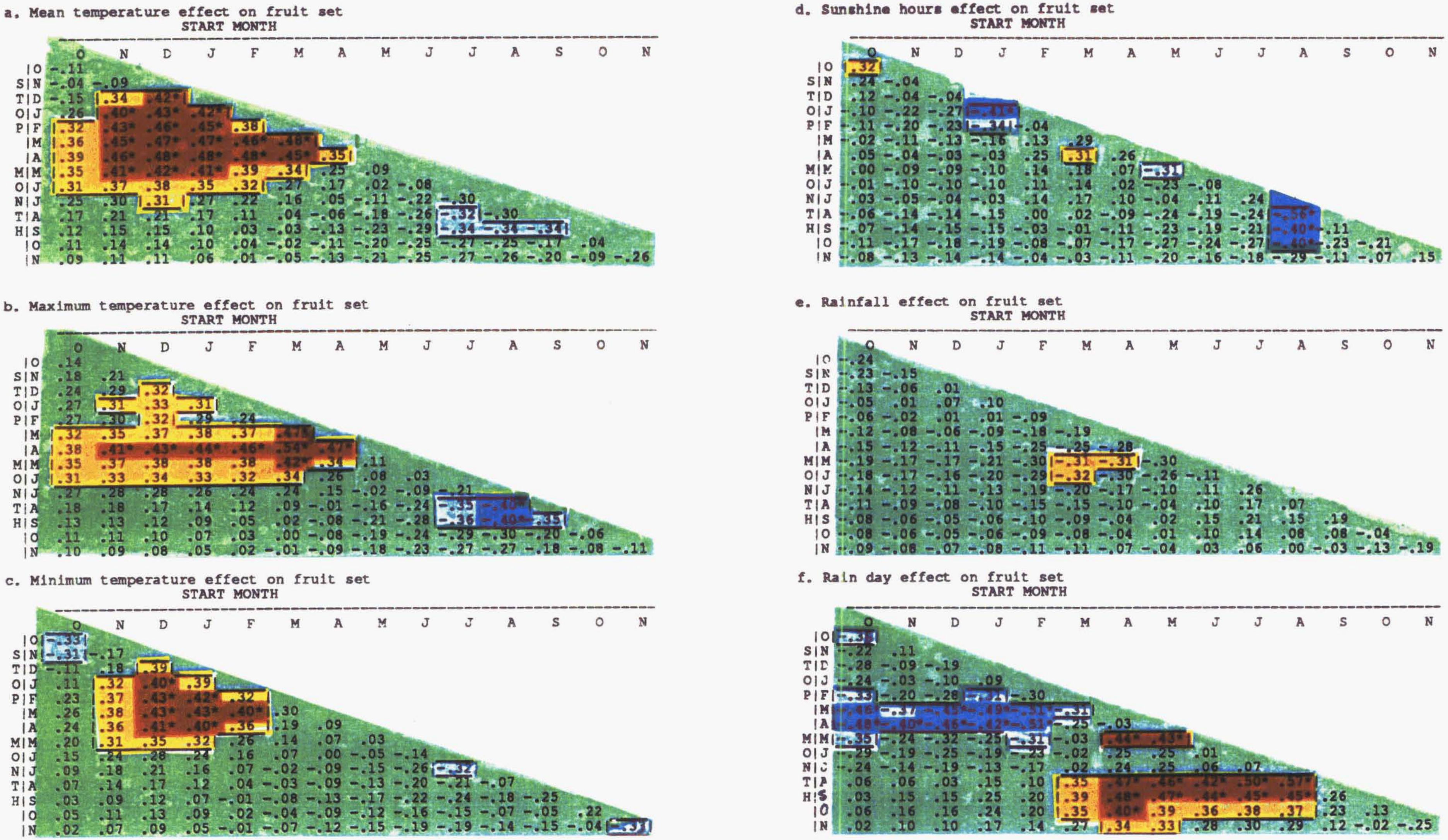

Figure 4.7 Contour map of r values for the relationships between fruit set and climatic parameters (N=41 $P_{.05}$=0.31 $P_{.01}$=0.40)

on yields. Higher rainfall normally reflects lower temperatures. However, the effect of monthly sunshine hours, monthly rainfall and monthly rain days on tree parameters, especially fruit set and fruit size, are usually not very clear. The correlations of these three climatic parameters with the tree parameters are reported in the contour maps but not used in the models, although in some instances the "r" value is relatively high.

For the initial fruit set and climatic parameter relationships, no curve tendency was found from plotting the data and therefore no transformations were used for climatic parameters in the model.

It was found that the relationships between initial fruit set and climatic parameters were not as good as those between the relevant endogenous tree parameters, such as flower bud number, suggesting that the role of tree parameters are more important than climate.

4.5.4 The Model of Initial Fruit Set

Based on the analyses given in section 4.5.2 and 4.5.3, flower bud number per CSA was chosen as the tree parameter. Multiple regression equations were calculated as follows:

$$\%SET = 1.10 - 0.76\ FB/X^{*} + 6.88\ MaxT_3^{**} - 6.13\ MaxT_{8\text{-}9}^{**} \qquad (4.1)$$
$$(R = 0.76^{**},\ N = 34,\ s = 12.11)$$

Key for equation 4.1 and hereafter:

** = significant at 1% level for each individual coefficient;

* = significant at 5% level for each individual coefficient;

R = the correlation coefficient of the multiple regression;

s = the standard deviation of the multiple regression.

Equation 4.2 applies a transformation of $\log_e$ because of a slight curve tendency but it did not provide significant improvement:

$$\%SET = 26.11 - 10.60\ Ln(FB/x)^{*} + 6.57\ MaxT_3^{**} - 6.33\ MaxT_{8\text{-}9}^{**} \qquad (4.2)$$
$$(R = 0.76^{**},\ N = 34,\ s = 12.01)$$

Although the percentage of lateral flower buds and the previous crop had better correlations with initial fruit set than fruit number per CSA, they were recorded only from the second year of monitoring. These two parameters are presented here for reference.

$$\%SET = 167.73 - 11.02\ Ln(FB/x^{*}) + 0.19\ Y/trLY^{**} - 8.16\ MaxT_{8\text{-}9}^{**} \qquad (4.3)$$
$$(R = 0.82^{**},\ N = 22,\ s = 9.38)$$

$$\%SET = 167.57 - 12.96\ ln(\%FBL)^{**} - 5.79\ MaxT_{8\text{-}9}^{**} \qquad (4.4)$$
$$(R = 0.82^{**},\ N = 27,\ s = 9.62)$$

Formula 4.1 is expressed in Figure 4.6. It is not feasible to plot a 4-dimensional (1 dependent and 3 independent variables) graph on 2-dimensional paper. In order to provide users a direct feeling for the formula, both climatic parameters were divided into 3 categories. Triangles represent 17 - 19°C maximum temperature in the previous March, circles represent 19 - 21°C and squares represent 21 - 22°C. The blue colour represents 11 - 13°C maximum temperature in the current August and September, the green colour represents 13 - 17°C and the red colour represents 17 - 18°C in the same months. Higher maximum temperatures in March and low maximum temperatures in August and September benefit initial fruit set, as shown by the blue squares, and blue circles. Flower bud number per trunk CSA seems to play a more important role when the number is higher than 18 buds/cm^2 CSA.

The following additional 1991/92 recordings were used to validate the work:

i flower bud number per trunk CSA = 8.12;

ii maximum temperature in the previous March = 19.8°C;

iii maximum temperature in the current August and September = 14.0°C.

The predicted percentage initial fruit set was 45.5%. The point shown in Figure 4.7 as a green dot is the real percentage set at 57.02%. This may be due to the unusually warm spring weather conditions causing flowering to occur at least 2 weeks ahead of normal.

Multiple curve regression testing did not provide any improvement.

$$\%SET = 106.43 + 5.32MaxT_{8\text{-}9}^{**} + 44.65 \cdot 0.9461^{\%FBL^{**}} \qquad (4.5)$$
$$(R = 0.76^{**},\ N = 27,\ s = 9.64)$$

4.5.5 Application of Principal Component Analysis

From the analysis of correlation and multiple regression, flower bud number per CSA,

maximum temperature last March and sunshine hours in August seem to play the most important roles but this is not the complete answer.

The "late winter effect" means that cold weather correlates with high initial fruit set in the spring. The cold weather should include lower temperatures and sunshine hours, possibly higher rainfall and some other climatic parameters. All of these add up to cold weather.

Of the tree parameters, yield per tree in the previous growing season, flower bud number and the percentage of lateral flower buds, all have a direct influence on initial fruit set. Unfortunately only one or two items can be chosen for the multiple regression and as a result some important information has to be omitted.

The interpretation of numbers of interrelated measurements is a common biological problem (Holland, 1969). A set of variables, which describe similar or relevant properties and highly correlated, may be orthogonally transformed into a new set of uncorrelated variables by means of principal component analysis. These new variables are linear combinations of the original variables and are derived in decreasing order of importance, so that the first few principal components account for as much as possible of the variation in the original data (Chatfield and Collins, 1980). Sometimes the new variable may be labelled a meaningful name according to its source. Pearce and Holland (1960), Holland (1966; 1968a; 1969), Moore (1965a; 1968b) all published papers on principal component analysis related to pomology. Explanation of this form of analysis is covered in the next section.

4.5.5.1 Principal Component Analysis of the Climatic Parameters in March of the Previous Season

Based on simple regression analysis, the monthly average temperature, monthly maximum average temperature and rain days in the previous March were used for the principle component analysis listed in an eigenanalysis table (Table 4.9).

Principal component analysis produced a set of new orthogonal variables, namely PC1, PC2 and PC3. For example, $PC1 = -0.627T_3 - 0.636MaxT_3 + 0.450RD_3$. From their composition (Table 4.9), the first principal component (PC1) is showing a contrast between temperature and rain days indicating that more rain days may lead to lower temperature. The table shows that PC1 accounted for 73.9% of the total variation of the 3 original

variables. PC1 correlates to the percentage of initial fruit set with r = -0.51**, which is slightly higher than only using maximum temperature (r = 0.47**). The PC1 of the previous March is named $PC1_3$ to distinguish it from other principal component variables.

Table 4.9 Eigenanalysis of the correlation matrices for the previous March

Variable	PC1	PC2	PC3
consists of			
T_3	-0.627	-0.348	0.697
$MaxT_3$	-0.636	-0.289	-0.716
RD_3	0.450	-0.892	-0.040
variation			
Eigenvalue	2.218	0.692	0.091
Proportion	0.739	0.231	0.030
Cumulative	0.739	0.970	1.000

4.5.5.2 Principal Component Analysis of the Climatic Parameters in August of the Current Season

The results of a similar analysis to that used in section 4.5.5.1 using data for August of the current season is given in Table 4.10. Again more rain days may result in lower temperatures and sunshine hours.

PC1 accounts for 68.4% of the total variation of the three original variables. PC1 correlates to the percentage of initial fruit set with r = -0.63**, which is slightly higher than only using sunshine hours (r = -0.56**). The PC1 for the current August is named $PC1_8$ to distinguish it from other principal component variables.

Table 4.10 Eigenanalysis of the correlation matrices for climatic parameters in the current August

Variable	PC1	PC2	PC3
consists of			
$MaxT_8$	-0.552	0.795	-0.251
S_8	-0.602	-0.172	0.780
RD_8	0.577	0.581	0.574
variation			
Eigenvalue	2.052	0.555	0.394
Proportion	0.684	0.185	0.131
Cumulative	0.684	0.869	1.000

4.5.5.3 Principal Component Analysis of the Tree Parameters Relevant to Initial Fruit Set

The results of the analysis using tree parameter data is given in Table 4.11.

Table 4.11 Eigenanalysis of the correlation matrices for tree parameters relevant to initial fruit set

Variable	PC1	PC2	PC3
consists of			
%FBL	0.627	0.329	0.707
Y/ha_LY	-0.463	0.886	-0.002
FB/x	0.627	0.326	-0.708
variation			
Eigenvalue	2.065	0.710	0.225
Proportion	0.688	0.236	0.075
Cumulative	0.688	0.925	1.000

The PC1 in Table 4.11 is showing a contrast of previous yield against flower bud number in the following growing season and the percentage of lateral flower buds. As a general rule higher yield is known to affect fruit production in the following year. PC1 accounts for 68.8% of the total variation of the 3 original variables. PC1 correlates to the percentage of initial fruit set with r = -0.54**, which is slightly higher than only using the percentage of lateral flower buds (r = -0.52**), flower bud number per CSA (r = -0.47**) and previous yield (r = 0.35*). To distinguish it from other principal component variables, this PC1 is named $PC1_{set}$.

4.5.5.4 Multiple Regression Using the Principal Components

$PC1_{set}$ correlates to $PC1_3$ (r = 0.57**). This is because the previous yield correlates with climatic parameters in the previous March. Thus, only $PC1_{set}$ and $PC1_8$ were used in the multiple regression analysis. The regression equation is

$$\%SET = 39.8 - 7.07\,PC1_{set}^{**} + 9.12\,PC1_8^{**} \qquad (4.6)$$

$$(R = 0.89^{**},\ N = 21,\ s = 7.35)$$

This equation reaches the highest r value of any of the regressions implying that principal component analysis has potential for use in pomological research.

Using principal component analysis is only in the development stage and cannot be confidently recommended yet for practical application in predictive models. It is not known with confidence how consistent the coefficients of the principal components will be and how many observations may be needed to produce the new variables (PC1).

4.6 THINNING

The key objective in the modelling work is to determine how many fruits are, or should be, retained on the trees, not how many are, or should be, removed. This is the reason that percentage of fruit retained after thinning is used in this paper.

In contrast to initial fruit setting, which is a natural process, thinning is mainly manipulated by orchardists. During the monitoring work, although the thinning programs in each orchard were recorded each year, the managers' purpose in thinning is to ensure normal economic

production. There were no designed experiments for determining optimum thinning in this work. Many orchardists hand thinned following chemical thinning in order to compensate for deficiencies in chemical thinning. This led to the effects of chemicals and natural drop from climatic effects being somewhat confused. Pending further detailed research it is considered warranted to include a thinning analysis in the model to reflect the thinning strategies of a range of orchardists, recognising that the biological relationships will need refining as additional information is recorded in the future.

4.6.1 The Influence of Tree Parameters on Thinning

Table 4.12 examines the relationship of fruit number retained after thinning to flower buds and fruit number before thinning, using data recorded over 3 years on the 15 monitored orchards.

Table 4.12 Relationship of the percentage of fruits retained after thinning with relevant tree parameters

Tree parameters	r value	N
Fruit number before thinning per ha	-0.78**	38
Ln(Fruit number before thinning per ha)	-0.79**	38
Fruit number before thinning per tree	-0.76**	38
Fruit number before thinning per CSA	-0.64**	30
Fruit number before thinning per flower bud	-0.51**	39
Percentage of initial fruit set	-0.51**	39
Flower bud number per tree	-0.41*	38
Flower bud number per ha	-0.37*	38

* significant at 5% level;
** significant at 1% level;

Fruit number before thinning, both per tree and per ha, produced better regression relationships than flower bud numbers with percentage set. The fruit number per ha before thinning with an r value of -0.78 was selected as the best parameter to incorporate in the model. The equivalent log transformation r value of -0.79 was not significantly different.

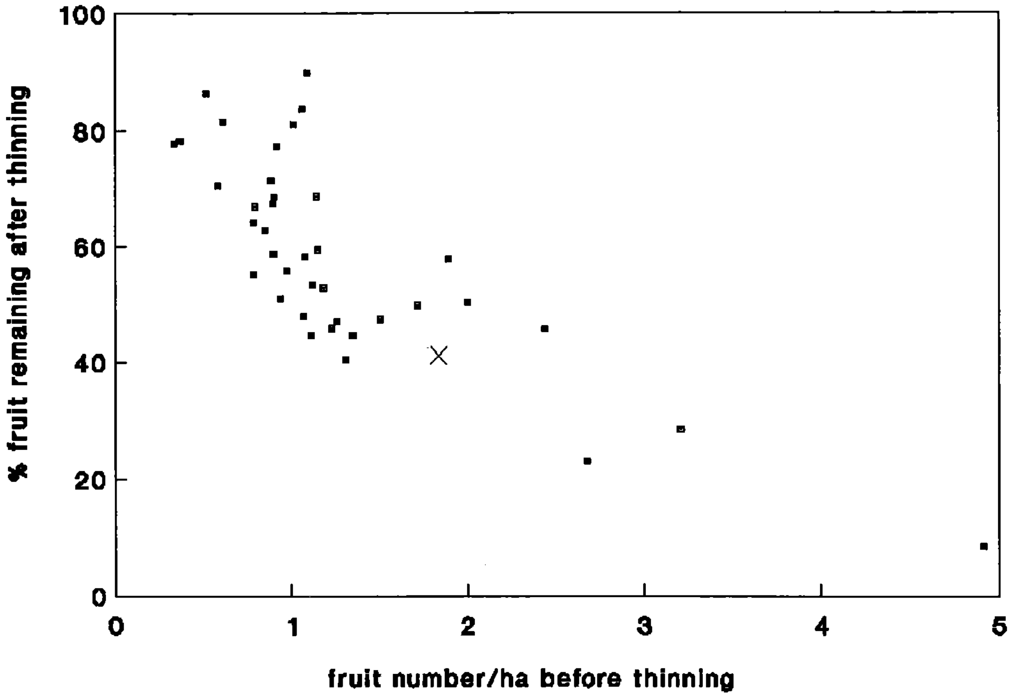

Figure 4.8 Relationship between % fruit remaining after thinning and fruit number/ha before thinning

Figure 4.8 shows the negative correlation of fruit number before thinning with percentage fruits retained on the trees after thinning. An asymptotic curve fitted to the data did not improve the coefficients.

$$\%FReAT = -7.7 + 98.5 \cdot 0.715^{FNBT/ha} \qquad (4.7)$$

$$(r^z = 0.78, N = 38, s = 10.83)$$

z r = the correlation coefficient of the simple regression for equation 4.7 and hereafter.

4.6.2 The Influence of Climatic Parameters on Thinning

Figure 4.9 is a contour map of r values for the relationships between thinning and climatic parameters. Because of the human element involved in thinning the contour map cannot represent the exact effect of climatic parameters. However, because of the known influence of temperature on fruit retention during this period it was considered worthwhile to test the climatic relationships.

Two of the six contour maps, namely sunshine hours and rain days, show significant effects. Higher sunshine hours or fewer rain days in the dormant period and early spring improve

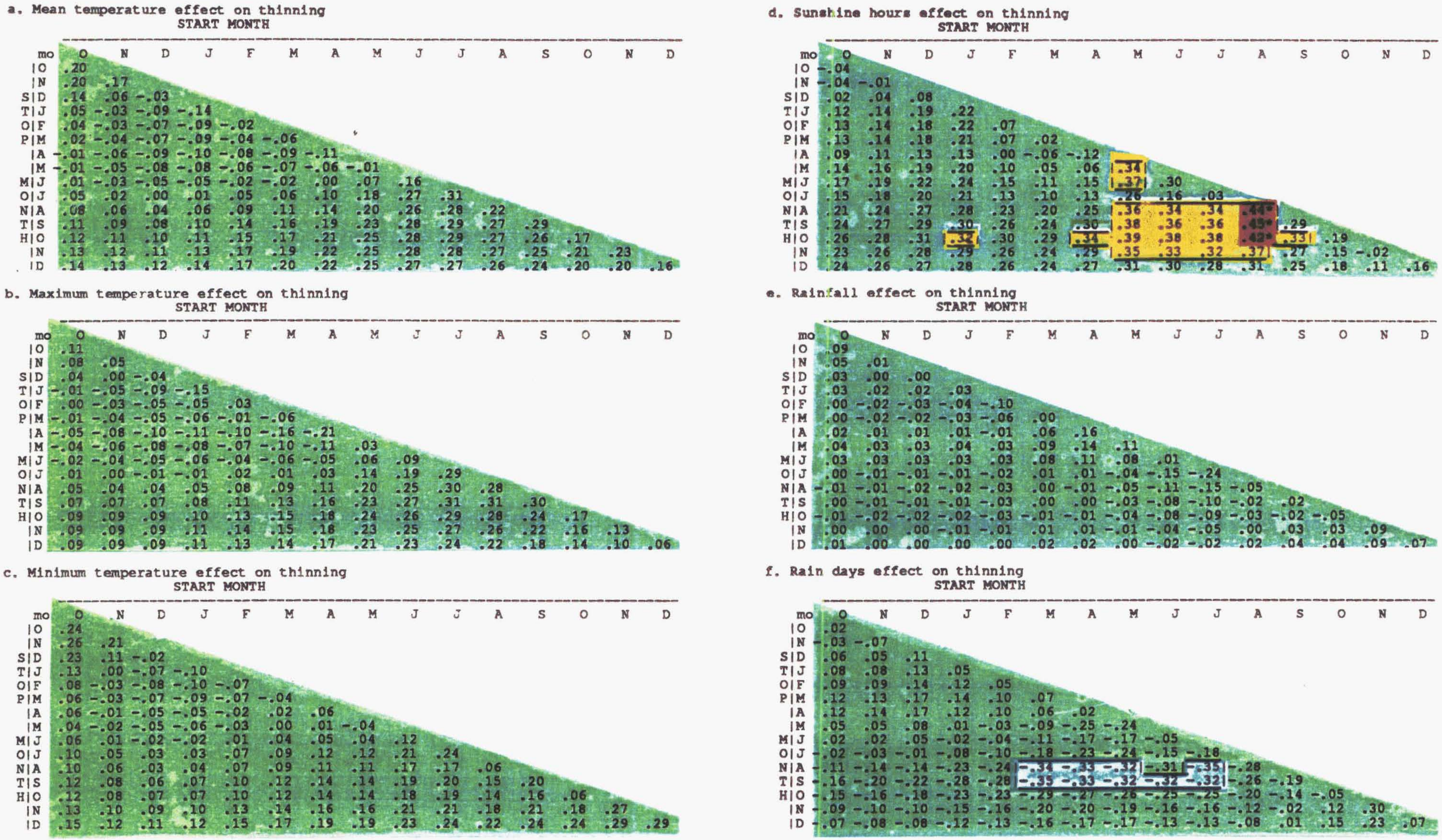

Figure 4.9 Contour map of r values for the relationships between thinning and climatic parameters (N=40 $P_{.05}$=0.32 $P_{.01}$=0.41)

fruit retention. There may be other interacting explanations. As higher, late-winter temperatures have already been shown to reduce fruit set, the amount of fruit needing to be thinned in this case will be less and the percentage retained after thinning will be higher.

Since the number of rain days is highly correlated with sunshine hours, the higher r value variable of sunshine hours was chosen for testing. The best three r values for sunshine hours related to Ln(FNBT/ha) are for August (r=-0.32*), August to September (r=-0.29) and August to October (r=-0.15). The significance of high sunshine hours in August is due to the "late winter effects" on initial fruit set. High sunshine hours in the longer period of August to October leaves more fruit on the trees before thinning and is the more reliable parameter to use for prediction. In general, a warmer spring leaves more fruit on the tree during the thinning process.

4.6.3 The Model of Thinning

The regression equation for the percentage of fruit remaining after thinning is:

$$\%FReAT = 60.98 - 26.20\ Ln(FNBT/ha)^{**} \qquad (4.8)$$

$$(r = -0.78^{**},\ N = 38,\ s = 11.13)$$

The multiple regression, with one more variable (formula 4.9), did not show much improvement over the single regression (formula 4.8). The effect of sunshine hours is not very clear and the multiple regression equation 4.9 was not chosen for inclusion in the final model.

$$\%FReAT = 13.63 - 24.75\ Ln(FNBT/ha)^{**} + 0.27\ S_{8\text{-}10}^{**} \qquad (4.9)$$

$$(R = 0.83^{**},\ N = 38,\ s = 10.05)$$

In a validation test, FNBT/ha was 1.763 million per ha; the average sunshine hours from August to October was 157; the predicted percentage of fruit remaining after thinning was 41.99%.

The actual percentage was 44.98%. The validation test is represented by the cross in Figure 4.8 and this appears to be in an acceptable position.

Application of principal component analysis did not show any advantage in these thinning calculations.

4.7 PRE HARVEST DROP

Some difficulty was experienced in analysing this pre harvest drop section because of the varying orchard management practices. In some instances, growers did not harvest the smallest fruit and the unharvested fruit could appear as pre harvest drop fruit. As a consequence of this potential error the pre harvest drop section is considered of little significance to the model. The fruit number after thinning is the most important parameter for predicting fruit size and fruit size distribution at harvest (see section 4.10).

Gala has a relatively long pedicel and is not normally prone to pre harvest drop. Figure 4.10 shows the frequency distribution of fruit retained after pre harvest drop from 42 observations. The highest concentration is about 90 - 92%.

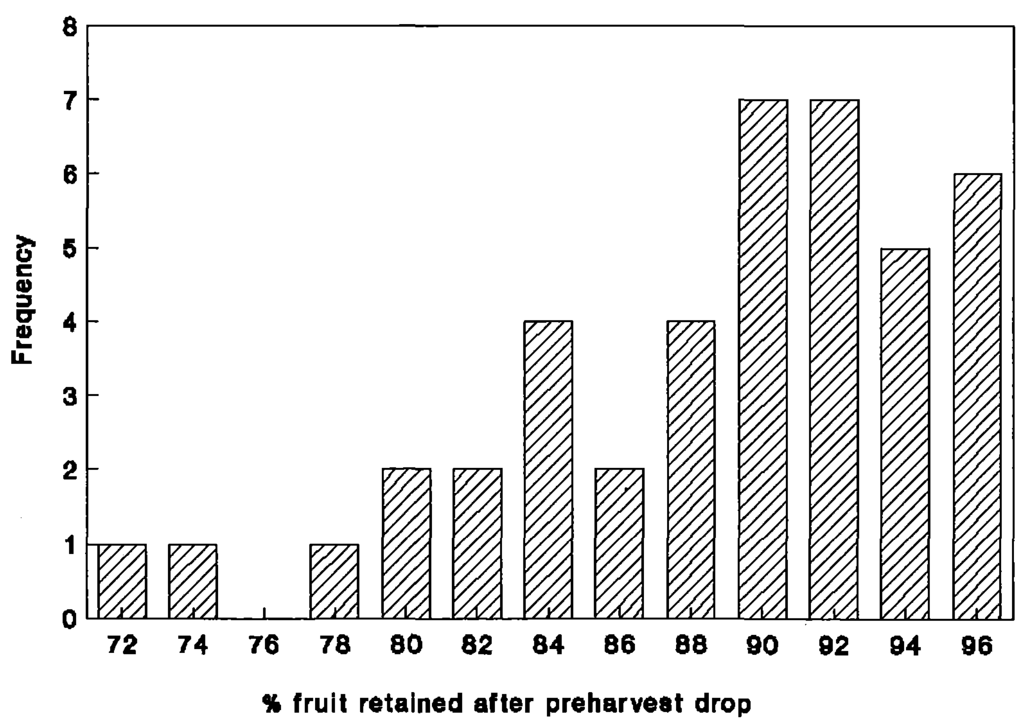

Figure 4.10 Histogram of percentage of fruit remaining after pre harvest drop (N=42)

Two of the 42 points look to be clearly outliers. The 72% recording is for orchard C5 in the third season when the hydraulic ladder was out of order and all fruits in a high position were

not harvested. The 74% recording is for orchard C1 in the fifth season. Chemical thinning was ineffective and fruit removed during late hand thinning in February had to be recorded in the pre harvest drop figures.

By omitting these two points, the average of fruits remaining after pre harvest drop is 89.62 ± 4.92. Using a 90% figure is the most reliable estimate in the meantime until more research can refine the accuracy but it is recognised that 10% drop may still be too high. The figure is important as removal of fruit from the tree during this period can still significantly affect final fruit size distribution.

No climatic parameters were identified with pre harvest drop.

4.8 FRUIT GROWTH

It is considered essential in any fruit modelling work to research and understand fruit growth in relation to climatic factors.

4.8.1 Ratio of Height to Diameter of Fruit

Figure 4.11 shows the change in the ratio of height to diameter of Gala apple fruit with the vertical bars showing the standard error of the means. Measurements were taken at 14 day intervals on 10 axillary and 10 terminal fruit. The ratios were more consistent in the vicinity of 0.8 to 0.9 from late December. In the young fruitlet stage, fruit height exceeded fruit diameter and the ratios were > 1. Terminal fruit on average had a higher ratio than the slightly flatter axillary fruit. These measurements not only define fruit shape but also provide the basis for calculating fruit volume.

4.8.2 Fruit Volume

The measurement of fruit volume is difficult when fruit is still on the trees but in some situations this is necessary. This section deals with the problem.

Apple fruit is assumed to be an ellipse shape. The formula for the volume of an ellipse is $4/3\pi abc$, where a and b are the radii (r) and c is half the height (h). The ratio of volume to πabc (or $\pi r^2 h$ if the radii are equal) is 4/3.

In general, the radii of an individual fruit should be the same but, in the case of uneven shape, an average of the radii taken in two directions has been taken. Figure 4.12 shows that the ratios of real fruit volume to $\pi r^2 h$ (orange and blue lines) is approximately 1.5 to 1.6 (say 1.55).

From section 4.8.1 the ratio of height to diameter from late December is taken as 0.85, that is h = 0.85r, and therefore volume = $1.55\pi r^2 h = 1.55\pi r^2(0.85r) = 1.32\pi r^3$. This is very close to the formula of a sphere $4/3\pi r^3$ and proves that a good estimation of volume could be obtained by assuming an apple fruit is sphere shaped.

Figure 4.12 also shows the ratios between real volume and πr^3 (red and green lines). After January the ratios are around 1.2 to 1.4 (say 1.3) again very close to the 4/3 figure for a sphere. Although Gala fruit is not exactly sphere-shaped the larger shoulder compensates for lesser height.

In November, the ratio of real volume to πr^3 is much higher at 1.64, due to a higher height to diameter ratio of about 1 to 1.03. In this early stage of fruit growth the use of the sphere formula is not very accurate.

A modification to the fruit volume formula is necessary. Because of the change in the ratios of height to diameter at various stages, the coefficient 4/3 in the formula $4/3\pi r^3$ needs adjusting using Figure 4.12 as the basis. Because of an obvious sampling error, the ratio for 1 February was discounted and the line smoothed. Because the standard error bars show no significant differences between axillary and terminal fruit they were averaged. It is now recommended that fruit volume be calculated by multiplying πr^3 by an adjustment factor given in Table 4.13.

Table 4.13 Adjustment factor for fruit volume calculation

Month	Nov	early Dec	late Dec	Jan to early Feb	Mid Feb	early March	Mid March
factor	1.64	1.42	1.35	1.30	1.29	1.28	1.27

Modifying πr^3 to $\pi r^2 h$, where h is the adjustment factor, does not improve the standard error very much but it does improve the consistency. The difficulty is in having to record height

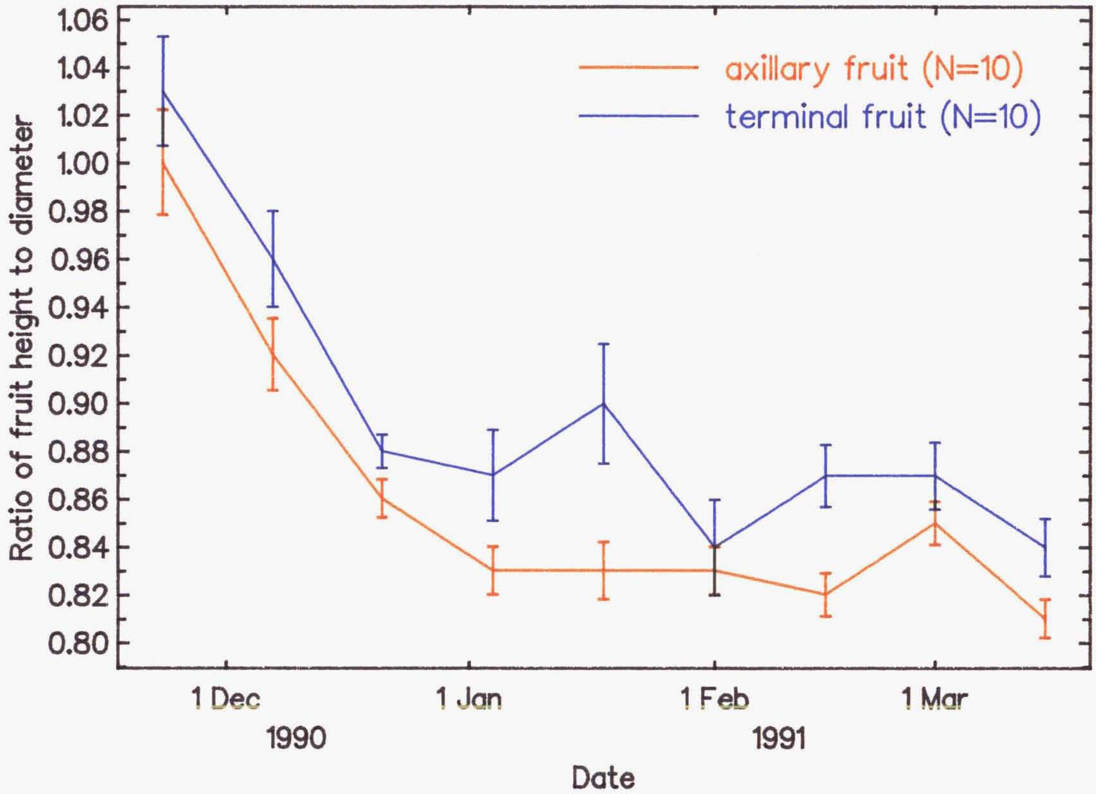

Figure 4.11 Ratio of fruit length to diameter over time

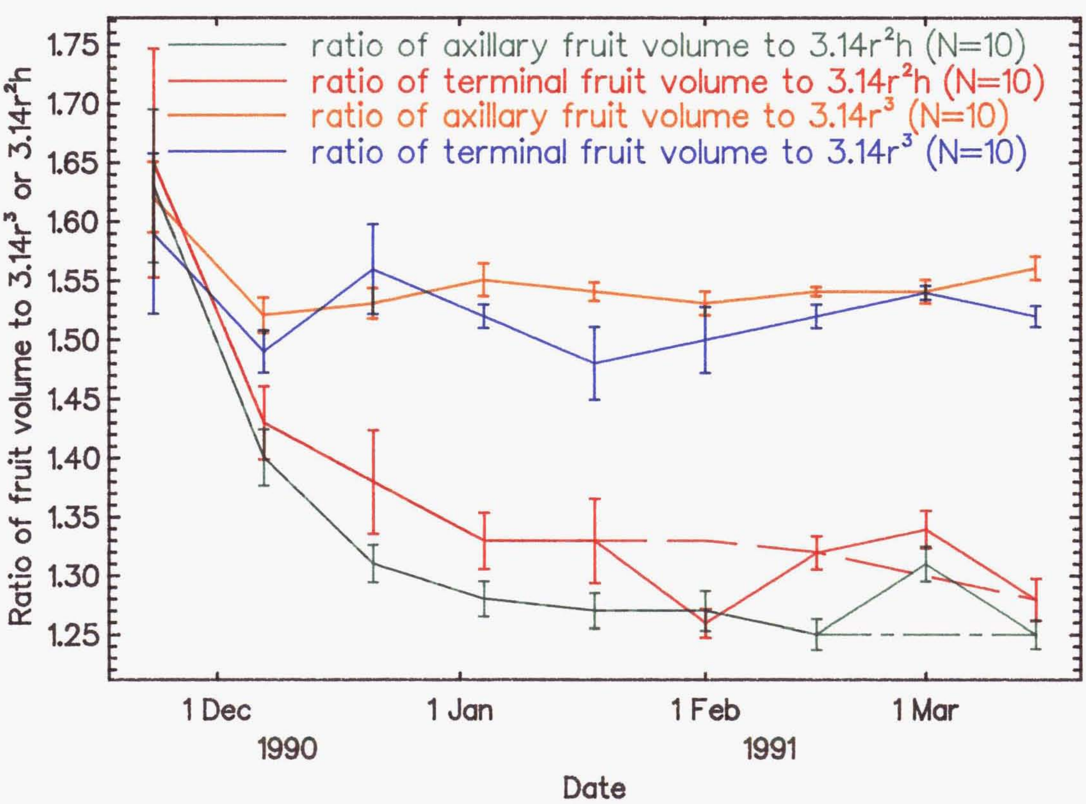

Figure 4.12 Ratio of fruit volume to $3.14r^3$ or $3.14r^2h$ over time

as well as diameter of fruit in field research work.

4.8.3 Fruit Growth Curves

Figures 4.13 - 4.14 show Royal Gala apple fruit growth during the 1989/90. On average, terminal fruit (red lines) are larger than axillary fruit (green lines). The growth curves are relatively parallel.

Average monthly temperatures have been included in the figures to determine any visual relationship. The low temperature in late December clearly slowed fruit growth as measured by diameter (Figure 4.13) and volume (Figure 4.14). The figures depict the same thing in terms of reduced incremental growth. This indicates the sensitivity of fruit growth to temperature at the late December stage. The growth curves for Golden Delicious are given in Figures 4.15 and 4.16. The analysis indicates a strong relationship between fruit growth and temperature about late December.

The incremental increase in fruit diameter over time shows a gradual reduction but the incremental increase in volume shows the reverse trend. That is, as the season progresses it becomes more important to estimate fruit volume as a potential indicator of fruit growth and eventual size at harvest. Although the two parameters are mathematically related as indicated in section 4.8.2 the reduction in diameter increase is often interpreted as a slowing in fruit growth. The importance of using fruit volume in predictive modelling work is further emphasised when interpreting temperature effects on fruit growth. The volumetric increment emphasises the importance of December - January temperature whereas use of diameter tends to emphasise the importance of higher average temperatures earlier in the season. Although the increase in diameter slowed from the end of December fruit volume showed a clear increase from about the same time because a small increase in diameter represents a larger increase in volume. From this point in the work, estimating potential fruit volume becomes more important than diameter.

The sensitivity of fruit growth to low temperatures did not show clearly in January 1991. The fruit was smaller on average because of a lack of thinning. However the fruit growth curves are quite clear. This low sensitivity in January can be seen in Figures 4.17 and 4.18. Fruit growth was not very sensitive to low temperatures in February and March either.

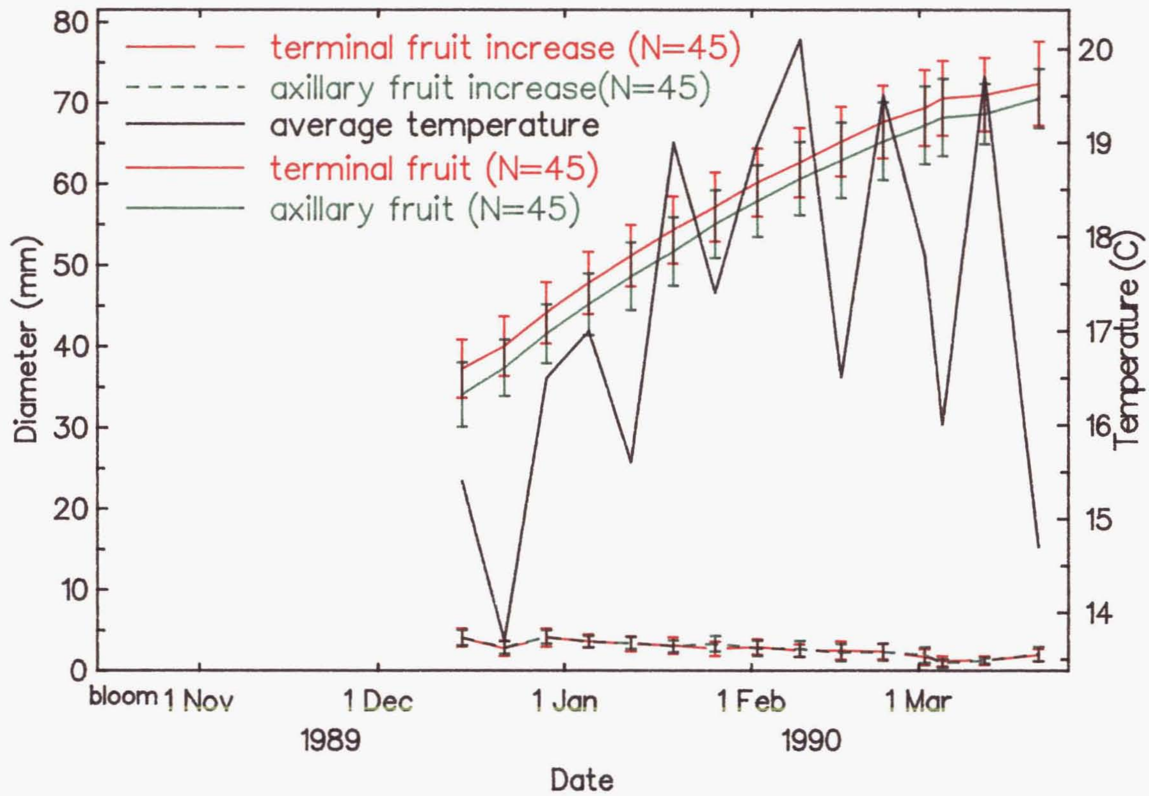

Figure 4.13 Royal Gala Fruit Diameter in 1989/90

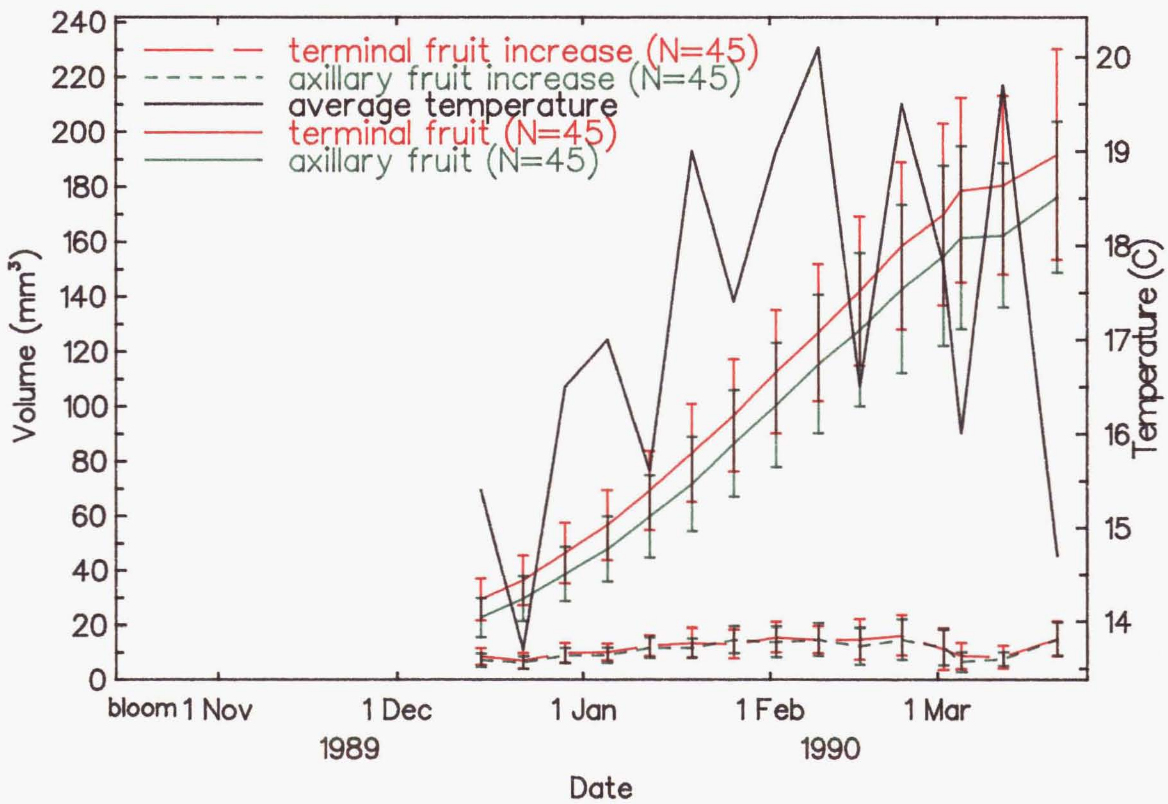

Figure 4.14 Royal Gala Fruit Volume in 1989/90

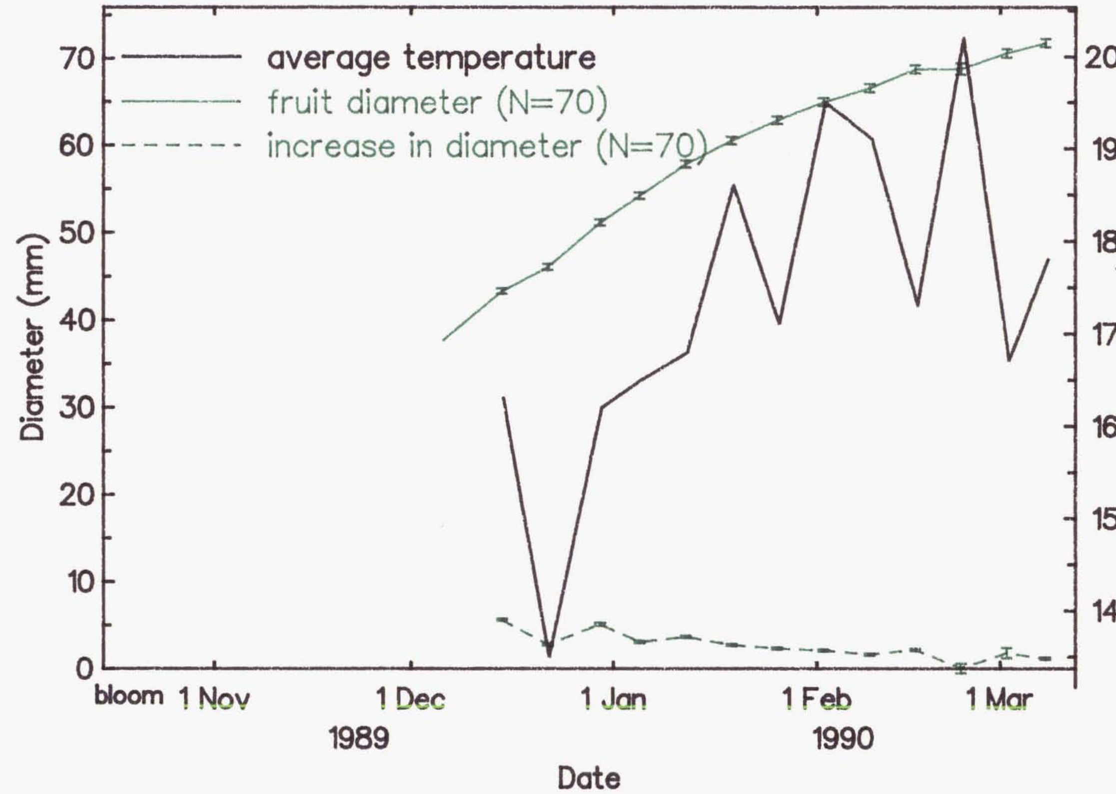

Figure 4.15 Golden Delicious Fruit Diameter in 1989/90

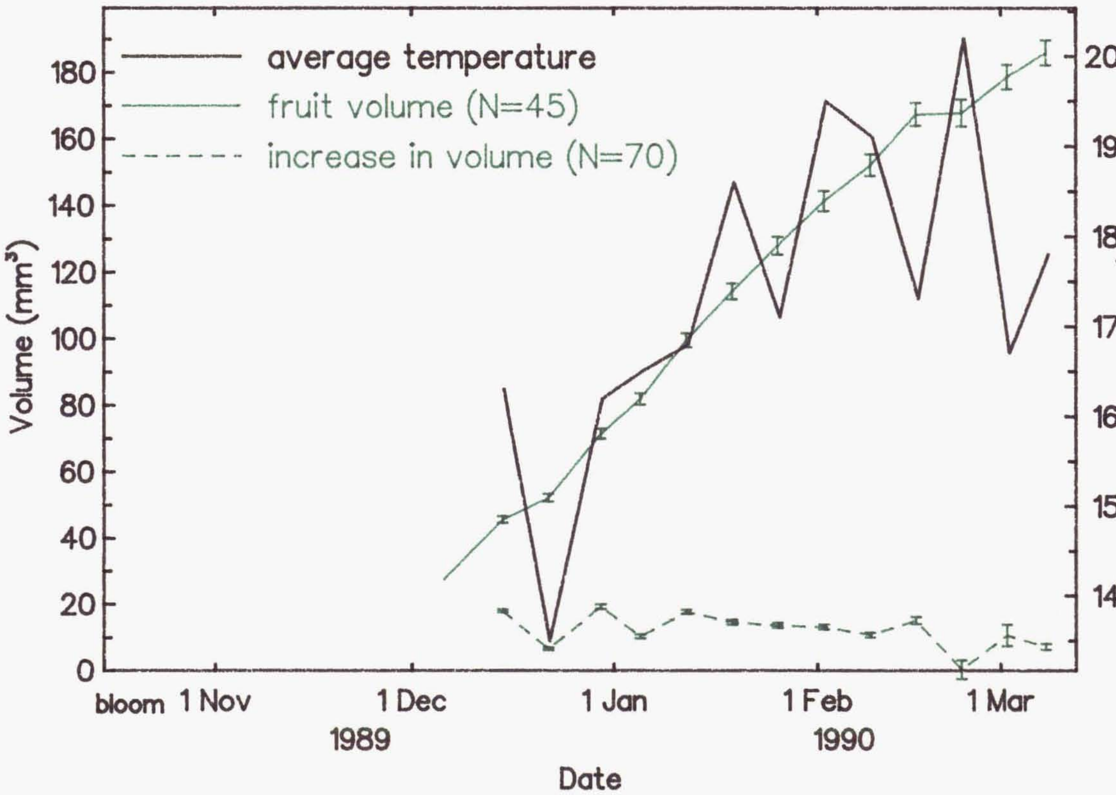

Figure 4.16 Golden Delicious Fruit Volume in 1989/90

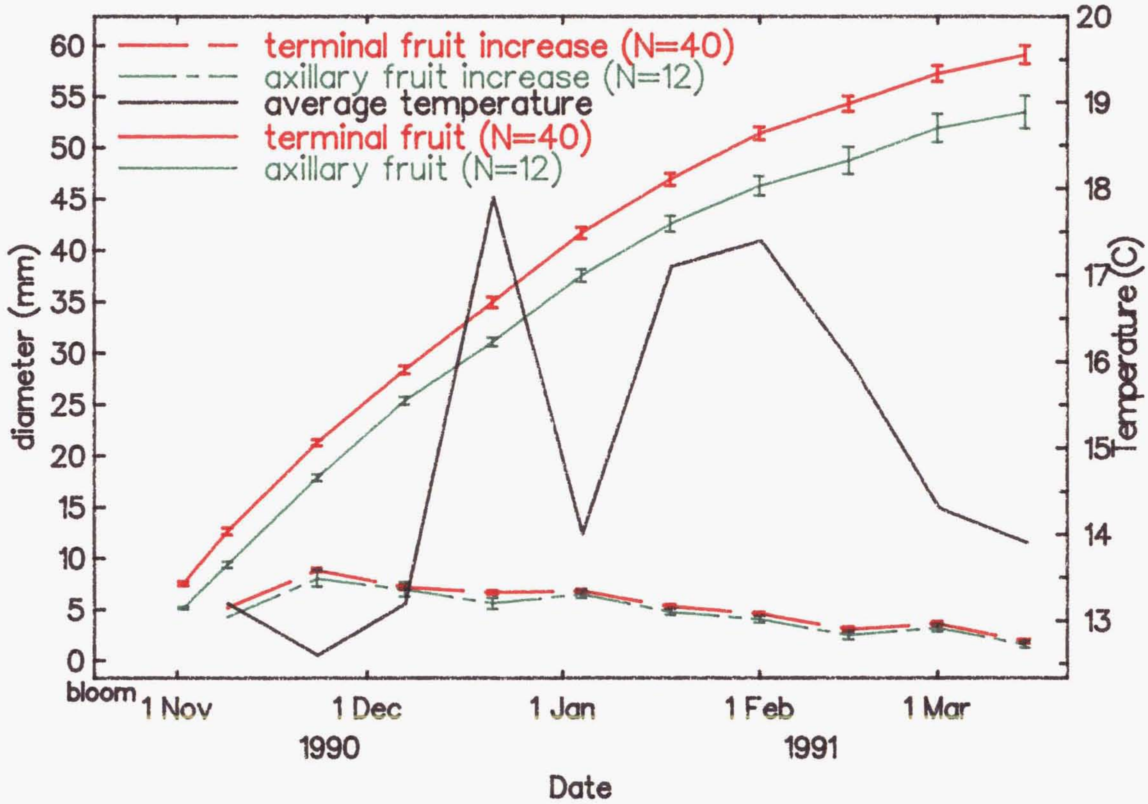

Figure 4.17 Gala Fruit Diameter in 1990/91

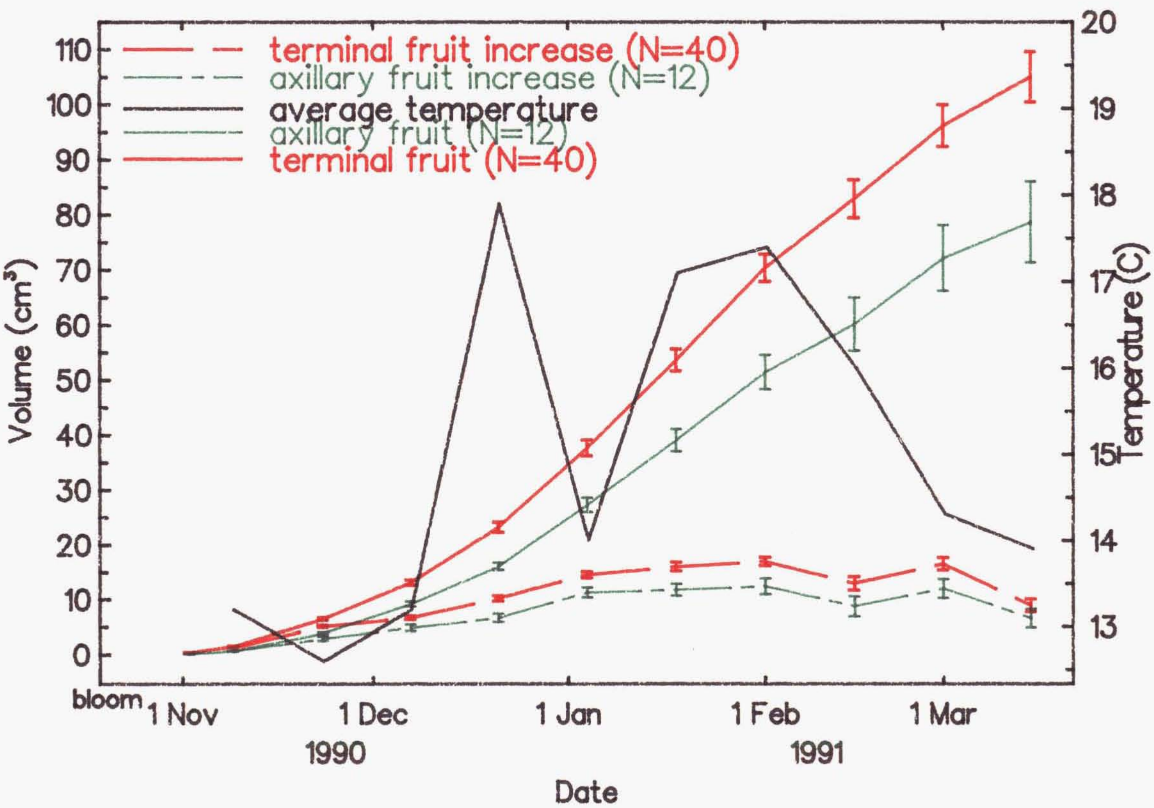

Figure 4.18 Gala Fruit Volume in 1990/91

In summary, from late December, fruit increases in volume much faster than before. The competition for nutrients is improved and all the seeds are nearly fully formed. About the same time, the cell division stage is complete and the cell enlargement stage begins. As the fruit starts to increase more rapidly in volume it is very sensitive to temperature. Hence the temperature in December and especially late December is very important for fruit growth and final fruit size.

4.8.4 Flesh Density

From December, flesh density remains quite consistent in the range 0.88 to 0.95 g/cm^3 (Figure 4.19) with just a slow decline from December to March. This confirms Westwood's (1962) and Blanpied's (1966) results. Figure 4.20 supports Figure 4.19 in that flesh density gradually decreases as fruit size (diameter) increases. Large fruit usually has more pore space and hence lower density.

In early November the densities were inconsistent. It was difficult to weigh small fruit accurately on a 0.1 g scale and in young fruit the sepals represent a large proportion of the volume measurement and hence increase the error risk. The differences between axillary and terminal fruit are not clear and in any case are not major.

4.9 FRUIT SIZE VARIATION

Measuring average fruit size for modelling work requires a sample number to be identified in terms of the desired accuracy level.

4.9.1 Fruit Sampling

It is common to require a standard error $< 5\%$. Figure 4.21 shows the coefficient of variation (CV) of the standard error of the means is steadily decreasing as the sample number increases. When the sample number is > 25, most CV's are $< 5\%$. The CV is safely $< 5\%$ when the sample number is > 50 (42 to be exact in this case). For monitoring work, at least 25 samples must be taken to get a valid estimate of fruit size but a sample of 50 fruit or more is recommended.

Figures 4.22 and 4.23 show results based on a tree and orchard respectively. When the

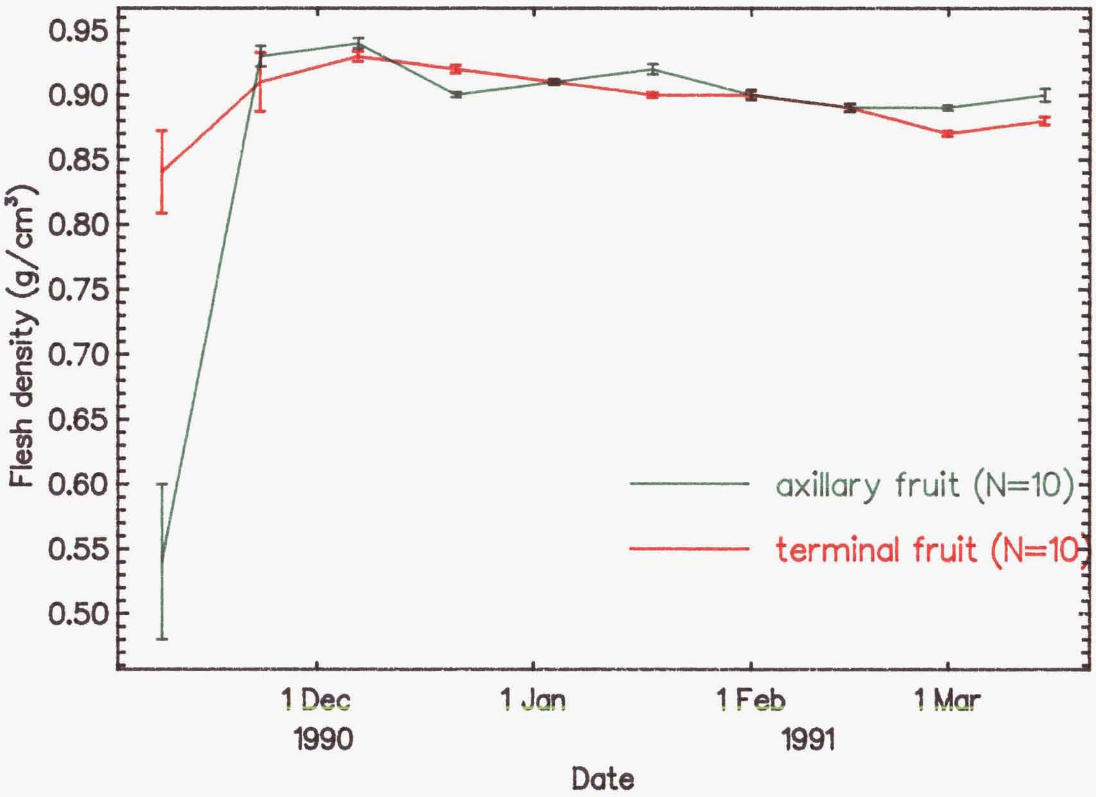

Figure 4.19 Flesh density changes over time

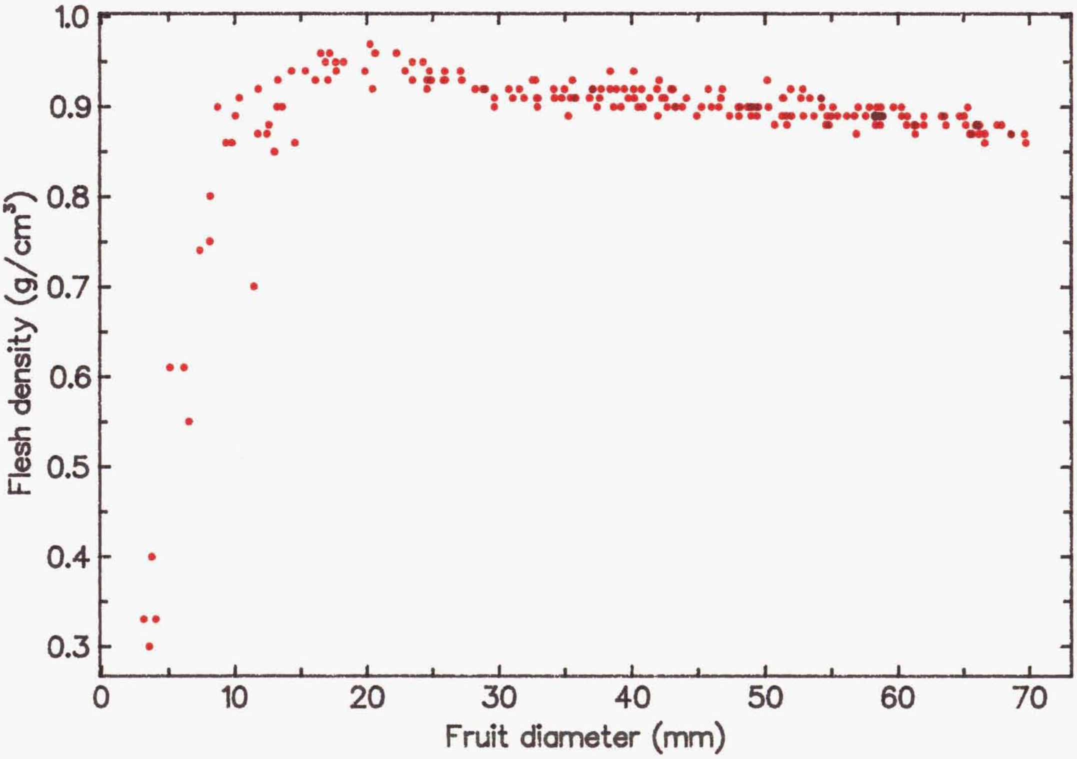

Figure 4.20 Relationship between flesh density and fruit diameter

sample number increases to 400 or more fruit, it may restrict the CV to < 1%. 50 fruit for each individual tree sample and more than 400 fruit for each orchard (or block) are recommended.

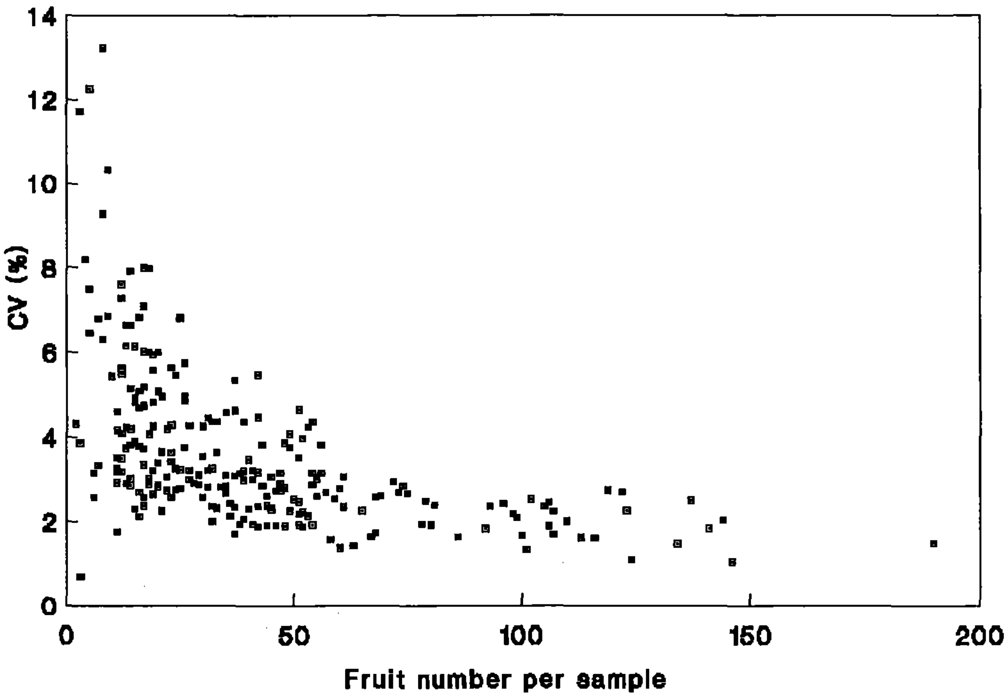

Figure 4.21 Relationship of the sample number to the coefficient of variation (CV) of the standard error of the means for the monitored branches

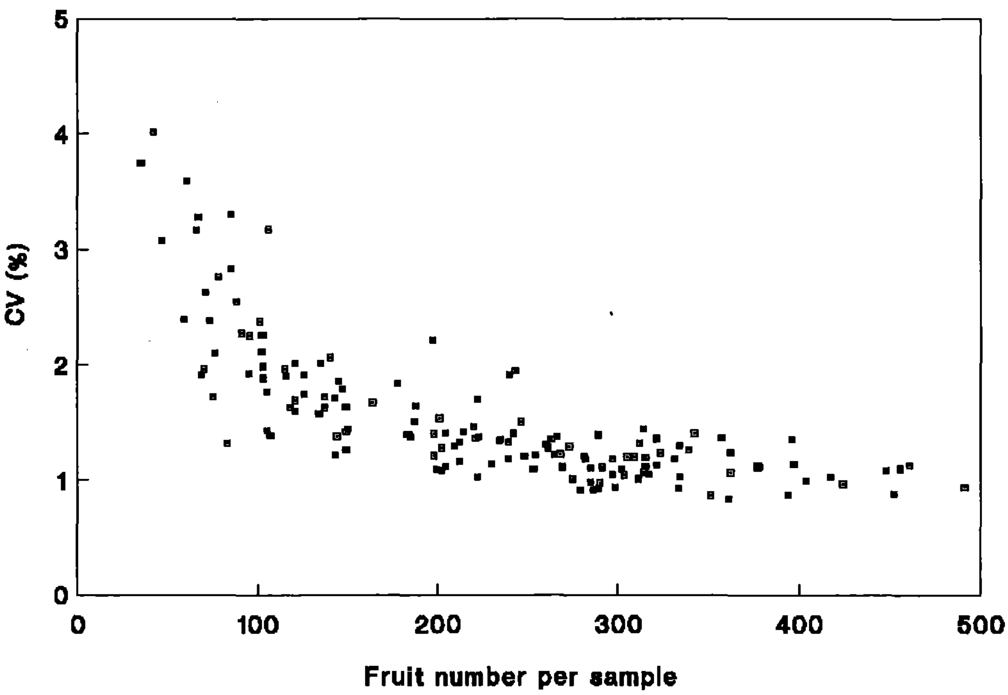

Figure 4.22 Relationship of the sample number to the coefficient of variation (CV) of the standard error of the means for random individual tree sampling

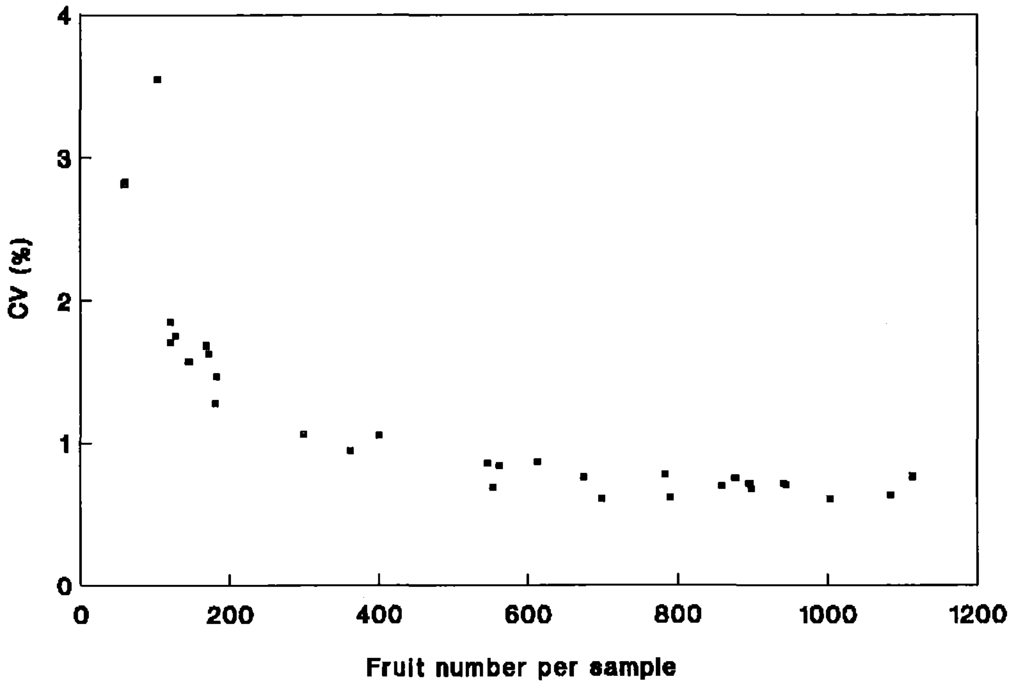

Figure 4.23 Relationship of the sample number to the coefficient of variation (CV) of the standard error of the means for pooled sampling on an orchard basis

4.9.2 The Effectiveness of Fruit Sampling to Estimate Average Fruit Size

This section deals with the methodology and accuracy of estimating average individual fruit size or weight on a tree or ha basis.

Three ways to sample fruit were compared. For each monitored orchard, exact yields and fruit numbers of the 5 monitored trees were recorded and average individual fruit weight for each tree calculated as "tree average". Then the individual average fruit weight for all the 5 trees was calculated from the 5 tree averages. This is designated the "real average" and could be considered to represent the orchard average (labelled "real fruit weight" in Table 4.14).

The first method used was to randomly sample 20 fruit from each level for each harvest from the 5 monitored trees, to the extent that such numbers were available. The samples were pooled and used to calculate average individual fruit weight for the 5 monitored trees (labelled "tree sampling" in Table 4.14). The second method was to harvest all the fruit on the 3 monitored branches for each of the 5 monitored trees and calculate average fruit weight from the total sample (labelled "branch sampling" in Table 4.14). The third method pooled the fruit from the first two sampling methods (labelled "pooled sampling" in Table 4.14).

The averages from the 3 methods are compared with the real averages in Table 4.14 and the differences between real and the three sampled averages are listed.

Table 4.14 Comparison of real average fruit weight with estimated average fruit weight

Mean of real fruit weight	Pooled sampling			Tree sampling			Branch sampling		
	av wt[z]	dif[y]	N[x]	av wt	dif	N	av wt	dif	N
100	101	1	2071	106	6	877	98	2	1194
128	126	2	664	126	2	120	126	2	544
129	133	4	1969	134	5	896	132	3	1073
130	127	3	1542	131	1	699	124	6	843
134	131	3	854	125	9	127	133	1	727
137	135	2	500	129	8	59	136	1	441
137	139	2	549	152	15	60	137	0	489
138	129	9	893	142	4	362	120	18	531
139	139	0	1709	138	1	1113	139	0	596
142	140	2	1695	141	1	859	138	4	836
143	145	2	1736	146	3	942	145	2	794
143	142	1	1392	144	1	790	139	4	602
145	144	1	1311	145	0	783	142	3	528
147	148	1	1072	147	0	400	148	1	672
148	146	2	1037	146	2	675	145	3	362
150	146	4	679	150	0	299	143	7	380
151	151	0	1525	150	1	1003	153	2	522
153	149	4	1826	153	0	1084	144	9	742
155	154	1	1386	155	0	945	152	3	441
159	159	0	1454	158	1	898	160	1	556
163	160	3	1060	164	1	553	156	7	507
174	163	11	507	169	5	120	162	12	387
185	188	3	879	184	1	547	194	9	332
mean		2.7	1231		2.9	618		4.4	613

[z] average fruit weight;

[y] the difference between the means of real fruit weight and average fruit weight from samples;

[x] fruit number in each sample.

On average, both tree sampling and branch sampling had similar sample numbers, but tree sampling produced the more accurate estimate. Differences over 6 g for tree sampling were all due to a small sample size (< 127 fruit per orchard).

Sometimes branch sampling included very small fruit resulting from long term retention of the monitored branches and inadequate pruning, producing a wider difference from the "real" tree mean.

As would be expected, the larger sample size of the pooled fruit method produced means slightly close to the real means.

It can be concluded that random tree sampling is the best way to estimate fruit weight.

4.9.3 Fruit Weight Distribution

Variation in fruit weight not only influences the accuracy for estimating average fruit weight, but also the accurate estimate of fruit number in each grade for selling. It is necessary to study fruit weight distribution. According to the analysis in section 4.9.2, random tree samples on an orchard basis were used in this research.

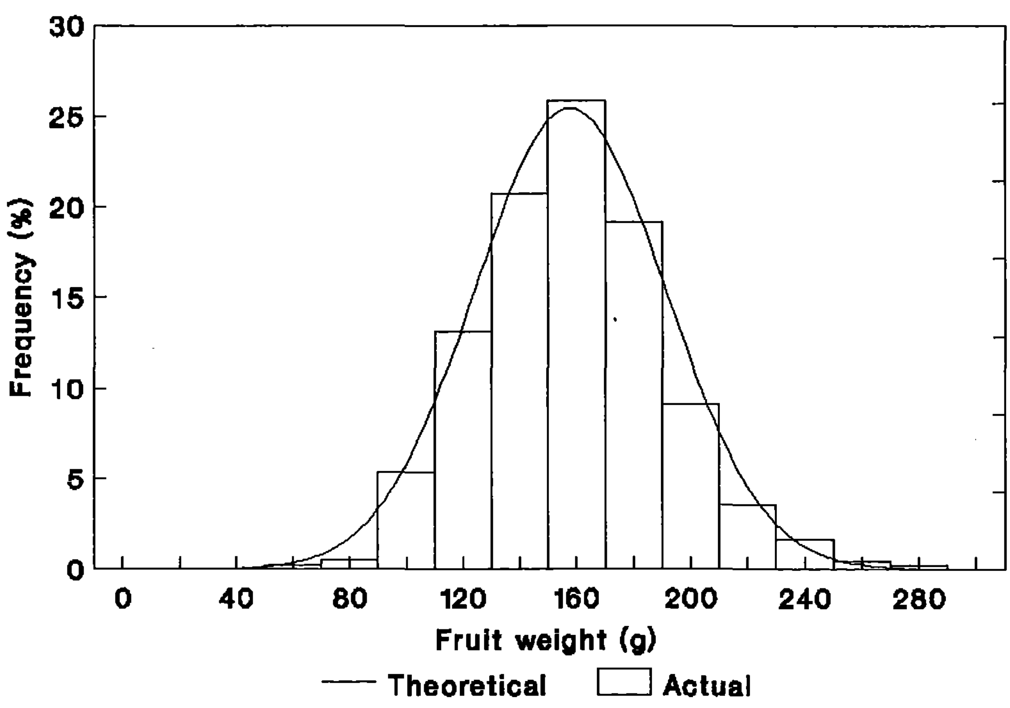

Figure 4.24 Comparison between normal distribution and actual distribution of fruit weight

Using the χ^2 test, all the groups of fruit are shown to have normal distribution at 5% confidence level. Orchard 4 in Hawkes Bay in the third growing season is taken as an example in Figure 4.24. The total random tree sampled fruit (from 5 trees) was 898. The bars in the figure show the actual percentage of each 20 g range of fruit weight, where the mean is 157.73, the standard deviation is 31.91. The figure shows how this theoretical line fits closely the real distribution. This concept is discussed further in Chapter 6.

4.9.4 Standard Deviation of Fruit Weight

Figure 4.25 shows the range of the standard deviation of fruit weight taken from the tree samples in each orchard each year. The range of the standard deviations is from 20 to 36g.

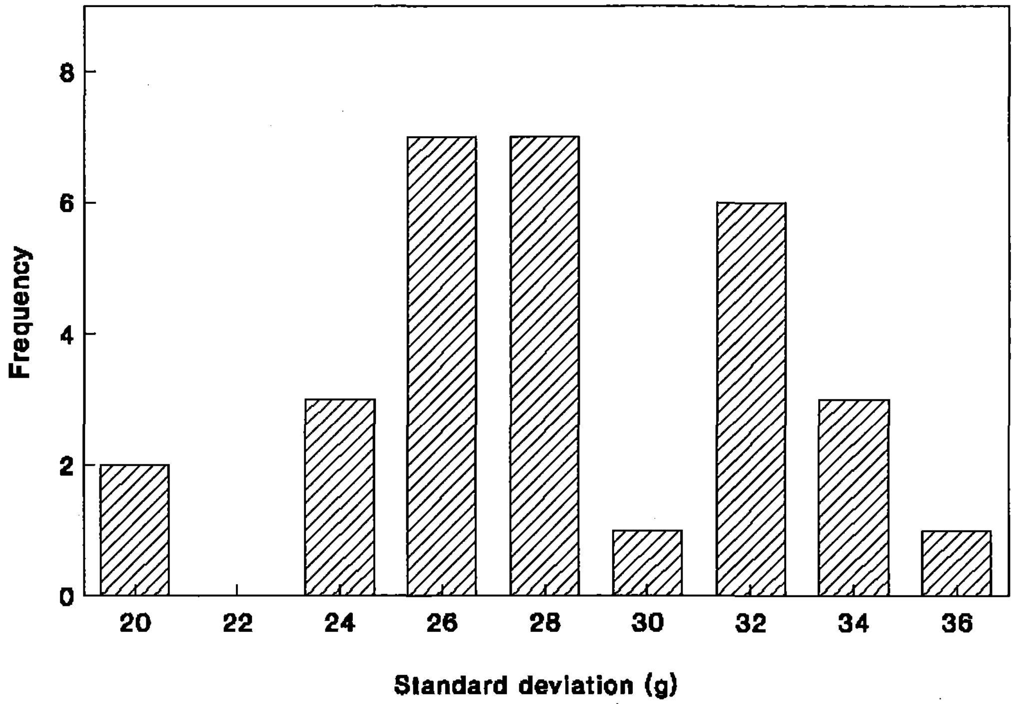

Figure 4.25 Histogram of standard deviation of fruit weight from tree samples on all branches

4.9.5 Relative Standard Deviations

The standard deviation of fruit weights correlates quite strongly with fruit weights (Figure 4.26). If average fruit weight is high, the standard deviation is usually high.

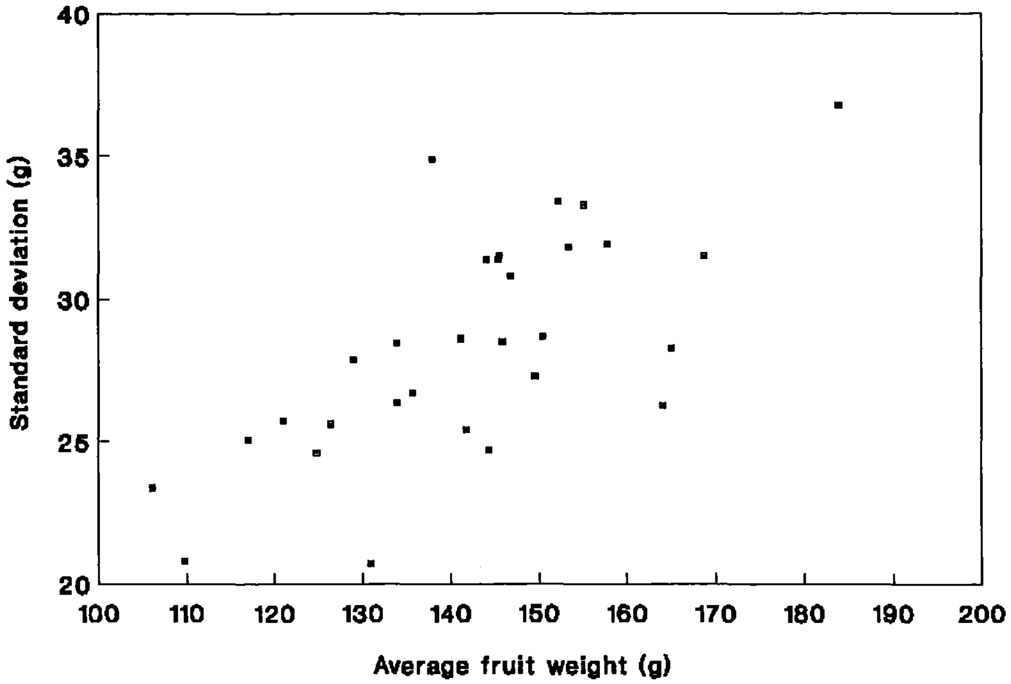

Figure 4.26 Relationship between standard deviation and average fruit weight (N=30, r=0.70**)

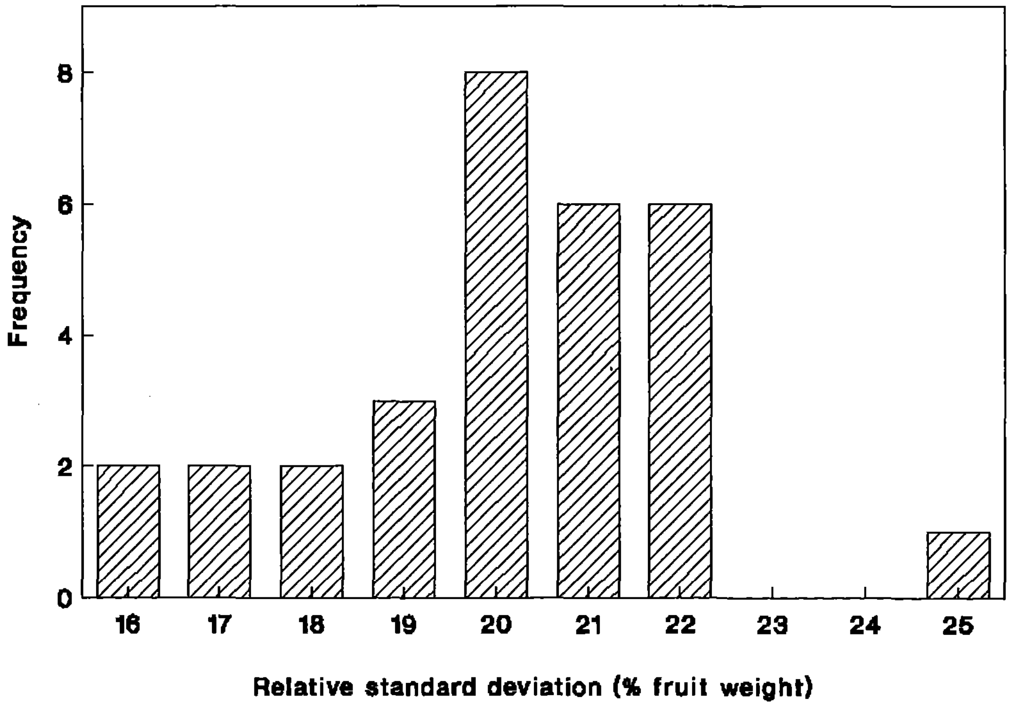

Figure 4.27 Histogram of relative standard deviation

The relative standard deviation of fruit weight (Figure 4.27) is the ratio of standard deviation to average fruit weight. This range is narrower, mainly around 20 - 22% of fruit weight, compared with that of the standard deviation (Figure 4.25).

4.9.6 Factors Influencing the Relative Standard Deviations

The relative standard deviation of fruit weight is more advantageous in research than the standard deviation of fruit weight. The relative standard deviation excludes the effect of fruit weight. When the absolute standard deviation of fruit weight was used to establish relationships with other relevant factors such as fruit weight or percentage of fruit in the various grades, most of the factors were directly related to fruit weight. It cannot reveal the real effects of fruit size variation.

Table 4.15 Relationship of selected variables to relative standard deviation of fruit weight

Variables	r value	N
LN(FNBT/ha)	0.45*	24
FNAT/ha	0.39*	29
FN/ha	0.42*	29
% of yield in level I	-0.37*	29

* significant at 5% level;

For tree parameters, the relative standard deviation of fruit weight is mainly affected by fruit number per ha at different stages during the season (Table 4.15). More fruit will result in a more uneven range of fruit sizes. A negative correlation was found between the relative standard deviation of fruit weight and the percentage of yield from level I. The more fruit produced in the lower level of a tree, the more uneven will the fruit size become. No significant correlations were found with the absolute standard deviation of fruit size.

For climatic parameters, the contour maps in Figure 4.28 show very few significant correlations with the relative standard deviation of fruit weight. Only the minimum temperature in March (during harvest) produced a significant correlation with any possible logical explanation. A higher minimum temperature at night may lead to higher respiration rates and stimulate fruit ripening. Under such conditions, smaller fruit ripens earlier resulting in more uneven fruit size.

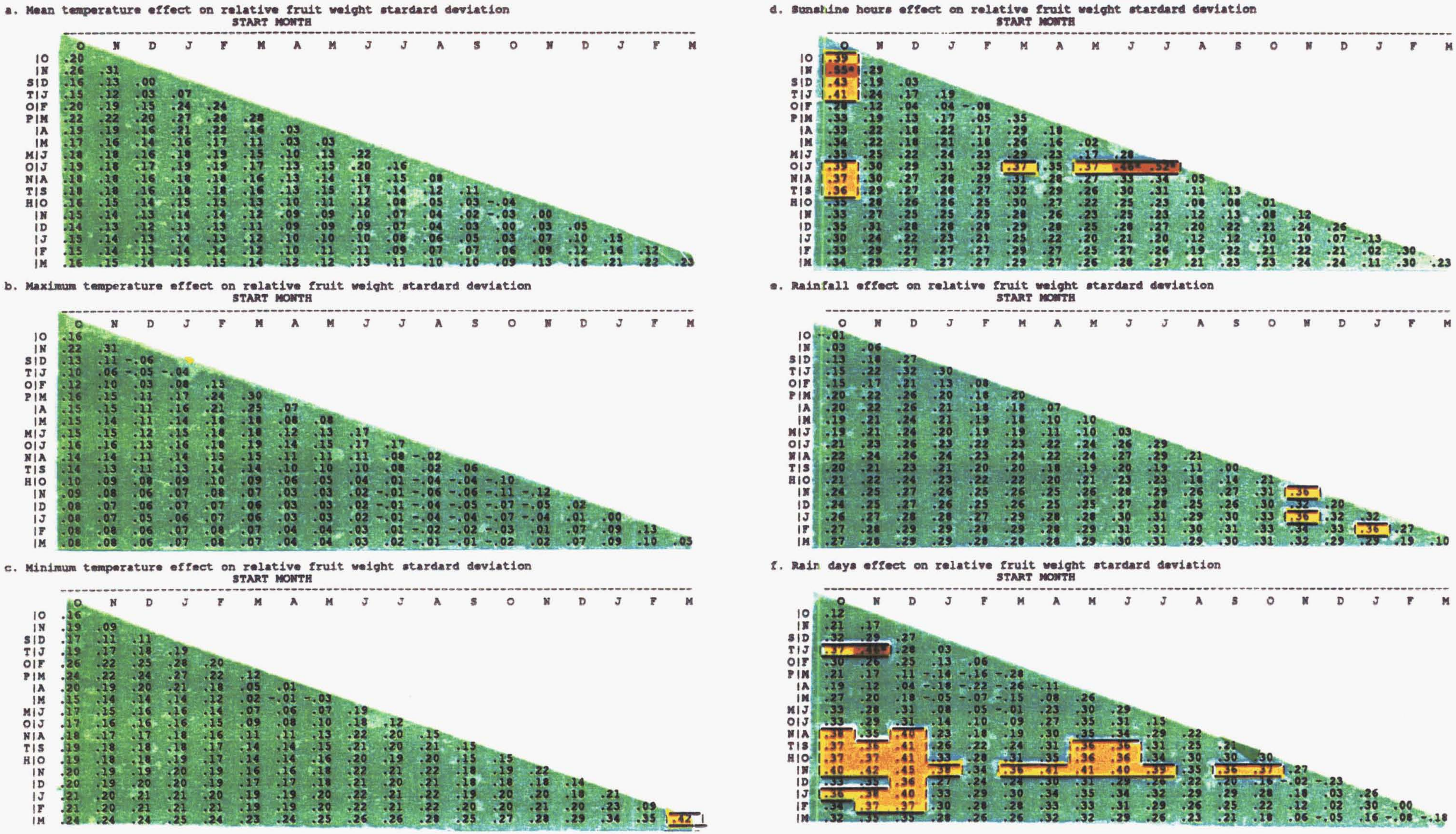

Figure 4.28 Contour map of r values for the relationships between relative fruit weight stardard deviation and climatic parameters (N=29 $P_{.05}$=0.36 $P_{.01}$=0.46)

4.10 AVERAGE INDIVIDUAL FRUIT WEIGHT AND FRUIT DISTRIBUTION IN THE VARIOUS GRADES

It is important to be able to predict for both yield and fruit quality because of the effect of average individual fruit weight on the prices paid for the various size grades and the ultimate influence on gross margins.

It is difficult to predict the likely number of fruit in each individual grade. An explanation of the New Zealand Apple and Pear Marketing Board grading system is given in Table 4.2. Table 4.16 shows that combining the percentages of grades AA and A produces a stronger positive correlation with average individual fruit weight than using grades AA and A individually. In effect the prices in grades AA and A are usually quite similar. Combining the percentages of grades C and D also shows a stronger negative correlation with average individual fruit weight than using grades C and D individually. The prices for grades C and D are usually similar as well. It is suggested the combination of the grades indicated will provide more reliable prediction for growers' financial estimates. The percentage of rejected fruit in this study showed quite high correlation with average individual fruit weight (r = -0.66**). The percentage of fruit in grade B did not show a strong correlation with average individual fruit weight (r = 0.11). The percentage of grade B is calculated as the remainder after subtracting the other three grades from the total. Prediction of fruit size distribution on an individual orchard basis requires further detailed study over a number of years.

Table 4.16 Correlation of the percentage in each grade with average individual fruit weight (r values)

AA	A	AA+A	B	C	D	C+D	R
0.55**	0.68**	0.90**	0.11	-0.57**	-0.62**	-0.84**	-0.66**

** significant at 1% level;

Reject fruit includes small fruit and fruit rejected for other faults. Although spray programs were recorded for each orchard no clear relationship between the percentage of rejected fruit and the control of diseases and pests was found. This means that the influence of fruit rejected for disease and pest incidence on the distribution of fruit in the various grades is not

very clear. Because of this, small fruit may have a biased influence on the reject grade regression analysis for disease and pest incidence. The introduction of a predictive sub model for disease and pest is considered a separate issue not within the boundary of this study.

4.10.1 The Influence of Tree Parameters on Average Individual Fruit Weight and Fruit Distribution in the Various Grades

This section deals with the various tree factors which could affect fruit weight and the percentages in each size grade according to the stage of development of the tree.

i The previous growing season

In Table 4.17 the yield per ha in the previous growing season has a weak positive correlation with the average fruit weight. Higher yields in the previous growing season may restrict the yield in the following growing season with the possibility of increased fruit size. The crop in the previous growing season has more influence on grade distribution, especially that of grade AA + A and the reject grade. All the results show that yields in the previous growing season have more influence than fruit number.

Table 4.17 Relationship of average individual fruit weight and fruit distribution with other relevant tree parameters in the previous growing season

Variable	N	FrWt	%AA+A	%C+D	%R
Y/trLY	30	0.33	0.47**	-0.31	-0.46**
Y/haLY	29	0.37*	0.43*	-0.31	-0.56**
FN/trLY	30	0.28	0.37*	-0.22	-0.33
FN/haLY	30	0.30	0.32	-0.21	-0.41*

* significant at 5% level;
** significant at 1% level;

ii During the blossom period

Table 4.18 shows that a higher number of flowers, and/or a higher percentage of lateral flower buds, may reduce average fruit weight at harvest time. This will decrease the percentage of fruit in grades AA + A and increase the percentage in grades C + D and

rejects. The percentage of lateral flower buds has a stronger influence on the percentage of reject fruit emphasising the need to thin the smaller fruit emanating from lateral flower buds for Gala and Royal Gala apple trees.

Table 4.18 Relationship of average individual fruit weight and fruit distribution with other relevant tree parameters in the flowering period

Variable	N	FrWt	%AA+A	%C+D	%R
FB/x	34	-0.39*	-0.38*	0.44**	0.26
%FBL	31	-0.40*	-0.40*	0.35*	0.45*

* significant at 5% level;
** significant at 1% level;

iii Fruit number at various stages

There is a high correlation of fruit weight with fruit number at the various stages of fruit development (Table 4.19). Even the fruit number before thinning has an important negative influence on the final fruit weight but too many missing values for this variable precluded its use in the final equation.

Table 4.19 Relationship of average individual fruit weight and fruit distribution with other relevant tree parameters during the growing season

Variable	N	FrWt	%AA+A	%C+D	%R
FNBT/x	30	-0.70**	-0.57**	0.63**	0.47**
FNAT/x	40	-0.54**	-0.46**	0.47**	0.25
FNAT/ha	43	-0.52**	-0.47**	0.54**	0.26
FNAT/tr	43	-0.48**	-0.39**	0.44**	0.26
FN/tr	45	-0.50**	-0.36*	0.39**	0.26
FN/x	42	-0.50**	-0.44**	0.42**	0.28
FN/ha	45	-0.43**	-0.40**	0.44*	0.20

* significant at 5% level;
** significant at 1% level;

Fruit number after thinning has a key influence on fruit enlargement and the final size and grade distribution. Although pre harvest drop may reduce fruit number in the later stage of fruit growth the effect on final fruit size is not as important as the fruit number immediately after thinning. For the predictive model, the after thinning number will be used although it is recognised that eventually a corrective factor may have to be built into the model for varieties more prone to drop during this final growth phase.

The analysis shown in Table 4.19 indicates that fruit number after thinning did not correlate with the percentage of reject fruit. The percentage of reject fruit relates more strongly to factors before thinning. The analysis indicates that thinning may reduce the percentage of fruit in grades C and D but may not help to reduce reject fruit. This is an unusual result because logically the number of small fruit should be reduced by thinning.

iv Level of fruit on the tree

Table 4.20 shows a tendency for larger average fruit weight if more of the fruit is carried on the top level of the tree. The percentage of yield only in level I or II did not show any significant correlation.

Table 4.20 Relationship of average individual fruit weight and fruit distribution on different levels with other relevant tree parameters

Variable	N	FrWt	%AA+A	%C+D	%R
%YL3	31	0.40*	0.44*	-0.41*	-0.46**

* significant at 5% level;
** significant at 1% level;

4.10.2 The Influence of Climatic Parameters on Average Individual Fruit Weight

Figure 4.29 shows that the mean monthly temperatures between the previous November and February, and the mean monthly temperatures and the mean maximum monthly temperatures between the current September and January have important effects on average individual fruit weight. The peaks appear in the current January for the mean monthly temperature (r=0.63**) and in the current December and January for the mean maximum monthly temperature (r=0.56**). This is the hand thinning period. To provide predictive information based on temperatures in February is too late to influence thinning strategies and

therefore the earlier the seasonal weather patterns are identified the better. A calender month may not be the best method to analyse temperature effects on fruit weight and hence an attempt was made to shorten the period to 5 day intervals (Figure 4.30a).

Figure 4.30a analyses the effects on individual average fruit weight of maximum temperatures for the current December and January in 5 day intervals. The important period is boxed at D4f and J1f; that is 16 December to 5 January. In order to examine the effect more clearly, this box was enlarged to a daily basis (Figure 4.30b). Although all the r values in Figure 4.30b are quite high, the peak appears between 16 December and 4 January, which is almost identical to the 5 day analysis. This implies that the most useful and reliable information about fruit size may be produced by 5 January. This is not too late to conduct further thinning if the predicted fruit size is too small.

Another important period identified in Figure 4.30a is boxed between D3f and J5f. This is 11 December to 25 January. This is enlarged in Figure 4.30c on a daily basis. The peak appears between 17 December and 23 January again very similar to the 5 day analysis. This is a wider period than the previous example but may still be valid for final prediction of fruit size.

Figure 4.31a shows the effect of mean temperatures for the current December and January in 5 day intervals on individual average fruit weight. The important period is boxed between D3f and J6f; that is 10 December to 31 January. The daily mean temperature effect during this period is shown in Figure 4.31b. There are 3 red boxed peaks showing in the figure: 15 December to 15 January, 14 December to 26 January and 17 December to 4 February. This implies the important temperature period is 15 Dec - 4 Feb similar to that shown in the 5 day interval analysis (10 December - 31 January).

Figure 4.30a indicates the importance of maximum temperatures in the mid December - early January period but Figure 4.31a indicates that the important period using mean temperatures extends over mid December - early February.

The use of maximum or mean temperatures needs further investigation to determine if either or both should be used in the predictions. The situation is further complicated when light effects are considered.

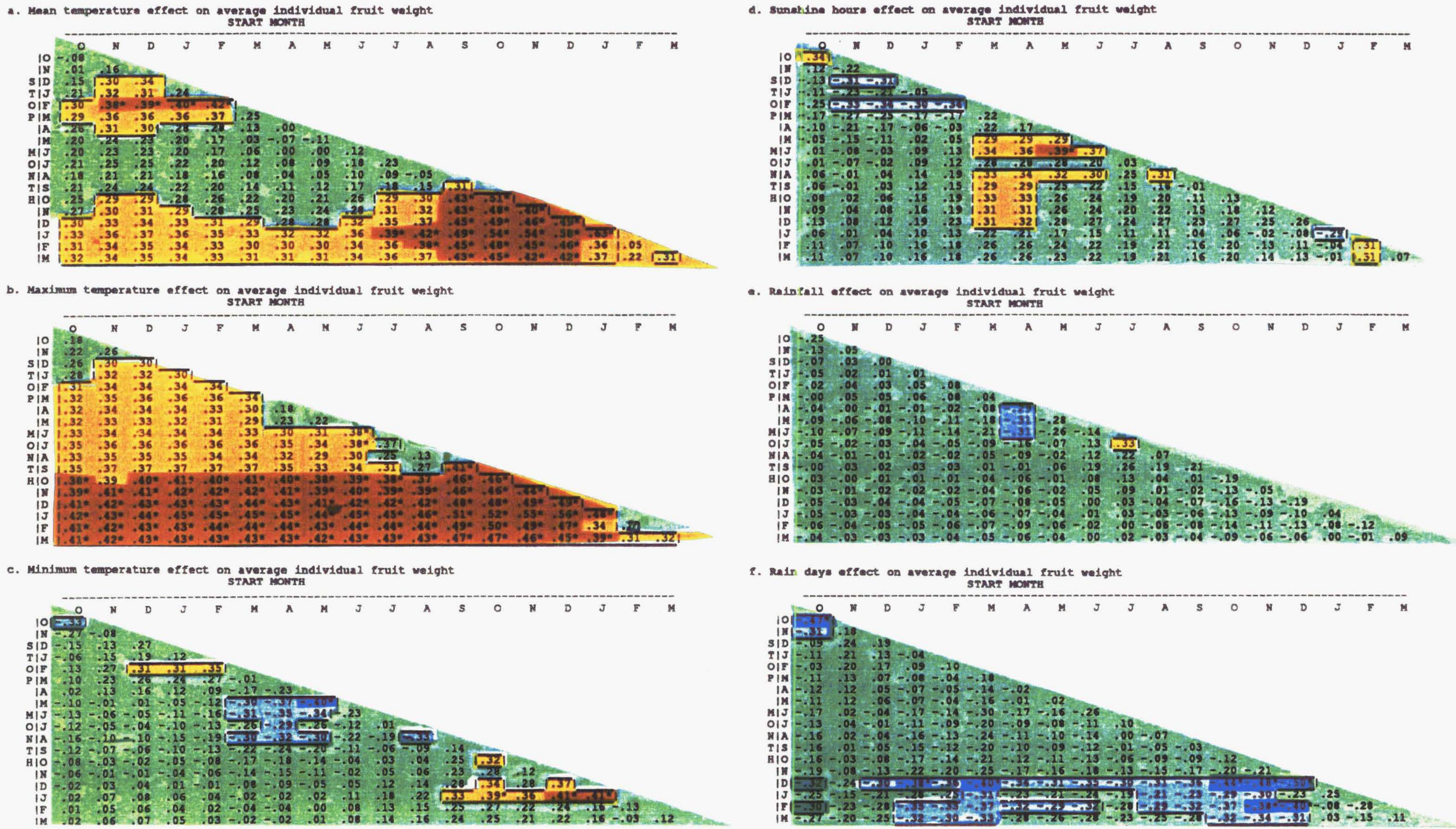

Figure 4.29 Contour map of r values for the relationships between average individual fruit weight and climatic parameters (N=46 $P_{.05}$=0.29 $P_{.01}$=0.38)

a. The effect of maximum temperature from Dec to Jan in 5 day intervals on average individual fruit weight

START DATE

	D1f	D2f	D3f	D4f	D5f	D6f	J1f	J2f	J3f	J4f	J5f	J6f
D1f	-.14											
D2f	.06	.25										
S D3f	.21	.35	.43									
T D4f	.35	.49	.58	.49								
O D5f	.48	.58	.63	.61	.62							
P D6f	.50	.59	.63	.64	.61	.45						
J1f	.52	.59	.64	.66	.61	.48	.36					
D J2f	.51	.58	.63	.64	.60	.49	.40	.27				
A J3f	.53	.60	.63	.63	.61	.54	.44	.19	.06			
T J4f	.58	.62	.63	.63	.61	.58	.51	.40	.34	.47		
E J5f	.59	.63	.64	.64	.63	.61	.61	.53	.49	.61	.38	
J6f	.57	.62	.61	.60	.58	.54	.50	.40	.37	.45	.24	-.04

NB
Dec1 = 1- 5 Dec., Dec2 = 6-10 Dec., Dec3 = 11-15 Dec.,
Dec4 = 16-20 Dec., Dec5 = 21-25 Dec., Dec6 = 26-31 Dec.,
Jan1 = 1- 5 Jan., Jan2 = 6-10 Jan., Jan3 = 11-15 Jan.,
Jan4 = 16-20 Jan., Jan5 = 21-25 Jan., Jan6 = 26-31 Jan..

b. The effect of maximum temperature from 14-20 Dec to 1-7 Jan on average individual fruit weight

START DATE

	D14	D15	D16	D17	D18	D19	D20
S J1	.62	.62	.64	.64	.65	.63	.64
T J2	.63	.63	.66	.65	.65	.64	.65
O P J3	.65	.66	.67	.67	.67	.67	.66
J4	.66	.66	.67	.67	.67	.66	.66
D J5	.65	.65	.65	.66	.66	.64	.64
A T J6	.65	.65	.65	.66	.66	.64	.64
E J7	.63	.63	.64	.64	.64	.63	.63

NB D14 = 14 December, J1 = 1 January, etc.

c. The effect of maximum temperature from 9-22 Dec to 20-26 Jan on average individual fruit weight

START DATE

	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22
S J20	.62	.63	.63	.62	.61	.61	.61	.63	.63	.63	.62	.63	.61	.59
T J21	.63	.63	.63	.63	.61	.61	.62	.64	.64	.63	.63	.63	.62	.60
O P J22	.63	.64	.64	.64	.63	.63	.64	.65	.66	.65	.64	.65	.63	.62
J23	.63	.64	.64	.64	.63	.63	.64	.65	.66	.65	.64	.65	.63	.62
D J24	.63	.64	.64	.64	.63	.63	.64	.65	.65	.65	.64	.65	.63	.62
A T J25	.63	.64	.64	.63	.62	.62	.63	.64	.65	.64	.64	.64	.63	.61
E J26	.63	.64	.64	.63	.62	.62	.63	.64	.64	.64	.63	.64	.62	.60

Figure 4.30 Contour map of r values for the relationships between average individual fruit weight and summer maximum temperatures (N=46 $P_{.05}$=0.29 $P_{.01}$=0.38)

a. The effect of mean temperature from Dec to Jan in 5 day intervals on average individual fruit weight

START DATE

	D1f	D2f	D3f	D4f	D5f	D6f	J1f	J2f	J3f	J4f	J5f	J6f
D1f	-.06											
D2f	.08	.23										
S D3f	.20	.31	.36									
T D4f	.35	.49	.52	.28								
O D5f	.48	.58	.59	.51	.61							
P D6f	.49	.58	.62	.61	.59	.44						
J1f	.49	.56	.61	.61	.54	.42	.36					
D J2f	.50	.56	.60	.60	.55	.46	.43	.49				
A J3f	.55	.61	.65	.66	.61	.56	.56	.55	.20			
T J4f	.59	.62	.65	.65	.63	.60	.59	.54	.42	.49		
E J5f	.58	.62	.65	.65	.62	.59	.61	.63	.59	.59	.33	
J6f	.58	.62	.64	.65	.63	.60	.62	.60	.52	.52	.21	-.15

b. The effect of mean temperature from 9-22 Dec to 1 Jan - 11 Feb on average individual fruit weight

START DATE

	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22
J1	.59	.61	.62	.62	.62	.62	.63	.62	.62	.62	.61	.60	.56	.53
J2	.60	.62	.62	.62	.63	.63	.63	.62	.63	.62	.61	.59	.56	.53
J3	.60	.62	.62	.63	.63	.64	.64	.63	.63	.62	.61	.59	.56	.54
J4	.59	.61	.61	.62	.63	.63	.63	.62	.62	.61	.59	.58	.55	.52
J5	.58	.60	.60	.61	.62	.62	.62	.61	.60	.60	.58	.57	.54	.51
J6	.57	.59	.59	.60	.61	.61	.61	.60	.59	.58	.57	.56	.53	.50
J7	.56	.58	.58	.59	.60	.60	.60	.59	.59	.57	.56	.55	.51	.49
J8	.57	.58	.59	.59	.60	.61	.61	.59	.59	.58	.57	.55	.52	.49
J9	.57	.59	.59	.60	.61	.61	.61	.59	.59	.58	.57	.56	.53	.50
J10	.58	.60	.60	.61	.62	.62	.62	.60	.60	.59	.58	.57	.54	.52
J11	.59	.60	.60	.62	.62	.63	.63	.62	.61	.60	.59	.58	.56	.54
J12	.60	.61	.62	.62	.63	.64	.63	.62	.62	.61	.60	.59	.57	.55
J13	.60	.62	.62	.63	.63	.64	.64	.63	.62	.61	.60	.59	.57	.55
J14	.61	.63	.63	.64	.64	.64	.64	.63	.63	.62	.62	.61	.58	.57
S J15	.63	.64	.64	.65	.65	.65	.66	.65	.65	.64	.63	.62	.61	.59
T J16	.63	.64	.64	.65	.65	.65	.65	.65	.65	.64	.64	.63	.61	.60
O J17	.62	.64	.64	.64	.64	.65	.65	.65	.65	.64	.63	.63	.61	.60
P J18	.63	.64	.64	.65	.64	.65	.65	.65	.65	.64	.64	.63	.62	.61
J19	.63	.64	.64	.64	.64	.65	.65	.65	.65	.64	.64	.63	.62	.61
D J20	.63	.64	.64	.65	.64	.65	.65	.65	.65	.65	.64	.63	.62	.62
A J21	.63	.64	.64	.65	.65	.65	.65	.65	.66	.65	.64	.63	.62	.62
T J22	.63	.64	.64	.65	.65	.66	.66	.66	.66	.65	.64	.63	.62	.62
E J23	.63	.64	.64	.65	.65	.66	.66	.66	.66	.65	.64	.63	.62	.62
J24	.63	.64	.64	.65	.65	.66	.66	.66	.66	.65	.64	.63	.62	.62
J25	.63	.64	.64	.65	.65	.65	.66	.65	.65	.64	.64	.63	.62	.61
J26	.63	.64	.64	.65	.65	.66	.66	.65	.65	.65	.64	.63	.62	.61
J27	.63	.64	.64	.65	.65	.65	.65	.65	.65	.64	.63	.63	.61	.60
J28	.63	.64	.64	.65	.65	.65	.65	.65	.65	.64	.63	.63	.61	.60
J29	.63	.64	.64	.64	.64	.65	.65	.65	.65	.64	.63	.63	.61	.60
J30	.63	.64	.64	.64	.64	.64	.65	.65	.65	.64	.64	.63	.62	.61
J31	.63	.64	.64	.64	.64	.64	.65	.65	.65	.64	.64	.64	.62	.61
F1	.64	.65	.65	.65	.65	.65	.65	.65	.66	.65	.65	.64	.63	.62
F2	.64	.65	.65	.65	.65	.65	.65	.65	.66	.65	.65	.64	.63	.62
F3	.64	.65	.65	.65	.65	.65	.65	.65	.66	.65	.65	.65	.64	.63
F4	.64	.65	.65	.65	.65	.65	.65	.65	.66	.65	.65	.65	.64	.63
F5	.64	.64	.64	.64	.64	.64	.64	.65	.65	.65	.64	.64	.63	.62
F6	.63	.63	.63	.63	.63	.63	.63	.64	.64	.64	.63	.63	.62	.61
F7	.62	.63	.62	.62	.62	.62	.62	.63	.63	.63	.62	.62	.61	.60
F8	.61	.62	.62	.62	.61	.61	.61	.62	.62	.62	.61	.61	.60	.59
F9	.61	.61	.61	.61	.60	.60	.61	.61	.61	.61	.61	.60	.59	.58
F10	.60	.60	.60	.60	.59	.59	.60	.60	.61	.60	.60	.60	.58	.56
F11	.59	.60	.60	.59	.59	.59	.59	.59	.60	.59	.59	.59	.57	.55

Figure 4.31 Contour map of r values for the relationships between average individual fruit weight and summer mean temperatures (N=46 $P_{.05}$=0.29 $P_{.01}$=0.38)

Figure 4.29 also shows that minimum temperatures in the previous May and August have an influence on fruit size with low minimum temperatures conducive to larger fruit. This may be due to the "later winter effects" on flower buds discussed in section 2.2.4 when low temperatures are helpful to the development of flower buds.

This section merely describes the results of the calculated contour maps. These results will be considered further in the discussion.

4.10.3 The Influence of Climatic Parameters on Fruit Distribution in the Various Grades

Figure 4.32 shows the contour pattern of grade AA+A is very similar to that of the average individual fruit weight in Figure 4.29. Heavier average individual fruit weight usually includes a higher percentage of fruit in grade AA+A. The pattern of grade C+D shows the reverse (Figure 4.33).

The percentage of reject fruit exhibits a slightly different pattern in that, it is not totally dependent on fruit weight (Figure 4.34). Various kind of defects contribute as well as very small fruit. The mean and maximum temperatures in the previous autumn and the minimum temperature in winter have more influence on reject fruit than on fruit in grade C+D. It appears that the grade C+D is mainly influenced by conditions in the current season, especially crop load, whereas reject fruit is determined at the flower bud initiation stage as well as during fruit development.

4.10.4 The Model of Average Individual Fruit Weight

4.10.4.1 Average Individual Fruit Weight

The equation to predict final individual fruit weight is based on fruit number after thinning per ha, adding the modifications for the mean temperature in the previous February and the minimum average temperature in the previous May, which may affect the quality of flower buds.

$$FrWt = 22.51 - 30.51\ Ln(FNAT/ha)^{**} + 6.84\ T_2^{**} - 3.92\ MinT_5^{**} \qquad (4.10)$$

$$(R = 0.78^{**},\ N = 43,\ s = 11.68)$$

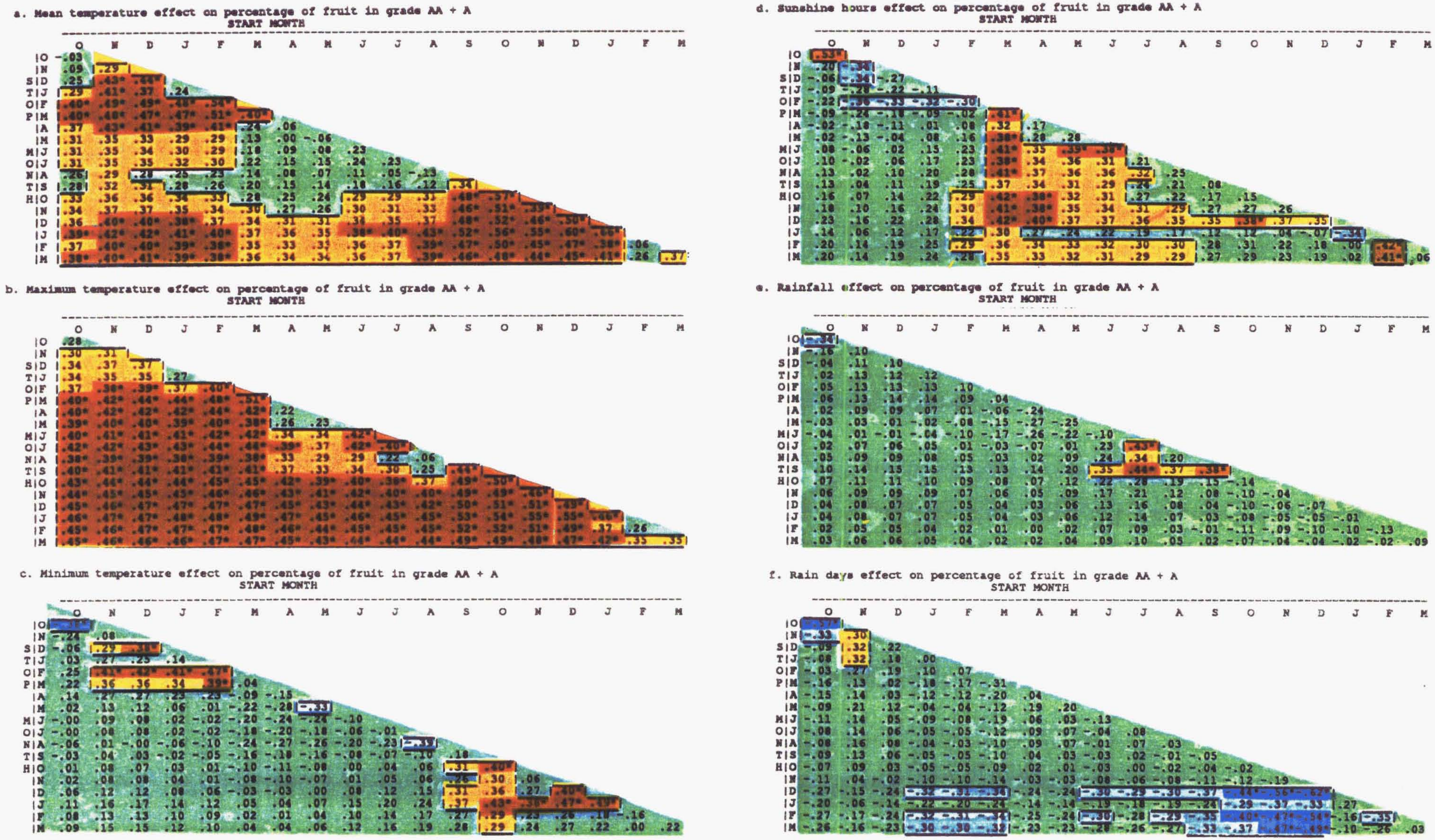

Figure 4.32 Contour map of r values for the relationships between percentage of fruit in grade AA & A and climatic parameters (N=40 $P_{.05}$=0.32 $P_{.01}$=0.41)

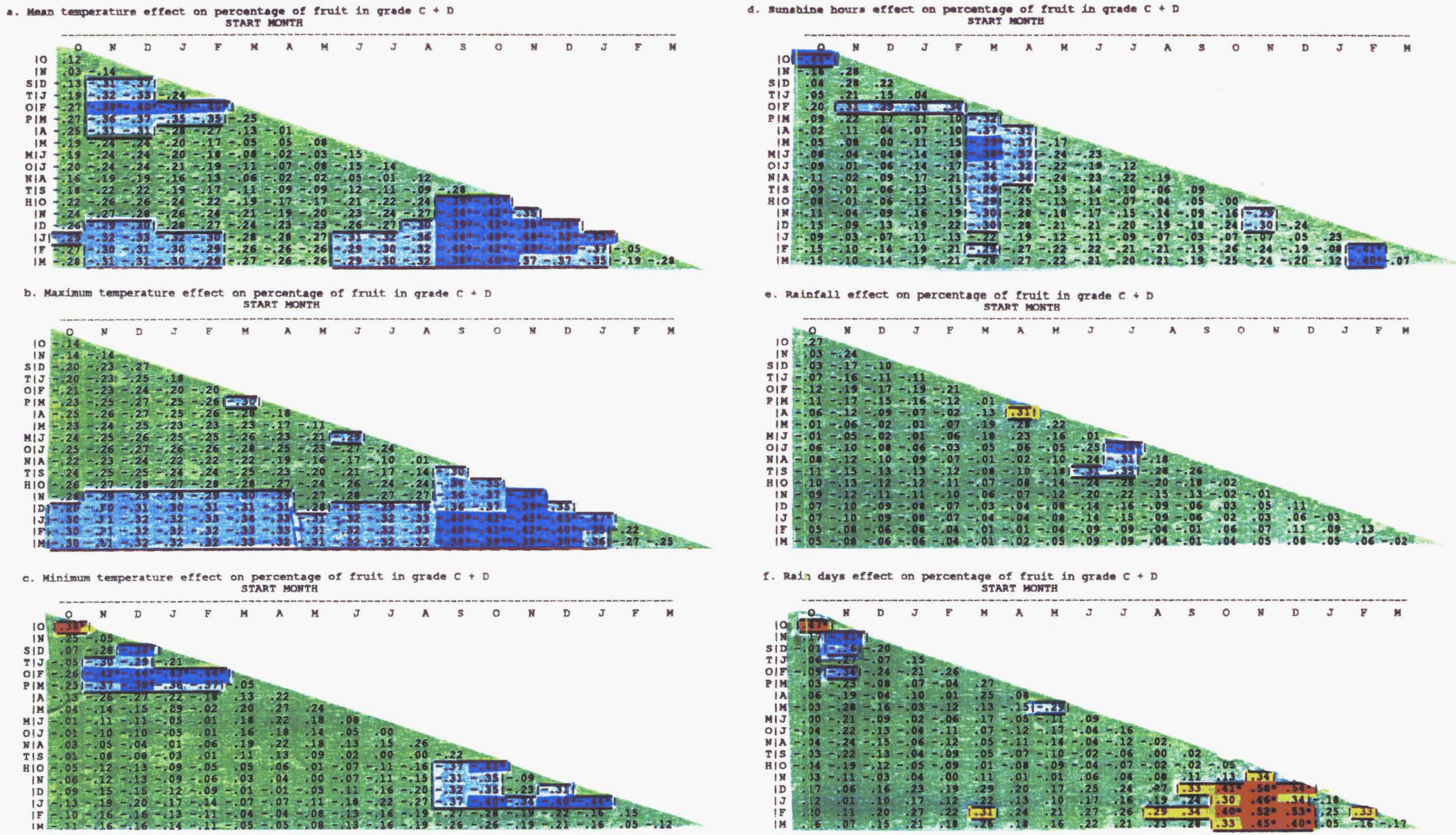

Figure 4.33 Contour map of r values for the relationships between percentage of fruit in grade C & D and climatic parameters (N=40 $P_{.05}$=0.32 $P_{.01}$=0.41)

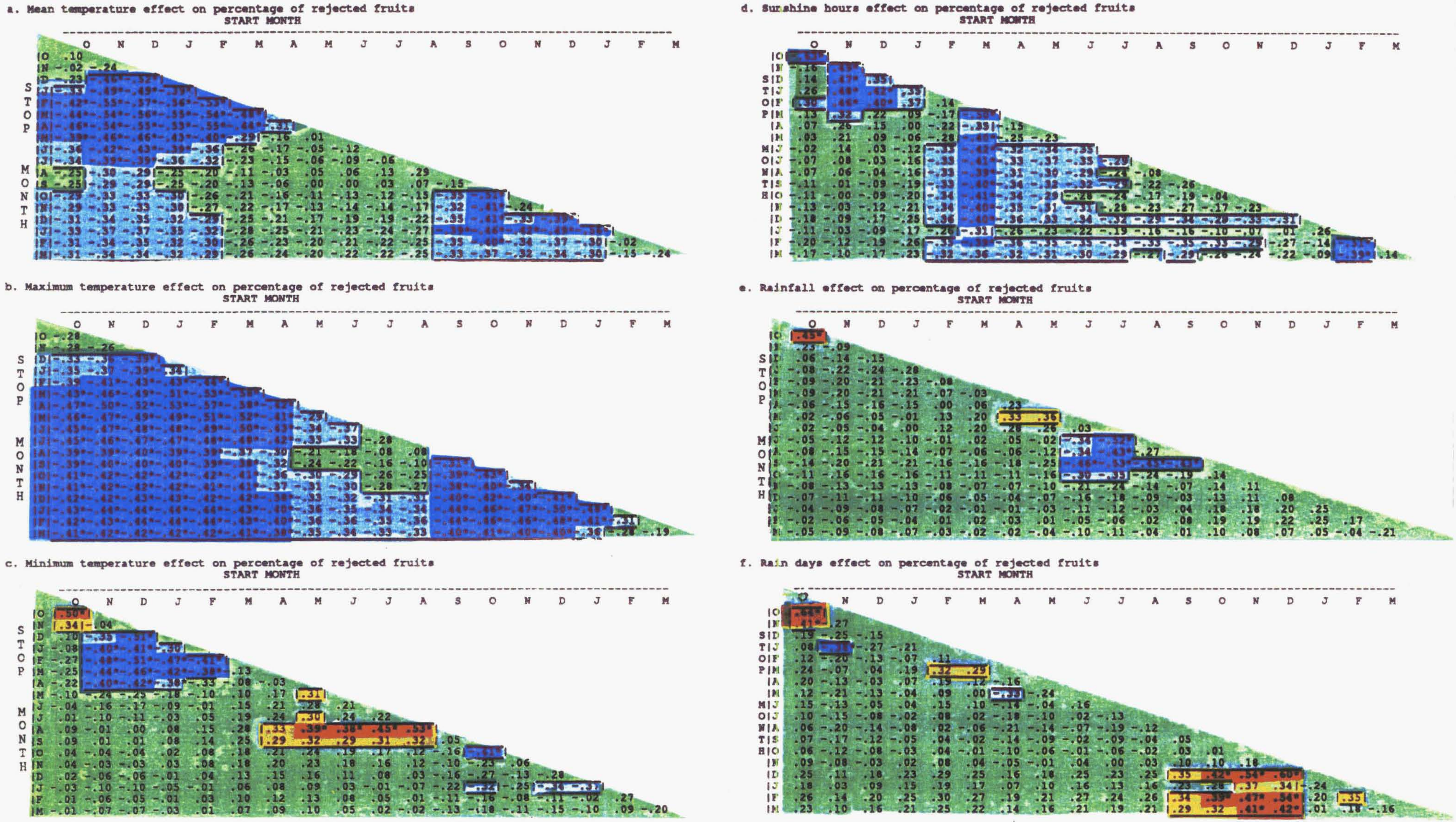

Figure 4.34 Contour map of r values for the relationships between percentage of rejected fruit and climatic parameters (N=40 $P_{.05}$=0.32 $P_{.01}$=0.41)

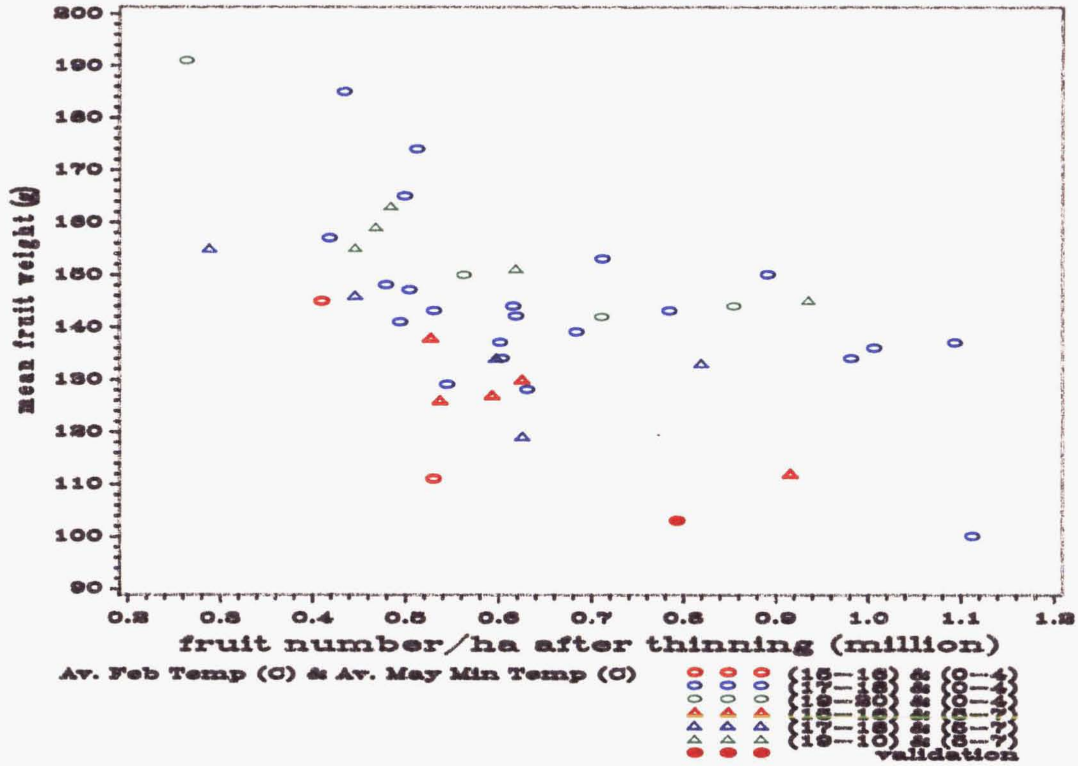

Figure 4.35 Fruit weight : fruit number after thinning per ha
Av. Feb Temp (C) & Av. May Min Temp (C)

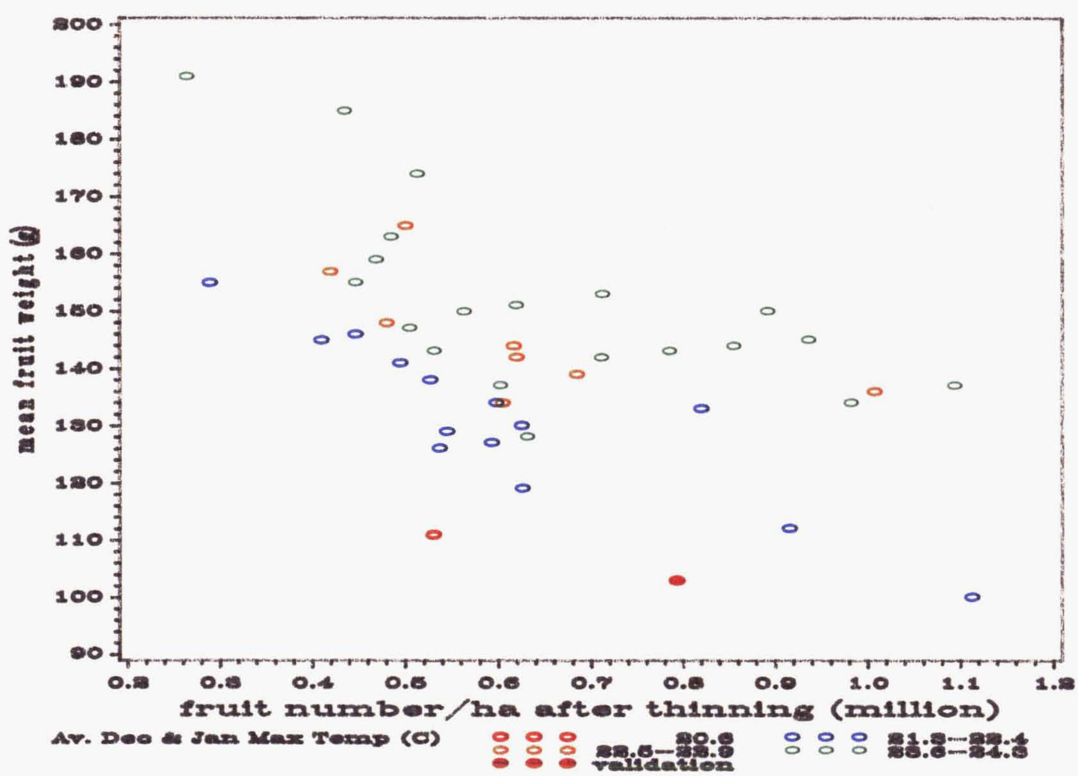

Figure 4.36 Fruit weight : fruit number after thinning per ha
Av. Dec & Jan Max Temp (C)

This is expressed in Figure 4.35. The circles show 0 - 4°C minimum temperature in May while the triangles show 5 - 7°C. The colours represent different ranges of temperatures in the previous February. For the same fruit number after thinning per ha a green circle should show larger fruit and a red triangle smaller fruit.

In the validation test, fruit number after thinning was 0.793 million per ha, the mean temperature in the previous February was 15.2°C, the minimum average temperature in the previous May was 3.4°C and the predicted average fruit weight was 120 g. However, the actual average individual fruit weight was 103 g, indicating relatively poor validation.

After the December drop and thinning, the weather before harvest will still have a very strong influence on fruit growth. Analysis of the contour maps shows that maximum temperatures in December and January have the most important influence on fruit growth and, although prediction at this time may be relatively late, it is likely to be more accurate.

$$FrWt = -98.15 - 34.42\ Ln(FNAT/ha)^{**} + 9.71\ MaxT_{12\text{-}13}{}^{**} \qquad (4.11)$$

$$(R = 0.81^{**},\ N = 43,\ s = 10.58)$$

This is expressed in Figure 4.36. Different colours show different ranges of average maximum temperatures in December and January. As expected, the green circles depicting higher temperature generally show large fruit size, the orange circles depict an intermediate position and the blue, representing the cooler temperatures, show smaller fruit.

The red dot represents the validation test when the average maximum temperature in December and January was 20.2, and the fruit was smaller than the other years averaging 106 g. This is very close to the real recorded figure of 103 g implying that the prediction by means of the current summer temperature is the most reliable. Although the climatic parameters in the previous growing season and the dormant period may influence the quality of flower buds and so influence fruit size in the following season, the current summer temperature is dominant. In the 1991/92 season, the one used for the validation, the maximum temperature in December was unusually low at 18.33°C, the fourth lowest reading since 1928. The effect of the unusually low summer temperature is clearly reflected in lower average fruit size (section 4.8).

The prediction using fruit number after thinning per ha produced more reliable results than

using fruit number at harvest time.

$$FrWt = -127.02 - 28.40\ Ln(FN/ha)^{**} + 10.88\ MaxT_{12\text{-}13}{}^{**} \qquad (4.12)$$

$$(R = 0.77^{**},\ N = 46,\ s = 12.17)$$

Based on daily temperature analysis formulae 4.13, 4.14 and 4.15 may also be used.

For the average maximum temperature between 18 December and 4 January equation 4.13 applies.

$$FrWt = 20.6 - 41.4\ FNAT/ha^{**} + 6.49\ MaxT_{D18\text{-}J4}{}^{**} \qquad (4.13)$$

$$(R = 0.80^{**},\ N = 43,\ s = 10.93)$$

For the average maximum temperature between 17 December to 23 January equation 4.14 applies.

$$FrWt = -27.6 - 42.2\ FNAT/ha^{**} + 8.35\ MaxT_{D17\text{-}J23}{}^{**} \qquad (4.14)$$

$$(R = 0.79^{**},\ N = 43,\ s = 11.10)$$

For the average mean temperature between 17 December to 4 February equation 4.15 applies.

$$FrWt = -37.8 - 39.2\ FNAT/ha^{**} + 11.3\ MeanT_{D17\text{-}F4}{}^{*} \qquad (4.15)$$

$$(R = 0.78^{**},\ N = 43,\ s = 11.19)$$

Several more years validation is required to determine which of these three formulae will be of most practical use.

4.10.4.2 Fruit Distribution in the Various Grades

For the grades AA, A, B, C and D, the percentages are determined by fruit weight. Although some tree or climatic parameters may influence these percentages, they also influence the average individual fruit weight. All of these effects have been included already in the fruit weight model and it is not necessary to include them again in calculating percentage of fruit in the various size grades.

For the percentage of fruit in grades AA + A, the equation is

$$\%AA{+}A = -94.30 + 0.93\ FrWt^{**} \qquad (4.16)$$
$$(r = 0.90^{**},\ N = 45,\ s = 8.69)$$

For the percentage of fruit in grades C + D, the equation is

$$\%C{+}D = 98.10 - 0.54\ FrWt^{**} \qquad (4.17)$$
$$(r = -0.84^{**},\ N = 45,\ s = 6.54)$$

The percentage of rejected fruit is not totally dependent on fruit weight but consists of defects as well as very small fruit. The percentage of reject fruit is based on the analysis outlined in section 4.10.3. The equation is

$$\%R = 123.88 - 0.21\ FrWt^{**} + 4.14\ MinT_8^{**} - 6.28\ T_{2\text{-}4}^{**} \qquad (4.18)$$
$$(R = 0.87^{**},\ N = 45,\ s = 5.24)$$

No advantage was shown by the application of principal component analysis in this section of the work.

4.11 AN EXAMPLE OF THE MODEL APPLICATION

4.11.1 Assembling the Model

The previous sections have used the basic data to develop biological relationships covering the flowering period through to harvesting.

It is necessary now to assemble the formulae into a model which will not only provide information for management strategies on flower and fruit number as the season progresses but, by the incorporation of quality and price data, provide financial estimates as well.

The formulae incorporated in the model may be summarised as follows:

Gross Margin = Total Revenue - Direct costs

Direct costs = $labour_{growing}$ + $labour_{harvest}$ + material cost + machinery cost

$labour_{growing}$ = hours · payment/hour

$labour_{harvest}$ = Y/ha · hours · payment/hour

machinery cost = hours · rate/hour

Total Revenue = Σ(Y/ha · $\%_{grade}$ · $Price_{grade}$)

Y/ha = FN/ha · FrWt

%AA+A = -94.30 + 0.93 FrWt

%B = 100 - %AA+A - %C+D - %R

%C+D = 98.10 - 0.54 FrWt

%R = 123.88 - 0.21 FrWt + 4.14 $MinT_8$ - 6.28 T_{2-4}

FrWt = -98.15 - 34.42 Ln(FNAT/ha) + 9.71 $MaxT_{12-13}$

FN/ha = FNAT/ha · %FReAD (NB %FReAD = 0.9)

FNAT/ha = %FReAT · FNBT/ha

%FReAT = 60.98 - 26.20 Ln(FNBT/ha)

FNBT/ha = %SET · FB/ha

%SET = 1.1 - 0.76 FB/x + 6.88 $MaxT_3$ - 6.13 $MaxT_{8-9}$

The gross margin consists of two parts, namely total revenue and direct costs but excludes property overheads such as rates, insurance, interest and other administrative costs.

Direct costs are those involved in growing the crop, such as chemicals, production labour and machinery operations, and costs which vary according to the yield such as harvesting labour and marketing costs.

When the fruit is sold through the New Zealand Apple and Pear Marketing Board the fruit is paid for net of marketing costs. There may be some marketing costs for which the grower is responsible such as delivery of the fruit to the Board depot.

Total revenue consists of three parts namely yield, fruit distribution in different grades and the prices for each grade. The pricing system is reported to growers each year by the New Zealand Apple and Pear Marketing Board. The other two parts of the revenue equation are covered by the biological formulae determining yield and fruit size which also govern harvesting and marketing costs. All the economic data relies on the individual user's input. The data used in the example model is based on average costs elicited from growers

participating in the monitoring program. This study has not incorporated economic research into orchard factors causing cost variation under different management regimes. Fruit distribution into grades is estimated from average individual fruit weight and modified by some climatic parameters according to the formulae stated.

Yield per ha is calculated from fruit number, average fruit weight and trees per ha. Fruit number changes during the season according to the various formulae associated with fruit set and thinning and modified by some climatic parameters. Fruit number, especially fruit number after thinning, has a clear relationship with average individual fruit weight.

The starting point for the system is the entry of flower bud number per trunk CSA based on counts taken at the pre flowering stage.

Historical or predictive climatic data may be entered at this point as well, to allow growers to plan their orchard management strategies at an early stage in the system.

As a general rule, if more fruit is left on the trees at the thinning stage, the ultimate yield will be higher but the average fruit size will be smaller. The calculation of total revenue and gross margin is complicated by the price variation for the various size grades. Various thinning strategies can be tested by the model to allow growers to make informed management decisions based on their own input data.

4.11.2 Computer Program Design Objectives

The program is designed for ease of management by the growers for individual orchard management decision making. It is not designed for growers to easily understand the mathematical and biological methodology of the model but this may follow as growers record and work with their individual orchard data.

The program is designed to reduce user input as much as possible. The long-term averaged regional climatic data and price system data can be stored in the program. Users have the choice as to which meteorological station data they wish to use. The user also has the opportunity to view the climatic and pricing data used in the model and modify it if desired for individual situations. The program will accept raw data directly recorded by the orchardist (eg flower and/or fruit number per sampled branches) and report and process that

data through to the predictive point required, along with statistical probabilities.

The program allows for modification in management strategies as the season progresses by entry of actual data; for example, fruit number after thinning.

The program allows for parametisation of input data to provide predictive outcomes for a range of management strategies at the various stages of the season.

4.11.3 Description of the Computer Program

The computer program named LUHAM is edited in turbo-pascal (Appendix 8). The program progresses as follows:

i Initial data

Users are asked to nominate an appropriate meteorological station, from 7 offered, or are given the opportunity to enter their own climatic data. The program then asks for the average trunk CSA and orchard planting density. Alternatively average tree fruiting volume may be entered instead of average trunk CSA.

ii Stage choice

The user may enter the program at any one of the following 4 points to pursue a strategy at any particular point of the season or to merely calculate financial estimates:

a Planning from the flowering period;

b Fruit number before thinning;

c Fruit number after thinning;

d Financial strategies.

The flow diagram is given in Figure 4.37.

iii Flowering stage

Selected branches are identified and flower numbers together with branch diameters (or circumferences) entered. Actual climatic data to date for the orchard for the current season can then be entered. If not available, appropriate long term average data can be substituted from an appropriate nearby meteorological station. Although this may not be exact for the particular season it will provide a better basis for estimation than not using climatic data at all. This section calculates the number of flower buds and fruit number before thinning per ha and the estimated initial percentage fruit set. After reading the results, users have the choice to continue or exit. The program continues at the before

thinning stage.

iv Before fruit thinning stage

At this stage, users have the choice to continue with the results calculated in the previous stage or to input new fruit number based on actual fruit number on the monitored branches. Again climatic data can be modified to provide actual recordings to this stage.

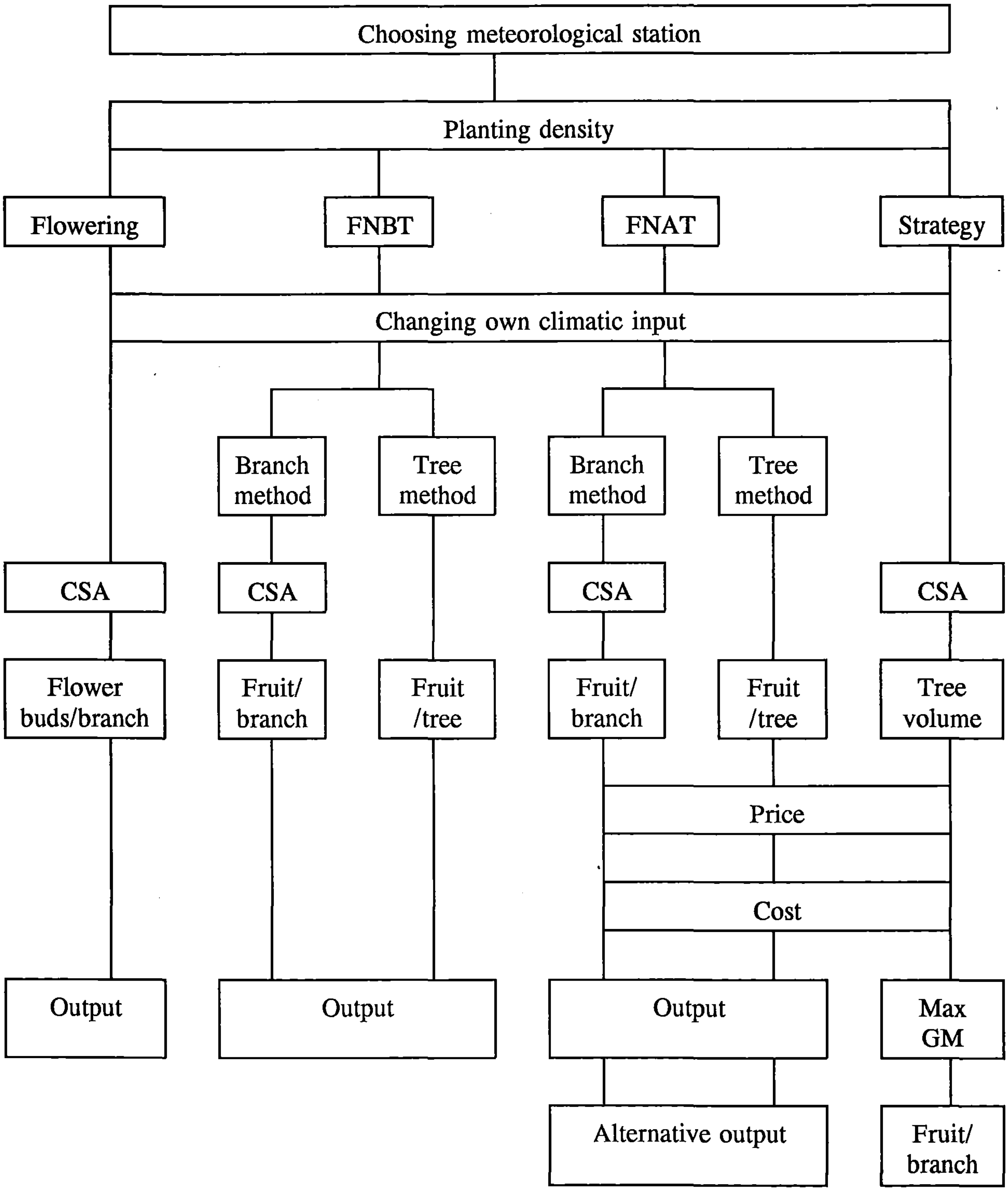

Figure 4.37 Flow chart

The program will calculate the number of fruit after thinning per ha and the percentage of thinned fruit. The user can again exit or continue to the next after thinning stage.

v **After fruit thinning stage**

This is the key stage of the program where the predicted biological and financial outcome at harvest will be produced.

a At this stage, just after thinning, users do not know exactly what the weather will be during the next 2 - 3 months until harvest. A temperature forecast may be entered here instead of using the long term average data already incorporated. The program will provide December and January temperature-based estimates of fruit production using 5 or 10% above and below the forecast (or above and below the long-term average).

b Users have the choice to use the price system stored in the computer or input a new seasonal update of prices.

c Users have the choice to use the cost database stored in the computer or input their own database. The cost database includes

harvest hours per tonne of fruit;
production labour hours per ha;
labour cost per hour;
material costs;
machinery hours and machinery rate per hour.

d The program will produce the following output

fruit number per ha at harvest;
average individual fruit weight;
yield per ha;
distribution of fruit in each grade (AA+A, B, C+D, R);
total revenue and gross margin.

vi **Financial strategies**

This section provides a chance to compare alternative economic strategies based on different crop loads. After checking or editing the price system and cost database, the user may enter a range of fruit number per tree (eg 500 - 2000) and a desired interval of the numbers (eg 10 or 50). The program will provide a 1-line result for each fruit number nominated. Each line will include gross margin, total revenue, fruit number after thinning per tree, yield per ha, average fruit weight, percentage of fruit in each grade and fruit number per tree. The results are tabulated in descending order of gross margin. This provides the grower with a range from which to decide on a final thinning strategy.

This section also provides information on how many fruit should be retained on branches of various sizes given a stated number of fruit required per tree. This is based on the branch sampling technique described in Chapter 3. It allows employees to thin according to the branch size as measured by base diameter or circumference. An alternative is provided if the grower wishes to use fruiting volume as a basis for thinning. The tree volume is calculated according to the volume of a cone. Using the volume of a tree as a basis for thinning is extremely difficult and, because of gaps in the fruiting area of a tree, sampling to a smaller volume (instead of using branch sampling) is not really feasible at this stage. The use of the volumetric basis will require further testing and modification.

CHAPTER 5

STARCH MEASUREMENT

5.1 INTRODUCTION

For most trees starch is considered to be the main form of carbohydrate reserve. The root system is the main storage organ during the winter dormant period. Starch stored in one season provides the energy for early shoot and fruit growth in the following season (Priestley, 1960; Tromp, 1983). The literature also suggests that the starch level influences flower initiation (Xia, *et al.*, 1983).

Although many papers report on starch analysis during the growing season (Tromp, 1983; Khatshevich, 1977) and at the beginning of the dormant period (Dolgova, 1974; Murneek, 1942), there are few papers which measure root starch in apple trees during mid-winter (eg Murneek, 1933). This may be due to the difficulty of taking root samples in many areas of the world at this time when soils are frozen.

In most producing regions of New Zealand, the soil is not frozen. During the winter, observations indicate that the root system of apple trees in New Zealand continues to grow. However, there appear to be no reports which have measured root starch during this period.

The objective in this chapter is to examine apple root growth during the winter and to establish a correlation between crop load and starch levels in above and below ground plant structures during the following winter and between starch levels in the plant during winter on flower and fruit numbers in the following season.

5.2 MATERIALS AND METHODS

5.2.1 Starch Analysis Sampling for Different Parts of the Trees (Analysis 1)

Two 18 year-old Red Delicious apple trees in the Horticultural Research area of Lincoln University were pulled out by a tractor in early and mid September 1990, respectively. The above ground and root system of the trees were sampled separately as follows:

i The above ground parts of each tree

a one-year-old shoots;

b spurs without bourse shoots;

c spurs with bourse shoots;

d the wood of spurs without bourse shoots;

e the bark of spurs without bourse shoots;

f the wood of spurs with bourse shoots;

g the bark of spurs with bourse shoots;

ii The trunk: 5 mm thick wedges of trunk were taken from each tree

a just above ground level;

b just below ground level;

iii Root samples: 2 samples were taken from opposite positions on each tree

a roots with a diameter between 1 - 4 mm;

b the wood of roots with diameters between 1 - 4 mm;

c the bark of roots with diameters between 1 - 4 mm;

d roots with diameters between 4 - 7 mm;

e roots with diameters between 7 - 10 mm;

f roots with diameters between 10 - 15 mm;

g roots with diameters between 15 - 25 mm;

h roots with diameters between 25 - 35 mm.

Each sample was divided into two sub-samples before extraction procedures were implemented (section 5.2.4.2.ii).

This starch and sugar analysis reported in section 5.3 was designed by the author and executed by a visiting German student Mr Christian Trimborn from Bonn University, Germany.

5.2.2 Starch Analysis Sampling for the Roots under Different Crop Loads (Analysis 2)

i Establishment of different crop loads

Nine 18 year-old Granny Smith apple trees were chosen in The Horticulture Research area at Lincoln University. The nine trees were divided into 3 plots and 3 crop loads per plot were achieved in the following manner:

a light crop load: heavy hand thinning at 2 weeks after the flowering period;

b medium crop load: chemical thinning with Carbaryl (100 ppm) at 4 weeks after the flowering period;

c heavy crop load: no thinning.

A randomized complete block design was used. Fruits were harvested, weighed and counted for each of the nine trees.

ii **Sampling roots**

Six bark pieces from 6 different roots with diameters between 20 to 30 mm, chosen at random around each tree, were peeled for analysis during late July 1991. The 6 bark samples were analysed separately.

iii **Recording in the second year**

Photos were taken for each of the 9 trees during the flowering period. Three first order branches were chosen as monitored branches on each of the 9 trees. The number of flower clusters, fruit before and after thinning and fruit weight and number at harvest were recorded on each of the 27 monitored branches.

5.2.3 Measurement of Starch

The technique used was described by Rose (1989) as follows:

MCW solution (methanol:chloroform:water 12:5:3 in volume) to remove soluble sugars, NaOH to solubilize the starch, two amylose/amylopectin starch degrading enzymes to hydrolyze the starch to glucose, and reaction with o-dianisidine for colorimetric analysis. The colour reaction is stable for several hours.

5.2.3.1 Solutions Used

i **MCW solution**: mix 1200 ml of methanol, 500 ml of chloroform and 300 ml deionized (18.3 megohm-cm) water (dH_2O). Reagent-grade solvents were used.

ii **0.05 M NaOAc (sodium acetate) buffer, pH 5.1**: add 2.84 ml HAc (glacial acetic acid) to 900 ml dH_2O. Adjust to pH 5.1 with addition of 30% NaOH. Bring to a total volume of 1000 ml with additional dH_2O.

iii **0.1 sodium phosphate buffer, pH 7.0**: dissolve 8.7 g di-basic sodium phosphate (Na_2HPO_4) and 5.3 g monobasic sodium phosphate monohydrate ($NaH_2PO_4 \cdot 2H_2O$) in 1000 ml dH_2O.

iv **α-amylase/amyloglucosidase digestion solution**: dissolve 5 mg of α-amylase (Sigma

#2643, 4450 unit) and 100 μl of 25 mg (2.8 ml) of amyloglucosidase (Sigma #3514) in 0.05 M NaOAc buffer (solution ii).

v **glucose oxidase/peroxidase/o-dianisidine solution**: dissolve 150 mg o-dianisidine dihydrochloride in 30 ml dH_2O. Mix the 30 ml o-dianisidine solution with 2970 ml 0.1 M sodium phosphate buffer, pH 7.0 (solution iii). Add 1365 mg glucose oxidase (GOD, Sigma #G6125) and 60 mg peroxidase (POD, Sigma #P8000) and mix well. The final solution is 0.16 mM o-dianisidine in 0.1 M sodium phosphate buffer, pH 7.0, containing about 5 units GOD/ml and 1 unit POD/ml. This solution is stable for up to 1 month if stored in the refrigerator in a brown bottle. However, it was made up for each analysis in this study.

vi **Glucose standards**: Glucose standards were made up just before each analysis in the study in the range 10 - 100 μg glucose per ml of 0.05 M NaOAc buffer, pH 5.1 (solution ii).

5.2.3.2 Procedure

i **Initial sample preparation**

a New plastic centrifuge tubes (10 ml) with covers were washed with Decon 90 detergent (Decon Laboratories, England), and then with dH_2O. They were labelled and put into a 50°C incubator for 24 hours to ensure that they were completely dry, cooled to room temperature in a desiccating chamber, and weighed to the nearest 0.1 mg.

b The samples, especially root samples, were washed until all soil was removed. The fresh plant tissue was dried in an oven at 100°C for 15 minutes to inactivate the enzymes. The temperature was reduced to 70°C and drying continued for between 24 and 48 hours. The tissue of each sample was ground in a herbage grinder N.V.TEMA (model S-aravenhage) for 30 seconds then passed through a 40 mesh sieve and stored in specimen bottles. Between samples, the grinding cell was washed with acetone to remove all residues.

c 50 mg samples of each tissue sample were weighed into the centrifuge tubes, and the tubes placed in a 50°C incubator overnight to remove any remaining moisture in the samples. The tubes containing the samples were cooled to room temperature in a desiccating chamber, and then weighed to the nearest 0.1 mg to obtain the tissue dry weight. The weight of the dried sample was recorded for use in the calculation of starch.

ii Extraction

a The sample in each tube was resuspended in 5.0 ml of MCW solution using a Vortex mixer.

b After 10 minutes at room temperature, the tubes were centrifuged at 1100G for 10 minutes. The supernatant was transferred into specimen bottles by aspiration.

c The extraction with MCW solution and centrifuging was repeated twice. The extracts were combined for the determination of soluble sugars.

iii Further drying

The extracted tissue samples in the unstoppered centrifuged tubes were placed over night in an incubator at 50°C to evaporate residual MCW.

vi Solubilization of starch

a The tubes were removed from the incubator and 1 ml of 0.1 N NaOH was added. A stainless steel rod was used for breaking up the residue. The tubes were stoppered and mixed on a Vortex mixer until the pellet was disintegrated and suspended in the solution. Three ml of 0.1 N NaOH was added to wash all the residue from the steel rod into the centrifuge tubes.

b The solution was incubated in a 50°C incubator for 30 minutes with occasional swirling.

c The sample solution was adjusted to pH 5.1 by addition of 5.0 ml of 0.1 N HAc. The starch was dissolved in a 0.05 M NaOAc buffer, pH 5.1, and was ready for enzyme digestion.

v Enzyme reaction

1.0 ml of the α-amylase/amyloglucosidase digestion solution was added to each of the tubes. The tubes were stoppered with a plastic seal, the tissue/enzyme solution mixed well with a Vortex mixer, and incubated for 48 hours at 50°C with occasional mixing during the starch digestion.

vi Starch assay

a After digestion, the sample solutions were mixed well with a Vortex mixer and centrifuged at 1100G for 10 minutes.

b 1 ml of the digested solution was diluted with 0.05 NaOAc buffer, pH 5.1 (solution ii) for assay on the basis of a preliminary test (usually 1:20).

c A 0.5 ml aliquot of sample solution was transferred to specimen bottles. 5 ml of the glucose oxidase (GOD/POD/o-dianisidine solution) was added to each 0.5 ml sample. This was stoppered, mixed well and incubated at 30°C for 45 minutes. The glucose standards were treated in the same manner. Each sample had two replicates in the

analysis.

d The tubes were transferred to a cold water bath and 1.0 ml 75% H_2SO_4 added rapidly to each tube to stabilize the colour formed.

e After the tubes cooled, they were stoppered and mixed well. The absorbance at 525 nm was read versus a buffer-reagent blank. The glucose concentration was determined by comparison with the glucose standard curve run simultaneously.

vii Calculations of starch concentration:

a solution concentration

The absorbance data from each sample were inserted in the linear regression formula generated from the glucose standards. The starch concentration (μm/ml) was calculated from the regression formula $y = a + bx$

where y = μg/ml of glucose;

a = intercept;

b = slope;

x = absorbance at 525 nm.

b sample starch content

The general equation for calculating the starch content is:

starch content (% dry weight) = $c \cdot r \cdot d_f \cdot h_f / dw$

where c = solution concentration (μm/ml);

r = the volume of digested solution;

d_f = dilution factor (eg 10 for a 1:9 dilution);

h_f = starch hydrolysis factor 0.9 (Volenec, 1986);

dw = dry weight of the sample.

5.2.4 Measurement of Soluble Sugars (Anthrone method)

i Sugar solution

The pooled sugar/MCW solution (Step 5.2.4.2.ii.c) was placed in a 50°C incubator for at least 24 hours, until all the MCW evaporated. Then, 20 ml dH_2O was added to the specimen tubes, stoppered and mixed well. A suitable dilution was made on the basis of a preliminary test.

ii Anthrone solution

1 g of anthrone was dissolved in 500 ml of concentrated H_2SO_4. This was made up just before sugar analysis and was stored in a refrigerator during use.

iii Glucose standards

The procedure was the same as for the starch analysis except that dH_2O replaced 0.05 NaOAc buffer in this analysis.

iv Sugar assay

2 ml of the diluted solution was pipetted into glass test tubes and cooled in an ice bath. 4 ml of the fresh anthrone reagent was added, stoppered and mixed. The tubes were heated in a boiling water bath for 10 minutes, cooled rapidly to 15°C and the absorbance at 620 nm was read versus a reagent blank. The glucose concentration was determined by comparison with the glucose standard curve run simultaneously. The calculation formulae were the same as for starch.

5.2.5 Observation of Root Growth of Apple Trees during the Dormant Period

The root systems of nine 4-year-old Royal Gala apple trees were cut vertically at a distance of 1 m from the trunk on both sides of the trees along the rows in early January 1990. Glass plates 30 x 30 cm were placed against the cut surface and fixed in place with two wooden bars. Black plastic was placed over the glass to exclude light. In order to periodically observe root growth against the surface of the glass, a plastic bag filled with earth was used to fill the excavation and covered with soil back to normal soil surface level. Root growth observations were recorded and photographed at times indicated in section 5.4.3.

5.3 STORED STARCH IN DIFFERENT PARTS OF AN APPLE TREE

Table 5.1 shows the stored starch in different parts of apple trees in the dormant period. On average, the root system contains more starch than the above ground parts. Even the portion of the trunk below the soil surface contained significantly more starch than the above ground portion of the trunk.

For the root system, most of the roots contained starch in the 10 - 20% range with the highest starch levels recorded in 7 - 10 mm roots. This result is quite similar to the result of Murneek (1933) who showed that small roots had higher starch content than larger roots.

New, growing roots contained significantly lower starch than all other root types. New, growing roots use starch for structure during the strong growth period, leaving little available for storage. However, during sampling, a small number of semitransparent rootlets were

inevitably included and possibly contained some stored starch.

Table 5.1 Starch and soluble sugar content for different parts of trees

Materials	Number of samples	Starch (% dry matter)	Soluble sugar (% dry matter)
<u>Above ground parts</u>			
shoot	2	2.81±0.38[z]	4.59±1.03
spur with bourse shoot	2	2.23±0.07	5.98±0.03
spur without bourse shoot	2	1.63±0.05	5.81±0.33
trunk above ground	2	1.09±0.38	3.11±0.90
<u>Root system</u>			
trunk below ground	2	2.19±0.49	2.09±0.39
1-4 mm root	4	12.18±3.32	5.96±1.07
4-7 mm root	4	18.71±2.43	5.84±0.95
7-10 mm root	4	20.55±2.75	5.83±0.64
10 mm root	4	16.78±2.34	5.94±0.67
20 mm root	4	14.90±0.46	5.02±0.51
30 mm root	4	11.69±0.97	5.07±0.33
new growing root	16	1.89±0.40	6.71±0.27

[z] standard error of means.

For the above ground parts, there was little difference in starch content between shoots and spurs, with or without bourse shoots.

Soluble sugar was relatively consistent compared with starch levels. It ranged from 2 - 7% (Table 5.1) with most results concentrated in the 5 - 6% range. The highest soluble sugar value was 6.71% found in new, growing roots.

5.3.1 Variation of Similar Roots in the Same Trees

Understanding the variation of starch content in the roots is important for determining appropriate sampling procedures.

Two trees were removed for the test. For each tree, two roots were sampled in opposite directions for each thickness group.

Table 5.2 Starch and soluble sugar content in similar roots in the same trees

Root type	Number of Samples	Starch		Sugar	
		% Dry matter	CV[z] (%)	% Dry matter	CV (%)
<u>Tree 1</u>					
1-4 mm root	2	12.75±4.00[y]	31.4	4.29±0.39	9.1
4-7 mm root	2	16.80±3.40	20.3	4.32±0.30	6.9
7-10 mm root	2	24.05±2.19	9.1	4.72±0.03	0.6
10 mm root	2	20.77±0.53	2.6	4.79±0.16	3.4
20 mm root	2	15.60±0.30	1.9	4.28±0.34	7.9
30 mm root	2	13.02±1.02	7.8	4.52±0.04	0.8
<u>Tree 2</u>					
1-4 mm root	2	11.61±4.09	35.2	7.64±0.66	8.6
4-7 mm root	2	20.63±1.58	7.6	7.36±0.57	7.7
7-10 mm root	2	17.05±2.36	13.9	6.93±0.04	0.5
10 mm root	2	12.79±0.47	3.7	7.08±0.00	0.0
20 mm root	2	14.20±0.20	1.4	5.75±0.36	6.3
30 mm root	2	10.35±0.13	1.2	5.63±0.11	1.9

[z] coefficients of variation;
[y] standard error of means.

Table 5.2 shows the variation in starch content of different root types. The roots above 10

mm are least variable. Most of the coefficients of variation of the roots above 10 mm are below 4% except one at 7.8%. The standard errors of the roots above 10 mm are also small. For small roots, most of the coefficients of variation were above 10%. The starch content in small roots varied markedly even in the same trees.

5.3.2 Starch Content in Wood and Bark

The starch content for bark and wood of roots is very different. Bark of roots contained much more starch than wood. The bark of roots appears to be the main storage place for starch (Table 5.3)

Table 5.3 Starch and soluble sugar content in wood and bark

Materials	Number of samples	Starch (% dry matter)	Soluble sugar (% dry matter)
wood of spur with bourse shoot	2	3.93±0.22[z]	6.44±0.93
wood of spur without bourse shoot	2	5.06±0.68	4.84±0.57
bark of spur with bourse shoot	2	0.61±0.06	6.86±0.84
bark of spur without bourse shoot	2	0.55±0.31	6.57±1.32
wood of 1-4 mm root	4	11.47±0.49	3.67±0.06
bark of 1-4 mm root	4	25.56±2.71	5.89±0.95

[z] standard error of means.

Table 5.4 shows that the coefficients of variation (CV) for starch content were less when bark and wood were separately tested. This is because the ratio of bark to wood varies between roots with the higher starch content recorded where the proportion of bark to wood is greater. The ratio of bark to wood in the samples tested varied, resulting in a higher root starch content when the proportion of bark was higher.

In order to minimize the variation, the bark of roots above 10 mm in diameter is recommended. Although sampling of this thickness roots might severely damage fruit trees, merely peeling off a small piece of bark as the sample will markedly reduce the damage, when sampling thick roots of productive fruit trees. This sampling method is used in next

section.

Table 5.4 The variation of starch and soluble sugar content in bark and wood of similar roots from the same trees

Materials	Tree	Number of samples	Starch		Soluble sugar	
			% dry matter	CV[z] (%)	% dry matter	CV (%)
1-4 mm root	1	2	12.75±4.00[y]	31.4	4.29±0.39	9.1
1-4 mm root	2	2	11.61±4.09	35.2	7.64±0.66	8.6
wood of 1-4 mm root	1	2	11.57±0.42	3.7	3.63±0.01	0.2
wood of 1-4 mm root	2	2	11.37±0.74	6.5	3.71±0.11	2.9
bark of 1-4 mm root	1	2	28.63±3.52	12.3	4.25±0.11	2.7
bark of 1-4 mm root	2	2	22.49±0.38	1.7	7.54±0.02	0.3

[z] coefficients of variation;
[y] standard error of means.

For the above ground parts of the tree, the wood contained more starch than the bark (Table 5.3). This may be because the starch in the bark and wood was transferred into the root system, while starch in pith (part of the wood sample) remained as stored starch. It is quite difficult to separate pith from wood and in any case it is difficult to get enough pith material to test from one-year-old shoots.

5.4 STORED STARCH AND SOLUBLE SUGAR IN TREES UNDER DIFFERENT CROP LOADS

Table 5.5 shows the yield data recorded for different crop loads. The low crop treatment was significantly lower in yield and crop load than the other two treatment. The chemical thinning treatment for the medium crop did not produce a significantly different crop load from the treatment without thinning and therefore these two could be combined.

Table 5.5 Crop in the first year under low, medium and high crop loads

Treat-ment	Tree	Trunk CSA (cm^2)	Fruit number	Yield (kg)	FFN (No/cm^2)	Cropload (kg/cm^2)
low	1	232	175	25.70	0.68	0.10
low	5	230	61	12.95	0.26	0.06
low	9	232	35	9.95	0.15	0.04
low	**av**		**90.3A**[z]	**16.20A**	**0.36A**	**0.07A**
med	2	191	1081	149.66	5.61	0.78
med	6	211	1067	150.18	4.81	0.68
med	8	182	868	127.79	4.54	0.67
med	**av**		**1005.3B**	**142.54B**	**4.99B**	**0.71B**
high	3	281	1522	207.48	5.40	0.74
high	4	235	1575	192.40	6.45	0.79
high	7	220	835	120.79	3.79	0.55
high	**av**		**1310.7B**	**173.56B**	**5.21B**	**0.69B**

[z] **different capital letters mean significant difference at the 1% level.**

5.4.1 Relationship between Stored Starch and Different Crop Loads

Table 5.6 shows the root starch and soluble sugar content in July, following different crop loading. Starch content in the winter following low crop treatment is significantly (1% level) higher than the medium and high crop loads. This indicates that lower crop loading established 2 weeks after flowering period, increases starch levels in the following winter.

For the average starch content of each tree based on 6 root samples, the standard errors and coefficients of variation are indicated. The maximum coefficient of variation is 11.66%. A theoretical calculation reveals that it needs 33 samples to obtain coefficients of variation of means below 5% level. This would considerably increase the difficulty of root sampling and the work involved in biochemical analysis and for practical reasons a coefficient of variation of 10% may have to be accepted.

Table 5.6 Starch and soluble sugar content in the roots of trees in July following various crop loading

Crop loading	Tree	Starch (% dry matter)	CV[z] (%)	Soluble sugar (% dry matter)	CV (%)
low	1	26.61±1.56[y]	5.87	7.61±0.11	1.37
low	5	28.99±0.74	2.57	6.80±0.29	4.33
low	9	26.50±1.98	7.46	7.49±0.27	3.55
low	**av**	**27.37A[x]**	**3.17**	**7.30c[w]**	2.12
med	2	17.41±0.72	4.13	8.79±0.35	3.95
med	6	14.10±1.55	10.96	9.46±0.31	3.25
med	8	11.37±1.28	11.27	9.72±0.36	3.65
med	**av**	**14.29B**	**6.28**	**9.32a**	**2.21**
high	3	16.53±1.26	7.62	8.64±0.22	2.58
high	4	9.54±1.11	11.66	8.39±0.17	2.04
high	7	22.74±0.43	1.90	7.80±0.30	3.82
high	**av**	**16.27B**	**8.71**	**8.27b**	**1.87**

[z] coefficients of variation;
[y] standard error of means;
[x] **different capital letters mean significant difference at the 1% level;**
[w] **different small letters mean significant difference at the 5% level.**

Table 5.7 shows that root starch content is negatively correlated with fruit number per tree, yield per tree, fruit number per cm^2 of CSA (fruitfulness) and yield per cm^2 of CSA (cropload). Figure 5.1 shows the negative straight line relationship between starch and fruitfulness ($r = -0.91^{**}$).

Table 5.7 Relationships between root starch content in the dormant period and yield or fruit number in the growing season (r values)

Fruit number	Yield	Fruitfulness	Cropload
-0.86**	-0.86**	-0.91**	-0.90**

** **significant at 1% level.**

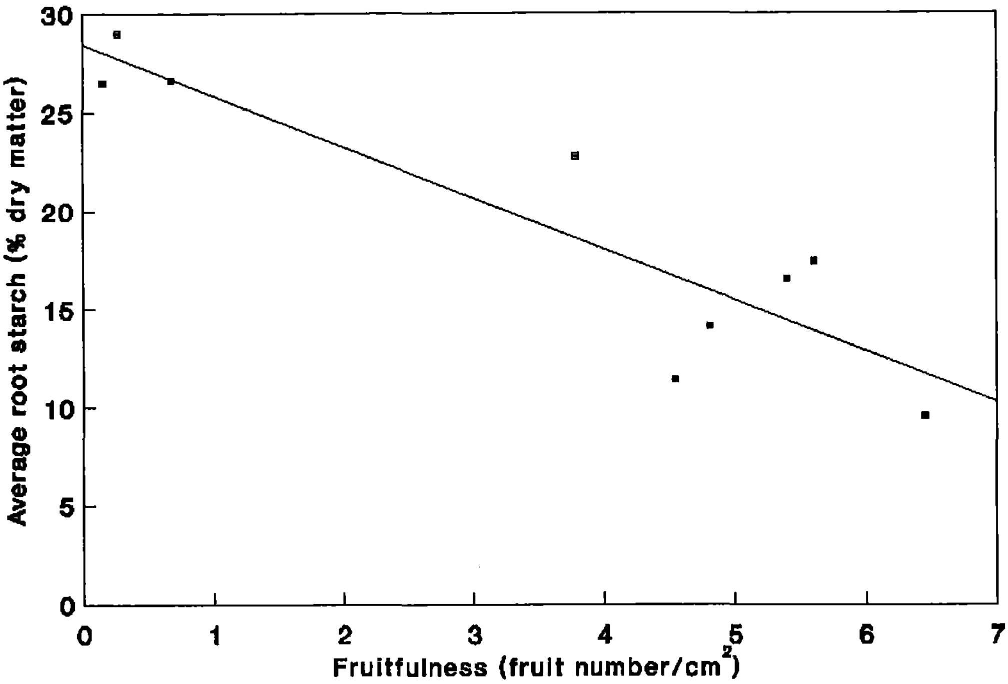

Figure 5.1 Relationship between root starch and fruitfulness

5.4.2 Relationship between Starch and Soluble Sugar

The range of soluble sugar levels throughout the tree, 6.80 to 9.72%, is relatively narrow compared with starch. However, it is a little higher than shown in the analysis for different parts of the tree (section 5.4.1). This investigation was carried out in the coldest period of the year, in mid-July. As observed in section 5.3, root growth is still occurring at this time of the year. Mid September sampling coincides with sap movement when starch utilisation would be expected to lead to a reduction in concentration.

Figure 5.2 shows the relationship between starch and soluble sugar content of all 54 root samples. The negative correlation is expressed by

soluble sugar concentration = 10.50 - 0.11 starch concentration (r = -0.75**)

A decrease in starch concentration of 0.11%, is accompanied by a rise of 1% in soluble sugar concentration. The ratio of starch to sugar is approximately 1:9.

This may reflect the vigour of root growth. Vigorously growing roots contain higher soluble sugar and lower starch. It is unlikely that every root grows with the same vigour at the same time. For slow growing or dormant roots, starch content appears relatively high and soluble

sugar low. This result may vary if frozen soil conditions restrict root growth in some regions.

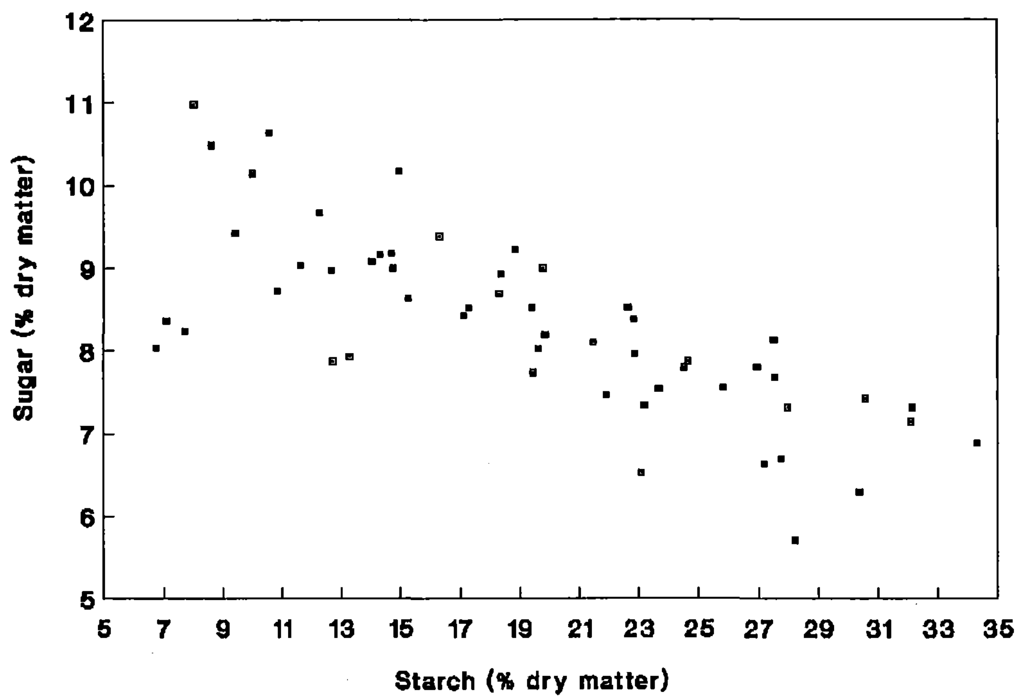

Figure 5.2 Relationship between starch and soluble sugar content in roots

5.4.3 Observation of Root Growth of Apple Trees during the Dormant Period

Plate 5.1 shows root growth against the glass plate from just after December drop 1989 until 17 May 1990. Many new roots without secondary structures are shown in the photograph.

Additional new roots were still observed on 2 July but no photograph was taken at this time. All the new roots were removed at this stage in order to compare subsequent root growth.

Plate 5.2 shows root growth from 2 July to 19 September 1990. During these 68 days of the dormant period, there had been strong new root growth but no secondary root structure was evident.

Plate 5.3 depicts the situation on 27 July 1991 showing extensive new root growth produced during the winter.

It is obvious that new root growth occurs during the winter in Canterbury, New Zealand.

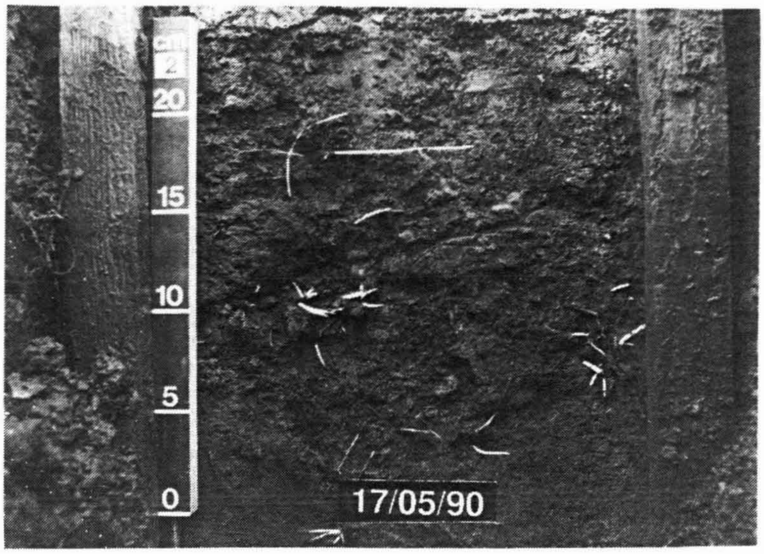

Plate 5.1 Root observation under a glass surface on 17 May 1990

Plate 5.2 Root observation under a glass surface on 19 September 1990

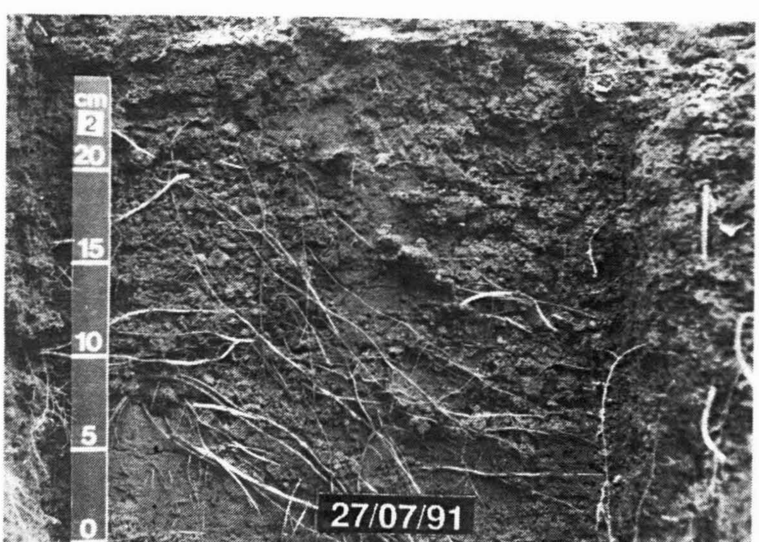

Plate 5.3 Root observation under a glass surface on 27 July 1991

5.4.4 Relationship between the Crop in Two Continuous Years

All 9, 18 year old Granny Smith trees used in this section of the work were left unpruned in the winter following crop adjustment. In the season following, no hand thinning was conducted to provide natural conditions with no human interference. Although the 3 trees under low crop treatment the previous season had many more flowers than the other 6 trees subjected to a heavy crop load the previous season, no significant differences could be found in fruit set between the treatments (Table 5.8). It may be the result of higher starch storage. Higher starch levels in the trees with more flowers could have influenced fruit set.

Table 5.8 Crop in the second year under low, medium and high crop loads

Crop load	Tree	Trunk CSA (cm^2)	Initial fruit set (%)[x]	Fruit number	Yield (kg)	FFN[z] (No/cm^2)	Cropload (kg/cm^2)
low	1	253.13	34.2±16.6[w]	1968	234.40	7.77	0.93
low	5	245.12	22.3±5.9	1366	172.93	5.57	0.71
low	9	239.85	21.1±1.3	1102	145.23	4.59	0.61
low	**av**		**25.9±4.2**[v]	**1478.7a**[y]	**184.19a**	**5.98a**	**0.75a**
med	2	199.74	39.3±5.4	777	116.51	3.89	0.58
med	6	221.85	19.9±2.7	384	65.39	1.73	0.29
med	8	193.41	26.8±9.1	523	86.98	2.70	0.45
med	**av**		**28.6±5.7**	**561.3b**	**89.63b**	**2.77b**	**0.44b**
high	3	290.31	31.5±10.9	810	130.00	2.79	0.45
high	4	254.93	25.8±11.1	163	27.85	0.64	0.11
high	7	241.60	26.1±4.4	297	48.75	1.23	0.20
high	**av**		**27.8±1.9**	**423.3b**	**68.87b**	**1.55b**	**0.25b**

[z] fruitfulness = fruit number / CSA;
[y] different small letters mean significant difference at the 5% level;
[x] no significant difference between treatment;
[w] the mean and standard error for tree is from 3 monitored branches;
[v] the mean and standard error for treatment is from 3 tree average.

The low crop treatment in the previous season showed a significantly higher yield (Table 5.8). Table 5.9 shows the influence of root starch content in the dormant period, on the cropping in the following growing season. All r values in the table are significant at the 5% level. This indicates that high levels of root starch in the dormant period will lead to a heavy crop in the following growing season.

Table 5.9 Relationships between root starch content in the dormant period and cropping in the following growing season (r values)

Fruit number/tree	Yield/tree	Fruitfulness	Cropload
0.76*	0.73*	0.74*	0.69*

* significant at 5% level.

Figure 5.3 shows the relationship between root starch level in the dormant period and the fruit number (per tree) in the following growing season. Fruit number clearly increases with increase in starch levels (r=0.76*).

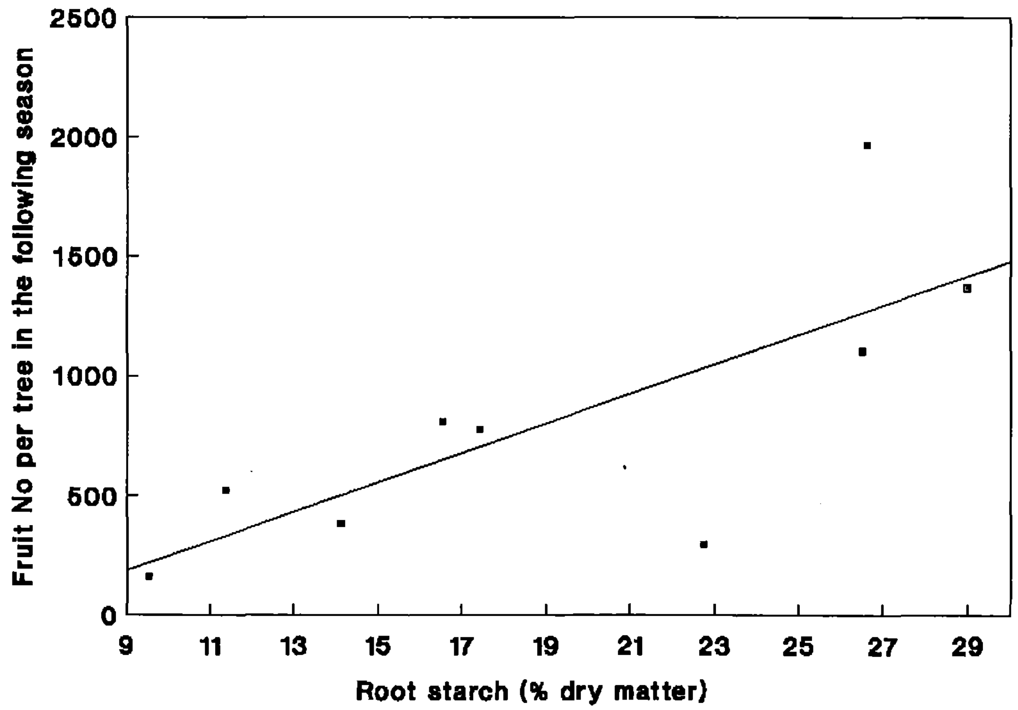

Figure 5.3 Relationship between fruit number in the second year and the root starch content in the dormant period

Table 5.10 shows the relationship of cropping between the first and second seasons. All parameters show negative correlations significant at the 5% level. Figure 5.4 shows the relationship of fruit number per tree between two consecutive years. Higher fruit number

per tree in the first season results in lower fruit number the following season (r = -0.74*).

Table 5.10 Relationships of cropping index between the first and second growing seasons (r values)

Fruit number/tree	Yield/tree	Fruitfulness	Cropload
-0.74*	-0.69*	-0.78*	-0.71*

* significant at 5% level.

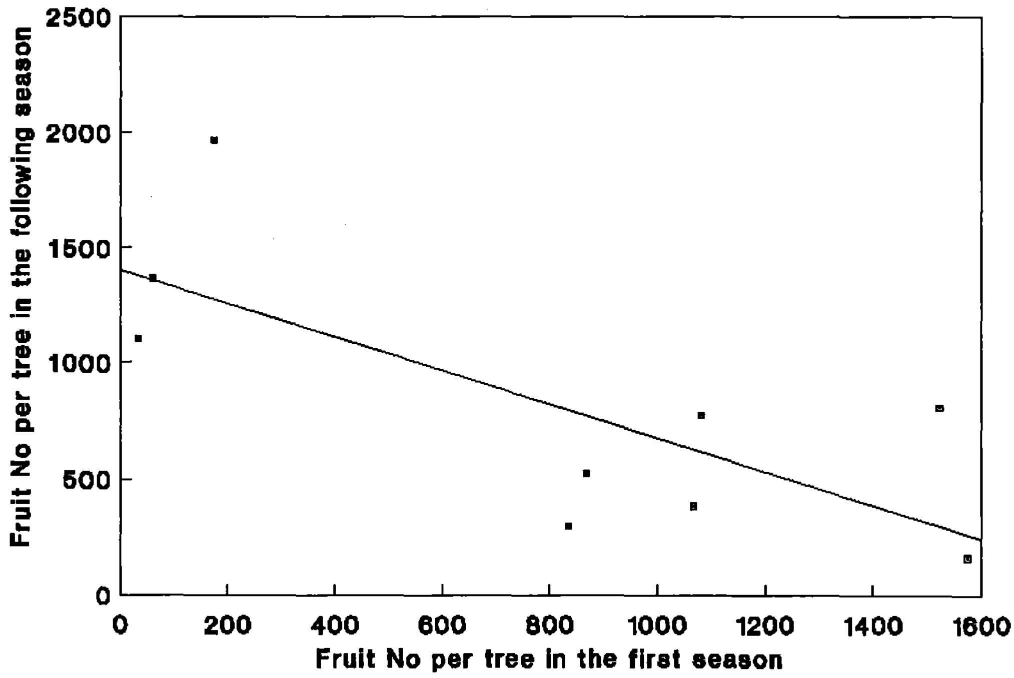

Figure 5.4 Relationship between fruit number in the first and second seasons

CHAPTER 6

DISCUSSION

This chapter discusses the key results of the research comparing pertinent developments with that achieved by previous authors. There are several areas of the model which still need further research and development to enable confident application in a wide range of individual situations. These are identified with recommended direction for the future. One particular area of concern is the prediction of fruit size distribution. One section enlarges on the way that this difficulty can be overcome with development of the data base and subsequent verification.

6.1 MODELLING FROM PHYSIOLOGY TO HUSBANDRY

As reviewed in Chapter 2, there has been considerable progress in the last 10 - 15 years with physiological modelling work in pomology. It is possible now to calculate respiration costs and photosynthesis from budbreak to leaf fall (DeJong, 1986; DeJong and Walton, 1989; Lakso and Johnson, 1990). Analysis of dry matter production show that apple leaves start exporting carbohydrate at 15 - 19 days after budbreak (Johnson and Lakso, 1986a; 1986b) and many models have been constructed to calculate the respiration cost of fruit and wood for the whole growing season. In the near future a complete modelling system, embracing all physiological and production aspects of a fruit tree, will be formulated.

There are still some knowledge gaps in the overall tree system. Alternate bearing is one of the characteristics of apple tree production but most models to date start at budbreak and fail to incorporate alternating perennial aspects (eg Beattie and Folley, 1978). In the research reported in this thesis, yield prediction based on the previous season's fruit number and yield has still not been accurate enough. It is possible that time series analysis could be used in future work on fruit tree modelling but a minimum of 10 years continuous yield records is necessary for alternate bearing research using this technique. This is not easy to obtain. Research on starch storage in the dormancy period endeavoured to understand the linkage between growing seasons. Clearly, a heavy crop in the previous growing season will result in low starch storage during the dormancy period and low flower bud production in the

following season. Apple shoots start exporting carbohydrate at 15 - 19 days after budbreak (Johnson and Lakso, 1986a; 1986b), but it has not been possible to establish shoot termination and total leaf area models of an apple tree for practical purposes before budbreak.

Although models studying respiration effects throughout the whole growing season have included different organs of fruit trees (Lakso and Johnson, 1990), these have not incorporated fruit drop at various stages. Fruit drop may be due to poor initial fruit set, chemical and hand thinning and pre-harvest drop. Some aspects, such as hand thinning, are really beyond the scope of physiological research and fall into the fruit tree husbandry category. The interaction of husbandry and physiological research is an important aspect still to be dealt with in completing the model of the whole system.

6.2 FRUIT SIZE PREDICTION

One of the key parameters in apple forecasting work is fruit size, not only to determine yield but also to predict financial outcomes.

As fruit size is more easily measured than fruit number per tree, many papers attempt to predict final fruit size from the size at an early stage of development, (Batjer *et al.*, 1957; Stolle and Schmidt, 1975). Using fruit size alone does not allow consideration of crop load, as final fruit size is affected by fruit number and a series of climatic factors during the growing season. Winter's (1976) predictive model was based mainly on fruit number after thinning together with regional climatic data. Bergh's (1982) model combined fruit size at 40 days after full bloom with fruit number in both the current and previous seasons. Neither Winter nor Bergh attempted to incorporate the climatic influence in the current season but this thesis has. In New Zealand, December temperatures in some years can be well below average. It has been clearly documented here from historical records that December temperatures influence fruit size; below average temperatures result in below average fruit size. Inclusion of current season's data of this nature is essential for accurate prediction.

The model developed in this work did not include fruit size at an early stage. It is possible that inclusion of fruit size parameters from an early stage will provide more accurate predictions but the problem is multicollinearity in multiple regression calculations (Wesolowsky, 1976). For example, fruit number after thinning usually shows a good

correlation with fruit size and therefore it is not really valid to include both fruit number and fruit size after thinning as independent variables in the same regression formula. There are two options. One is to use these variables in different formulae using expert knowledge to interpret which formula will provide the more exact prediction. The other option is to work on improving the statistical validity with such techniques as principle component analysis.

When the relationship between crop load and fruit size is established, fruit number may be estimated at any stage by determining fruit size at that stage in association with branch sampling.

6.3 FRUIT SIZE DISTRIBUTION

In section 4.10.4.2, the fruit percentage in various grades is estimated by empirical regression formulae. Only grades AA+A and C+D can be estimated from the regression formulae produced. This is useful but for practical application, further work is needed on final fruit size distribution.

Based on the analysis in section 4.9.4 - 4.9.5, fruit distribution is shown as a normal distribution with most standard deviations around 20% of the mean fruit weight. This means that, when each average fruit weight is determined, each standard deviation can be ascertained; that is 20% of the average. A unique normal distribution curve will be ascertained in each case. Figure 6.1 shows the fruit size normal distribution curve based on the following formula solving for probability density Y (Snedecor and Cochran, 1982):

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-\Sigma(x-\mu)^2}{2\sigma^2}} \qquad (6.1)$$

Key for equations 6.1 and 6.2:
μ = mean;
σ = standard deviation;
x = independent variable (individual fruit weight);
a & b = limitation of required individual fruit weight.

Each colour shows a different fruit weight distribution according to the mean fruit weight given in the colour key.

Packed fruit is sorted into various count sizes based on individual fruit weight (Table 6.1). This is shown also in Figures 6.1 and 6.2. The vertical lines in the figures represent the

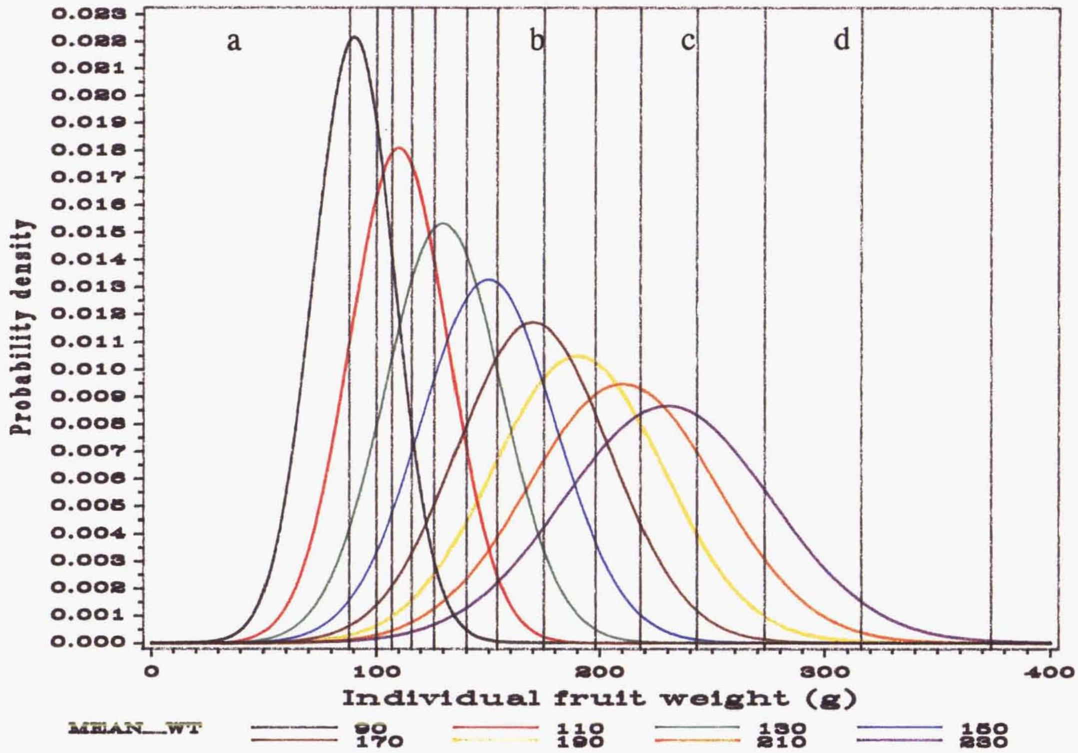

Figure 6.1 Fruit size distribution based on a standard deviation equal to 20% of the mean

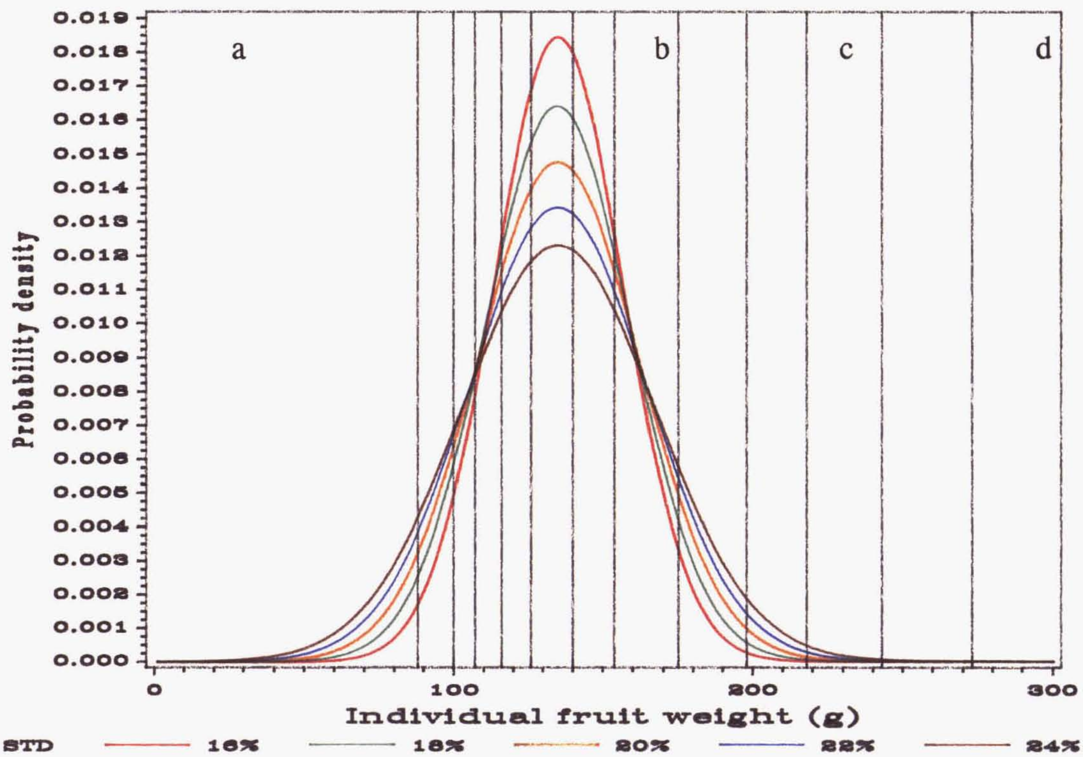

Figure 6.2 Fruit size distribution based on mean weight 135 g with standard deviation varied

boundaries between the number of packed fruit per 18.5 kg carton ranging from 216 fruit/carton labelled 'a' to the left of the figures progressing to the right for lower fruit counts (larger fruit). For example, 'b' = 113 fruit/carton, 'c' = 80 fruit/carton and 'd' = 64 fruit/carton. When the normal distribution curve is fitted, the percentage required of each count size (P) can be calculated based on the following integral calculation:

$$P = \int_b^a \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-\Sigma(x-\mu)^2}{2\sigma^2}} dx \tag{6.2}$$

Here a and b can be chosen as any digit representing a required range. For example, when a and b are 218 and 243 (g) respectively, the fruit falls into count 80 (Table 6.1). In this case equation 6.2 calculates the percentage of fruit in count 80. When μ and σ are decided, the percentage of fruit in each count size can be calculated.

Using a relatively wide range of relative standard deviations of the means from 16 to 24% Figure 6.2 shows the calculated distributions based on a mean fruit weight of 135 g. To make it easy for growers to check the percentage fruit in each count size to match the prices, Appendix 6 provides percentage fruit size distributions for a range of mean fruit weight from 90 - 250 g, for each of the 5 relative standard deviations of the mean. The tables still need practical validation. If growers know their normal, relative standard deviation they could use the table to estimate financial outcomes according to a planned mean fruit weight.

Table 6.1 NZ Apple and Pear Marketing Board grade classifications

Count	216	198	175	163	150	138	125	113	100	88	80	72	64	56	48
Fruit weight (g)	< 88	100	107	116	126	140	154	175	198	218	243	273	316	374	>

6.4 THE COMPLETE PRODUCTION CYCLE

Simulating apple production throughout the season is important in helping the manager to control production more effectively. However, the models developed so far are mainly interested in the final yield (Forshey, 1975; 1976; Winter, 1976; 1983; 1988; Beattie and Folley, 1977; Goldwin, 1982). The model developed in this thesis has established the dynamic process from the flowering period through until harvest, incorporating climatic effects from the stage of initial fruit set.

One of the most difficult sections of this work was dealing with the process of fruit thinning. In 1986, chemical thinning was used to a greater extent in Hawkes Bay than in Nelson and Canterbury but, by 1988, it had become more universal. The monitoring program failed to adjust to this change and the data recorded did not differentiate between the effects of chemical and hand thinning. There was no alternative with the data available but to accept that thinning was the result of both chemical and hand thinning to a greater or less extent. A new monitoring program is needed to incorporate recording of fruit number before chemical thinning, before hand thinning and after hand thinning, so that fruit thinned by chemical and hand means can be separated.

Ideally, orchardists should rely mainly on chemical thinning, supplemented by hand thinning, so that excess fruit is removed as early as possible to avoid nutrient competition. How many fruit should be left on the tree after chemical thinning should be based on the optimum fruit number indicated by the model for the most favourable year. When the temperature pattern for the season is established, more fruit can be removed by hand if necessary as late as December or January, without creating a severe problem. Future research on thinning should be directed towards introducing a refined sub model into the overall fruit tree program.

Apart from the initial fruit drop after fruit set and the so called December drop (southern hemisphere), fruit falling at other stages needs further investigation. Even the initial and December fruit drops are not well documented according to cultivar, nor are axillary and terminal positions of the fruit. Further variation can occur between years and regions. From a practical point of view, understanding these variations is very important in deciding on thinning strategies. For predictive modelling work, the number of fruit on a tree at any one time ultimately determines final fruit size.

On average, only 90% of the fruit remaining after thinning was finally harvested. What happened to the other 10% was not established during the monitoring program. It has an important effect on final fruit size and size distribution and needs further investigation.

Although the starch analysis research was successful in clarifying the sampling methodology and variations in starch levels occurring in the various organs, the main objective of relating starch levels to potential load has not been achieved to the extent that it can be confidently used in practice for prediction. Nevertheless the relationship between bienniality and starch

levels was established but the technique is very time consuming and, at this stage, is unlikely to have practical application in the model.

6.5 CLIMATIC DATA EXPLORATION

Climate varies from season to season affecting the physiology and production of an apple tree. This thesis has incorporated climatic data into the model and identified critical climatic parameters at key times of the year. Temperature is important in estimating fruit growth and ultimate Royal Gala apple fruit size, particularly during the December - January period. Average fruit size is larger when the temperature during these months is higher. Results also showed that higher temperatures during the late winter and early spring period have a negative effect on fruit set.

Some relationships established in this thesis do not have a clear explanation. Although regression for sunshine hours versus initial fruit set produced slightly higher negative r values than using temperature data, logic suggests that sunshine hours should have a relationship with temperature. Similarly, as the number of rain days per month increases, so should the average temperature decrease. But no strong relationship was found between monthly sunshine hours and monthly maximum or monthly minimum temperature. It is not necessary that higher sunshine hours should always correlate with higher maximum temperature. However, higher sunshine hours may be correlated to hourly accumulated temperature. Hourly temperature recording has been established in recent years and used mainly for research into chilling requirements (Anderson, *et al.*, 1986; Anderson and Richardson, 1987). In future, it may be possible to establish a relationship between sunshine hours or rain days and temperatures and perhaps incorporate these in the model. In the meantime temperature is the most practical parameter for orchardists to use.

Although the original monitoring program incorporated light intensity measurements on particular days, this was directed towards tree structure and light penetration rather than to the effect on yield. It is fundamental that light intensity has a relationship to photosynthesis and therefore should influence fruit growth. The question of accumulated solar radiation in relation to the effect on fruit size and ultimate yield is a different consideration. To incorporate this in the model would require suitable meterological data available at all stations in the vicinity of the orchards. Although major stations may be able to supply solar radiation measurements the data was not universally available to test in the model. It is

reasonable to assume that the temperature parameters used in the model closely relate to solar radiation.

It is suggested that climatic investigations in the future should be developed in relation to the stage of development of the tree, rather than calendar date. Relating temperature to days after full bloom for each orchard for each year should provide more accurate information for the model.

6.6 BRANCH SAMPLING AND TREE STRUCTURE

Fruit tree research has always been restricted by the physical difficulty of counting flower buds and fruit on a whole tree. Reliable extrapolation from sampled branches to a whole tree basis is essential if fruit tree modelling work and management information systems are to be useful to individual orchardists.

Considerable effort has been directed in this thesis towards developing effective branch sampling methodology. The use of branch and trunk CSA has been demonstrated as a reliable means of extrapolation. The relationship is more suited to a homogenous individual orchard, managed in a particular way, than to a generalised formula based on the average of a number of orchards. The larger a tree the larger are the primary branches as a general rule. These primary branches also become too large to sample. Relationships between primary, secondary and tertiary branches were investigated also but more detailed monitoring work is still required. Use of the CSA of primary and secondary branches to control the number of flower buds retained during pruning was not entirely satisfactory. The same applies to hand thinning. Some growers use shoot length to control fruit number during thinning. Although this is practical it is not entirely accurate. Further research combining these two methods may provide more practical accuracy.

6.7 DATABASE UTILITY

Roversi *et al.* (1979) established a large data base with 14 apple cultivars collected over 5 years from 15 environments in Northern Italy but did not attempt modelling work with the data. In ecology research, a world wide network "International Tree Ring Data Bank" has been established to share a data base (Fritts and Grissino-Mayer, 1992).

Clearly the work in this thesis has been limited by the extent of the data base although it is still one of the largest data banks ever established for apples. The data was mainly limited to the Gala group of apples. Extension of the data base to other cultivars and districts is an obvious objective but the method of recording and sharing the data needs to be coordinated so that it is accurate, uniformly recorded and interactive. The apple industry needs to address the standardisation of scientific, economic and practical information of this nature. The ideal would be to established an agreed, uniform, international data base which would be suitable to share and develop for modelling research in pomology.

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APPENDICES

Appendix 1 Minimum sampling size from published papers

Object	Sample size	Accuracy	References
diameter of apple fruit	16 ps[z] & 2 pt[y]	5%	Schultz & Schneider, 1955
fruit weight of apple	20-50 ps	--[v]	Müller, 1977
starch in apple trees	4 pt	10-20%	Priestley, 1960
starch and sugar in apple tree	5 pt	20%	Reich, 1985
pressure resistance of apple fruit	20 ps & 6 pt	10%	Schultz & Schneider, 1955
refractive index of apple fruit	16 ps 10 pt	5%	Schultz & Schneider, 1955
fruit juice gravity of cider apples	50 ps	5°	Burroughs & May, 1954
% apples over 2.5"	40 ps & 14 pt	20%	Schultz & Schneider, 1955
% apples over 2.5"	24 ps & 4 pt	40%	Schultz & Schneider, 1955
fruit size of cherries	200 ps & 12 ptree[x]	[n] & 5%	Davidson & George, 1959
fruit colour of peaches	12 ptree & 4 tree pt	10-15%	Marini & Trout, 1984
soluble solids of peach fruit	4 ptree & 4 trees pt	0.5°	Marini & Trout, 1984
refractive index of peach fruit	16 ps & 4 pt	5%	Schultz & Schneider, 1955
fruit firmness of peaches	16 ptree & 6 trees pt	6 N/cm^2	Marini & Trout, 1984
pressure resistance of green peach fruit	20 ps & 4 pt	10%	Schultz & Schneider, 1955
pressure resistance of "ripe" peach fruit	32 ps & 6 pt	10%	Schultz & Schneider, 1955
% peaches over 2"	48 ps & 12 pt	20%	Schultz & Schneider, 1955
% peaches over 2"	20 ps & 4 pt	40%	Schultz & Schneider, 1955
juice soluble solids of citrus fruit	10 ptree	repr[w]	Habeeb & Ismall, 1969
ascorbic acid of citrus fruit	10 ptree	repr	Habeeb & Ismall, 1969
solids/acid ratio of citrus fruit	10 ptree	repr	Habeeb & Ismall, 1969
N, P in citrus fruit pedicels	20 ps	--	Habeeb & Ismall, 1972
leaf area of apples	60 ps	repr	Freeman, 1957
chemical analysis of apple leaves	100 leaves at least from 5 trees	80%[c]	Holland *et al.*, 1967
dry matter of apple leaves	40 ps	10%	Moon & Hymas, 1964

N in apple leaves	40 ps	10%	Moon & Hymas, 1964
P in apple leaves	40 ps	10%	Moon & Hymas, 1964
K in apple leaves	40 or >100 ps	10%	Moon & Hymas, 1964
Ca in apple leaves	40 ps	10%	Moon & Hymas, 1964
Mg in apple leaves	80 or >100 ps	10%	Moon & Hymas, 1964
Fe in apple leaves	100 ps	15%	Moon & Hymas, 1964
Na in apple leaves	40 ps	10%	Moon & Hymas, 1964
chemical analysis of pecan leaves	40 ps & 8 pt	repr	Sharpe & Gammon, 1951
net photosynthesis of peach leaves	18-25 rep[t] & 2-5 treat	2[m]	Elkner & Coston, 1989
net photosynthesis of peach leaves	5-6 rep & 2-5 treat	5[m]	Elkner & Coston, 1989
shoot growth of apples	20-25 ptree	repr	Jolly & Holland, 1957
terminal growth of apples	20 ps & 8 pt	20%	Schultz & Schneider, 1955
trunk circumference of apples	5-20 ps	--	Müller, 1977
tree height of apples	5-10 trees	--	Müller, 1977
terminal shoot length of peaches	6-22 ptree	15%	Marini, 1985
terminal growth of peaches	30 ps & 4 pt	10%	Schultz & Schneider, 1955
TCA[u] of peaches	28 pt	15%	Marini, 1985
increase in TCA of peaches	60-85 pt	15%	Marini, 1985
wood hardiness (twig) of peaches	6-21 ps	0.75-1.0[b]	Cain & Andersen, 1976
yield of apples	15-20 ps	--	Müller, 1977
% set of apple fruiting points	30 branches ps & 10 pt	20%	Schultz & Schneider, 1955
yield of peaches	28-115 pt	15%	Marini, 1985
yield efficiency of peaches	45-109 pt	15%	Marini, 1985
% fruit retained on peaches	16 branches ps & 6 pt	20%	Schultz & Schneider, 1955

[z]ps per sample;
[y]pt per treatment;
[x]ptree per tree;
[w]repr author believed it was representive;
[v]-- author did not metion reason;
[u]TCA trunk cross sectional area;
[t] replication;
[m] mg CO_2/dm^2 per hour;
[b] browning unit;
[c] confidence limits;
[n] author found the distribution was normal and decided on it's use.

Appendix 2 Density, length, diameter, weight and volume of shoots

Shoot No	Density (g/cm^3)	Length (cm)	Diameter (mm)	CSA (cm^2)	Volume (cm^3)	Weight (g)
1	0.87	3.3	0.73	0.41	0.69	0.60
2	0.92	6.3	0.38	0.11	0.87	0.80
3	0.93	4.5	0.46	0.17	0.86	0.80
4	0.94	5.7	0.41	0.13	0.69	0.65
5	0.95	2.7	0.60	0.28	0.95	0.90
6	0.95	3.0	0.87	0.59	1.47	1.40
7	0.96	7.2	0.36	0.10	1.99	1.90
8	0.97	6.6	0.86	0.58	1.64	1.60
9	0.98	2.4	0.67	0.35	1.12	1.10
10	0.99	1.5	0.64	0.32	0.61	0.60
11	1.01	9.0	0.50	0.20	3.03	3.05
12	1.01	6.8	0.81	0.52	5.45	5.50
13	1.01	5.5	0.46	0.17	1.04	1.05
14	1.01	2.8	0.34	0.09	0.35	0.35
15	1.01	68.0	1.22	1.16	67.13	67.95
16	1.03	15.8	0.64	0.32	3.11	3.20
17	1.04	4.5	1.05	0.86	2.51	2.60
18	1.04	7.3	0.75	0.44	2.16	2.25
19	1.04	6.0	0.45	0.16	0.87	0.90
20	1.04	2.0	0.69	0.37	0.86	0.90
21	1.05	15.0	0.61	0.29	4.93	5.15
22	1.05	23.0	0.78	0.48	10.64	11.15
23	1.05	14.8	0.99	0.77	3.72	3.90
24	1.05	8.0	0.59	0.27	3.89	4.10
25	1.05	22.0	0.61	0.29	5.88	6.20
26	1.06	29.0	0.80	0.50	15.90	16.90
27	1.07	7.8	0.57	0.26	3.28	3.50
28	1.07	3.1	0.62	0.30	1.12	1.20
29	1.07	9.6	0.61	0.29	1.73	1.85
30	1.07	3.7	0.78	0.48	1.21	1.30
31	1.08	9.0	0.59	0.27	3.11	3.35

32	1.08	6.7	0.47	0.17	2.51	2.70
33	1.08	25.3	0.63	0.31	6.31	6.80
34	1.08	84.0	1.23	1.19	68.37	73.80
35	1.08	25.7	0.60	0.28	8.13	8.80
36	1.08	25.3	0.55	0.24	4.07	4.40
37	1.08	26.0	0.49	0.19	4.06	4.40
38	1.08	57.2	1.28	1.29	24.29	26.35
39	1.09	10.5	0.83	0.54	7.74	8.40
40	1.09	21.5	0.74	0.43	13.58	14.80
41	1.09	68.7	0.88	0.61	22.92	25.00
42	1.09	64.5	0.73	0.42	15.92	17.40
43	1.09	24.0	0.85	0.57	14.36	15.70
44	1.10	12.0	0.37	0.11	1.64	1.80
45	1.10	7.7	0.52	0.21	2.60	2.85
46	1.10	45.0	0.73	0.42	14.01	15.45
47	1.10	52.9	0.83	0.53	21.54	23.75
48	1.10	9.7	0.60	0.28	3.89	4.30
49	1.11	69.6	1.01	0.79	40.22	44.45
50	1.11	31.7	0.61	0.29	8.04	8.90
51	1.11	24.5	0.75	0.44	10.47	11.60
52	1.11	61.5	0.81	0.52	22.06	24.45
53	1.11	35.5	0.77	0.47	7.79	8.65
54	1.11	14.7	0.66	0.34	4.50	5.00
55	1.11	47.3	0.80	0.50	18.51	20.60
56	1.11	139.0	1.35	1.43	106.75	118.90
57	1.12	72.0	1.09	0.93	49.91	55.70
58	1.12	17.0	0.47	0.17	2.60	2.90
59	1.12	83.2	0.87	0.59	34.34	38.40
60	1.12	95.0	0.93	0.68	38.15	42.70
61	1.12	55.5	0.80	0.50	19.64	22.00
62	1.12	116.0	1.22	1.17	77.36	86.75
63	1.12	38.0	0.84	0.55	16.00	17.95
64	1.12	27.5	0.57	0.26	7.35	8.25
65	1.12	4.4	0.72	0.41	1.56	1.75

66	1.13	11.2	0.44	0.15	1.73	1.95
67	1.13	186.5	1.60	2.00	170.07	192.00
68	1.13	26.1	0.51	0.20	4.15	4.70
69	1.13	41.0	0.84	0.55	13.58	15.40
70	1.13	63.4	0.95	0.71	28.03	31.80
71	1.14	109.5	1.23	1.19	75.61	85.85
72	1.14	60.3	0.83	0.53	23.10	26.25
73	1.14	54.5	0.72	0.41	11.42	13.00
74	1.16	10.9	0.40	0.12	1.12	1.30
75	1.16	4.4	0.44	0.15	0.61	0.70
76	1.16	13.4	0.46	0.17	1.99	2.30
77	1.16	8.0	0.48	0.18	1.99	2.30
78	1.16	2.7	0.49	0.19	0.48	0.55
79	1.16	4.2	0.78	0.48	1.99	2.30
80	1.16	3.1	0.42	0.14	0.35	0.40
81	1.16	3.5	0.36	0.10	0.35	0.40
82	1.16	2.2	0.56	0.25	0.43	0.50
83	1.16	2.0	0.54	0.23	0.43	0.50
84	1.16	3.3	0.46	0.17	0.52	0.60
85	1.18	34.0	0.55	0.24	8.25	9.70
86	1.18	7.0	0.47	0.17	1.82	2.15
For the central axis without branches						
1	1.14	277.0	4.44	15.45	1844.64	2102.85
2	1.13	225.0	3.14	7.74	837.08	949.90
3	1.15	127.0	2.67	5.60	355.15	408.30
For the whole branches						
1	1.13	300.0	4.44	15.45	2626.47	2970.70
2	1.12	256.7	3.14	7.74	1106.27	1242.85
3	1.14	179.9	2.67	5.60	560.10	574.50

Appendix 3 Record for harvested fruit number on each tree or branch

The figures are presented on a per tree basis with column 2 being primary branches and column 3 showing the figures for secondary branches on each individual primary branch.

For example, under Tree 1, the figures in column 1 are for the whole tree:

i 1420/243.36=5.84 represents 1420 fruit/tree with a trunk CSA of 243.36 cm^2 = 5.84 fruit/cm^2 of CSA (ie FFN);

ii 1420/384.65=3.69 represents 1420 fruit/tree with the sum of the CSA of all branches on the tree of 384.65 cm^2 = 3.69 fruit/cm^2 of ΣCSA of the branches.

In column 2, there are 18 primary branches on tree 1. The first branch is recorded as 211/80.98=2.61 representing 211 fruit on the branch with a branch CSA of 80.98 cm^2 = 2.61 fruit/cm^2.

In column 3 the secondary branches on each primary branch are recorded. The first primary branch has 3 secondary branches with 5.36, 3.65 and 1.76 showing the FFN on a per cm^2 CSA basis for the respective secondary branches.

The division into rows (horizontal lines) represents the height above ground level divided into <1.2 m, 1.2 - 2.6 m and >2.6 m.

Tree 1

tree	premary branches	secondary branches	height
		5/ 0.93= 5.36	
	211/80.98 =2.61----	128/35.09= 3.65	
		78/44.32= 1.76	
		6/ 0.59=10.09	
	121/62.39= 1.94----	26/ 6.70= 3.88	
		51/14.39= 3.54	
		30/ 5.90= 5.09	
	________________	________________	1.2 m
		33/ 6.29= 5.25	
	152/34.76= 4.37----	74/ 8.42= 8.78	
		33/ 5.81= 5.68	
		57/ 5.23=10.90	
		13/ 1.77= 7.36	
		12/ 1.43= 8.38	
		27/ 3.70= 7.30	
	408/47.38= 8.61----	8/ 1.84= 4.35	
		92/ 6.51=14.12	
		29/14.79= 1.96	
		131/15.03= 8.71	
1420/243.36=5.84---------		28/ 5.98= 4.68	
1420/384.65=3.69		6/ 4.12= 1.46	
		23/ 7.26= 3.17	
	45/37.13= 1.21-----	19/ 4.15= 4.57	
		9/ 1.81= 4.96	
	85/36.10= 2.35-----	38/15.00= 2.53	
		44/18.78= 2.34	
		46/ 5.77= 7.97	
	129/23.27= 5.54----	9/ 7.55= 1.19	
		60/ 5.45=11.00	
	8/ 1.65= 4.84		
	14/ 1.94= 7.23		
	________________	________________	2.6 m
	13/ 5.15= 2.53		
	8/ 0.97= 8.27		
	40/11.28= 3.55		
	12/ 2.41= 4.99		
	61/20.43= 2.99		
	11/ 0.97=11.37		
	65/ 8.24= 7.88		
	10/ 4.60= 2.17		
	3/ 3.20= 0.94		

<u>Tree 2</u>

tree	premary branches	secondary branches	height
		30/ 9.19= 3.27	
		24/ 9.73= 2.47	
		13/ 2.75= 4.73	
	196/98.60= 1.99	17/ 8.68= 1.96	
		7/ 1.58= 4.42	
		5/ 0.36=13.77	
		93/16.73= 5.56	
		10/ 2.90= 3.45	
	142/45.46= 3.12	119/19.09= 6.23	
		13/12.41= 1.05	
		7/ 1.69= 4.15	
		14/ 7.62= 1.84	
		19/ 3.73= 5.09	
	114/35.09= 3.25	9/ 5.98= 1.50	
		9/ 1.77= 5.09	
		15/ 4.12= 3.64	
1081/192.63= 5.61		29/ 3.11= 9.32	
1081/313.74= 3.44			1.2 m
		11/ 3.56= 3.09	
	133/25.78= 5.16	58/ 7.21= 8.04	
		23/ 1.89=12.19	
		38/ 9.35= 4.06	
		5/ 0.79= 6.37	
		21/ 2.57= 8.16	
	68/17.90= 3.80	11/ 3.17= 3.47	
		8/ 3.60= 2.22	
		22/ 6.16= 3.57	
		11/ 4.19= 2.62	
	31/11.27= 2.75	3/ 2.41= 1.25	
		16/ 4.71= 3.39	
	128/10.71=11.95		
	65/14.19= 4.58		
			2.6 m
	15/ 4.52= 3.32		
	89/18.39= 4.84		
	97/31.83= 3.05		

Tree 3

```
tree                          premary branches        secondary branches        height

                                                   | 15/ 1.54= 9.74
                                                   | 18/ 3.73= 4.82
                                                   | 33/ 8.14= 4.05
                                                   |  8/ 1.96= 4.08
                                                   | 29/ 2.78=10.45
                             |279/76.97= 3.62----  |  4/ 1.15= 3.48
                             |                     |  6/ 1.29= 4.66
                             |                     | 30/ 6.70= 4.48
                             |                     | 21/ 7.16= 2.93
                             |                     | 24/ 4.12= 5.83
                             |                     | 89/ 7.21=12.34
                             |
                             |                     |  1/ 3.14= 0.32
                             |125/66.92= 1.87----  | 77/ 9.73= 7.91
                             |                     | 40/ 9.95= 4.02
                             |
                             |                     |  5/ 5.43= 0.92
                             |                     | 28/ 9.24= 3.03
                             |                     |100/16.95= 5.90
                             |                     |  4/ 0.90= 4.45
                             |212/55.04= 3.85----  | 21/ 1.19=17.67
                             |                     |  9/ 7.12= 1.26
                             |                     | 23/ 4.08= 5.63
                             |                     | 11/ 2.72= 4.05
                             |                     | 11/ 0.92=12.01
                             |
                             |                     | 81/31.83= 2.54
1522/281.72= 5.40--------|264/87.71= 3.01-----     | 23/ 4.71= 4.88
1522/468.16= 3.23            |                     | 18/ 5.73= 3.14
                             |                     |134/49.34= 2.72
                             |________________________________________________ 1.2 m
                             |                     | 10/ 2.72= 3.68
                             |126/54.21= 2.32----  |  7/ 1.54= 4.55
                             |                     | 42/ 7.50= 5.60
                             |                     | 67/18.47= 3.63
                             |
                             | 90/17.43= 5.16----- | 29/ 9.90= 2.93
                             |                     | 61/ 9.73= 6.27
                             |  5/ 0.79= 6.37
                             | 46/ 4.56=10.08
                             |  7/ 1.54= 4.55
                             |  9/ 1.52= 5.93
                             | 33/14.09= 2.34
                             | 29/20.03= 1.45
                             | 20/ 4.71= 4.24
                             |  8/ 0.93= 8.57
                             |  8/ 3.17= 2.52
                             |________________________________________________ 2.6 m
                             | 13/ 2.99= 4.35
                             |130/23.07= 5.63
                             |110/32.47= 3.39
```

Tree 4

tree	premary branches	secondary branches	height
		45/ 8.95= 5.03	
		34/ 5.64= 6.03	
	202/53.38= 3.78----	12/ 2.35= 5.11	
		16/ 3.40= 4.71	
		24/ 5.49= 4.37	
		54/ 7.74= 6.97	
		61/11.34= 5.38	
	104/26.36= 3.95----	13/ 6.18= 2.10	
		18/ 0.88=20.40	
		37/ 3.36=11.02	
	88/16.85= 5.22-----	42/11.49= 3.66	
		7/ 0.38=18.19	
		32/ 3.20= 9.99	
		4/ 0.93= 4.29	
	180/50.74= 3.55----	75/16.19= 4.63	
		29/ 2.84=10.23	
		29/10.58= 2.74	
		9/30.88= 0.29	
			1.2 m
	28/ 9.80= 2.86-----	2/ 1.06= 1.89	
		22/ 4.79= 4.59	
		8/ 1.11= 7.19	
		23/10.18= 2.26	
1575/244.24= 6.45--------		25/ 5.83= 4.29	
1575/372.51= 4.22		3/ 0.88= 3.40	
	162/47.18= 3.43----	6/ 3.94= 1.52	
		12/ 3.70= 3.24	
		8/ 1.25= 6.42	
		6/ 1.65= 3.63	
		50/15.90= 3.14	
		17/ 5.09= 3.34	
		33/ 4.45= 7.42	
		12/ 2.41= 4.99	
	209/63.96= 3.27----	33/ 5.73= 5.76	
		19/ 8.60= 2.21	
		13/ 1.89= 6.89	
		96/23.33= 4.12	
	6/ 0.49=12.24		
		6/ 1.19= 5.05	
		7/ 8.04= 0.87	
	204/27.83= 7.33----	101/ 8.81=11.46	
		22/ 2.60= 8.46	
		68/19.37= 3.51	
		5/ 0.69= 7.20	
		6/ 1.99= 3.02	
	157/19.62= 8.00----	59/ 6.16= 9.58	
		20/ 5.60= 3.57	
		64/ 5.68=11.26	
			2.6 m
	232/56.31= 4.12		

<u>Tree 5</u>

tree	premary branches	secondary branches	height
		123/28.73= 4.28	
	244/58.44= 4.18	29/15.38= 1.89	
		84/21.40= 3.92	
	105/35.43= 2.96	35/ 8.71= 4.02	
		70/19.79= 3.54	
		23/ 2.99= 7.70	
	80/48.16= 1.66	17/16.40= 1.04	
1067/221.85= 4.81		34/20.55= 1.65	
1067/334.28= 3.19			
	113/66.00= 1.71	25/ 4.26= 5.86	
		88/20.47= 4.30	
			1.2 m
	61/13.14= 4.64		
	149/37.47= 3.98	30/ 3.94= 7.61	
		118/11.43=10.32	
	81/26.07= 3.11		
	100/21.14= 4.73	13/ 3.98= 3.27	
		83/19.28= 4.30	
			2.6 m
	134/28.43= 4.71		

Tree 6

tree	premary branches	secondary branches	height
		21/ 6.54= 3.21	
		6/ 2.09= 2.88	
		4/ 1.29= 3.11	
		22/ 6.07= 3.62	
	89/43.57= 2.04	3/ 3.05= 0.98	
		3/ 3.46= 0.87	
		2/ 4.45= 0.45	
		4/ 1.54= 2.60	
		20/ 8.97= 2.23	
		5/ 4.49= 1.11	
	31/34.76= 0.89	16/12.25= 1.31	
		10/13.20= 0.76	
		8/ 1.45= 5.51	
		1/ 1.67= 0.60	
	96/38.87= 2.47	19/ 8.63= 2.20	
		43/ 6.29= 6.84	
		24/ 3.50= 6.86	
		21/13.14= 1.60	
		8/ 3.14= 2.55	
	73/69.25= 1.05	14/ 2.84= 4.94	
835/220.17= 3.79		12/12.44= 0.96	
835/392.52= 2.13		2/17.80= 0.11	
			1.2 m
		57/12.66= 4.50	
	219/77.96= 2.81	53/10.46= 5.07	
		16/ 4.62= 3.46	
		92/ 4.01=22.93	
		17/10.81= 1.57	
		11/ 3.30= 3.33	
	119/49.74= 2.39	16/14.39= 1.11	
		7/ 2.24= 3.12	
		68/28.51= 2.39	
		16/ 5.73= 2.79	
		6/ 1.47= 4.07	
	95/39.93= 2.38	4/ 0.77= 5.20	
		7/ 1.43= 4.89	
		10/ 5.23= 1.91	
		47/ 8.04= 5.84	
	15/ 2.99= 5.02		
	3/ 3.30= 0.91		2.6 m
	95/32.15= 2.95		

Tree 7

tree	premary branches	secondary branches	height
	19/58.87= 0.32-----	11/11.64= 0.94	
		5/20.43= 0.24	
	34/35.09= 0.97-----	20/12.32= 1.62	
		14/ 8.14= 1.72	
		29/12.25= 2.37	
	51/33.44= 1.53-----	4/ 2.91= 1.37	
		15/ 8.30= 1.81	
		34/10.58= 3.21	
		8/ 2.20= 3.63	
		8/ 2.27= 3.52	
868/191.07= 4.54----------	165/41.01= 4.02-----	28/ 7.55= 3.71	
868/304.30= 2.82		12/ 1.99= 6.04	
		9/ 3.46= 2.60	
		16/ 2.60= 6.15	
		44/10.46= 4.21	
			1.2 m
	251/65.09= 3.86----	141/25.64= 5.50	
		110/38.87= 2.83	
	40/ 7.07= 5.66		
	15/ 2.22= 6.77		
	22/14.52= 1.51		
	5/ 0.87= 5.72		
	22/ 8.74= 2.52		
	82/10.61= 7.73		
	59/ 6.70= 8.81		
			2.6 m
	94/20.07= 4.68		

Appendix 4 Average content of starch and soluble sugar in different parts of trees on a per sample basis (2 replicates for each sample before digestion)

Materials	Tree	Sample	Starch	Soluble sugar
shoot	1	1	3.19±0.17[z]	3.57±0.01
shoot	2	1	2.42±0.05	5.62±0.10
spur with fruit	1	1	2.15±0.04	6.01±0.10
spur with fruit	2	1	2.30±0.01	5.95±0.28
spur no fruit	1	1	1.68±0.03	6.14±1.24
spur no fruit	2	1	1.58±0.02	5.48±0.05
wood spur with fruit	1	1	4.15±0.13	5.50±0.18
wood spur with fruit	2	1	3.70±0.14	7.37±0.01
wood spur no fruit	1	1	5.73±0.24	4.27±0.13
wood spur no fruit	2	1	4.38±0.63	5.41±0.04
bark spur with fruit	1	1	0.55±0.04	6.02±0.01
bark spur with fruit	2	1	0.66±0.06	7.70±0.18
bark spur no fruit	1	1	0.86±0.01	5.25±0.08
bark spur no fruit	2	1	0.23±0.01	7.89±0.03
trunk above ground	1	1	1.47±0.01	2.21±0.12
trunk above ground	2	1	0.71±0.06	4.02±0.08
trunk under ground	1	1	2.68±0.11	1.70±0.14
trunk under ground	2	1	1.70±0.04	2.48±0.01
1-4mm root	1	1	7.08±0.01	4.84±0.14
1-4mm root	1	2	18.41±0.03	3.73±0.95
1-4mm root	2	1	5.83±0.21	6.72±1.14
1-4mm root	2	2	17.39±0.17	8.57±0.20
wood of 1-4mm root	1	1	10.96±0.23	3.62±0.14
wood of 1-4mm root	1	2	12.17±0.12	3.64±0.04
wood of 1-4mm root	2	1	10.33±0.32	3.85±0.02
wood of 1-4mm root	2	2	12.40±0.04	3.56±0.05
bark of 1-4mm root	1	1	23.65±0.08	4.09±0.21
bark of 1-4mm root	1	2	33.61±0.20	4.41±0.01
bark of 1-4mm root	2	1	21.95±3.59	7.50±0.02
bark of 1-4mm root	2	2	23.03±0.50	7.57±0.04
4-7 mm root	1	1	11.99±0.21	3.90±0.04

4-7 mm root	1	2	21.61±0.32	4.74±0.10
4-7 mm root	2	1	18.40±0.69	8.16±0.19
4-7 mm root	2	2	22.85±0.54	6.55±0.11
7-10 mm root	1	1	20.95±0.23	4.68±0.21
7-10 mm root	1	2	27.16±0.78	4.77±0.01
7-10 mm root	2	1	20.39±0.25	6.98±0.13
7-10 mm root	2	2	13.71±1.14	6.88±0.19
1cm root	1	1	21.51±0.57	4.56±0.06
1cm root	1	2	20.02±0.08	5.02±0.18
1cm root	2	1	13.45±0.50	7.09±0.10
1cm root	2	2	12.12±0.63	7.08±0.09
2cm root	1	1	15.18±0.15	4.76±0.06
2cm root	1	2	16.02±0.09	3.79±0.09
2cm root	2	1	14.48±0.03	6.26±0.11
2cm root	2	2	13.91±0.01	5.25±0.20
3cm root	1	1	11.58±0.06	4.57±0.03
3cm root	1	2	14.46±0.06	4.46±0.13
3cm root	2	1	10.53±0.21	5.78±0.11
3cm root	2	2	10.17±0.30	5.47±0.02

[z] standard error of means.

Appendix 5 Relationship between trunk CSA and root size

Data is presented to establish the correlation between trunk CSA and the weight of the above and below ground parts of the tree during the dormant period.

Materials and Methods

Thirteen 16 years-old Granny Smith apple trees were pulled out vertically by a tractor in winter 1990 (see section 3.2.2). Trunk circumference, the weight of the above ground and the root system of the trees were measured. The ratio of the weight of the above ground parts to the root system was calculated.

Results

An example of one of the trees removed is shown in Plate A5.1 and a close-up of the root system in Plate A5.2. The removal process caused most of the frame lateral roots to be broken at a distance of 0.5 - 1 m from the trunk at a thickness point of 1.5 - 3 cm.

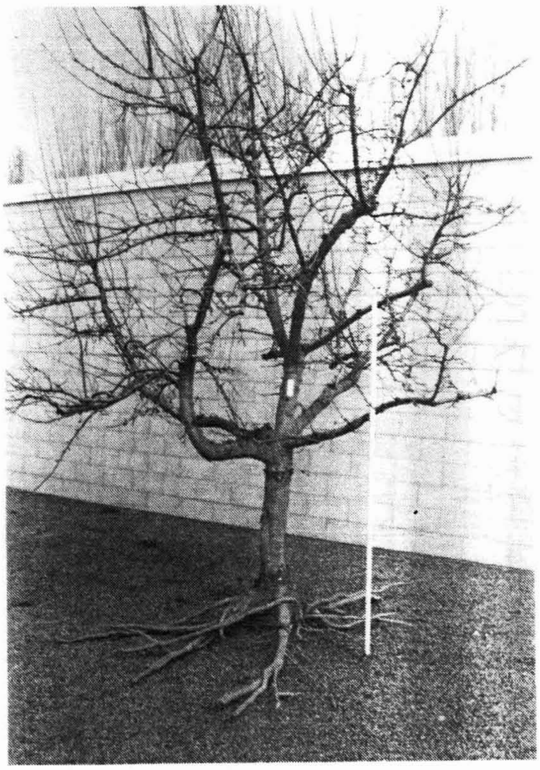

Plate A5.1 The whole tree removed

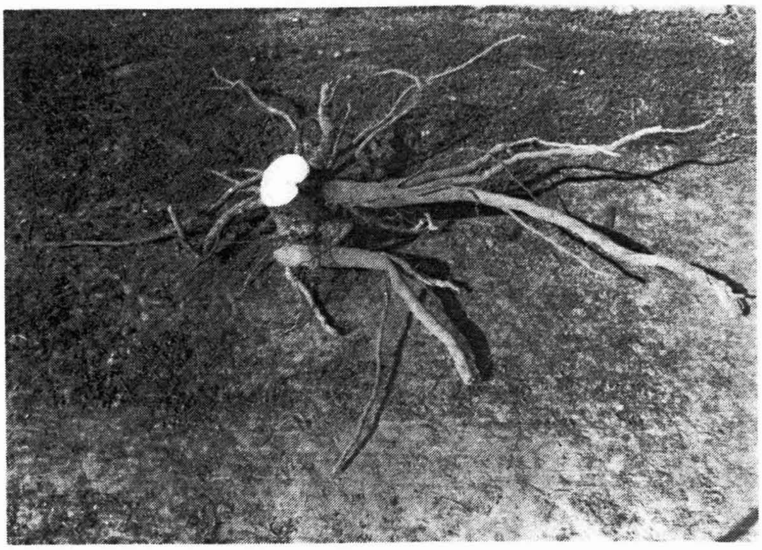

Plate A5.2 The root system removed from the soil

Table A5.1 Measurement of trunk CSA, and the weight of above and below ground parts

Tree No	Trunk CSA (cm^2)	Above ground weight (kg)	Root weight (kg)	Weight ratio (above ground:root)
1	209	93.88	24.06	3.90
2	205	78.96	29.11	2.71
3	200	91.67	25.57	3.59
4	136	38.36	23.31	1.65
5	265	146.65	33.22	4.41
6	216	99.62	28.50	3.50
7	218	99.60	25.07	3.97
8	208	82.48	27.07	3.05
9	169	79.40	22.79	3.48
10	177	79.51	19.61	4.05
11	142	55.63	15.91	3.50
12	204	86.15	25.75	3.35
13	141	82.28	19.38	4.25

The root systems showed a range in size between 15 - 33 kg (Table A5.1) although variability would be expected in proportion of the root actually removed when pulled from the ground.

The root weight correlated to trunk CSA (r=0.85**, Figure A5.1). This correlation was stronger than the correlation between root weight and the above ground weight (r=0.68*). Trunk CSA showed better prediction for root weight than total weight of the above ground parts of trees. This may be because pruning directly influences the weight of the above ground parts of the trees. However, pruning only indirectly influences trunk CSA and root weight.

The ratios of weight of above ground parts to the root system of trees are concentrated around 3.5 (Table A5.1). If the roots remaining in the soil as the result of the removal method were added, this would be quite close to the 3:1 result shown by Murneek (1933). The sample with the highest ratio of 4.41 was the largest tree sampled. Possibly the tractor method of removal led to a greater proportion of the root system being extracted from the soil with a larger tree leading to a higher above ground : root ratio for that tree.

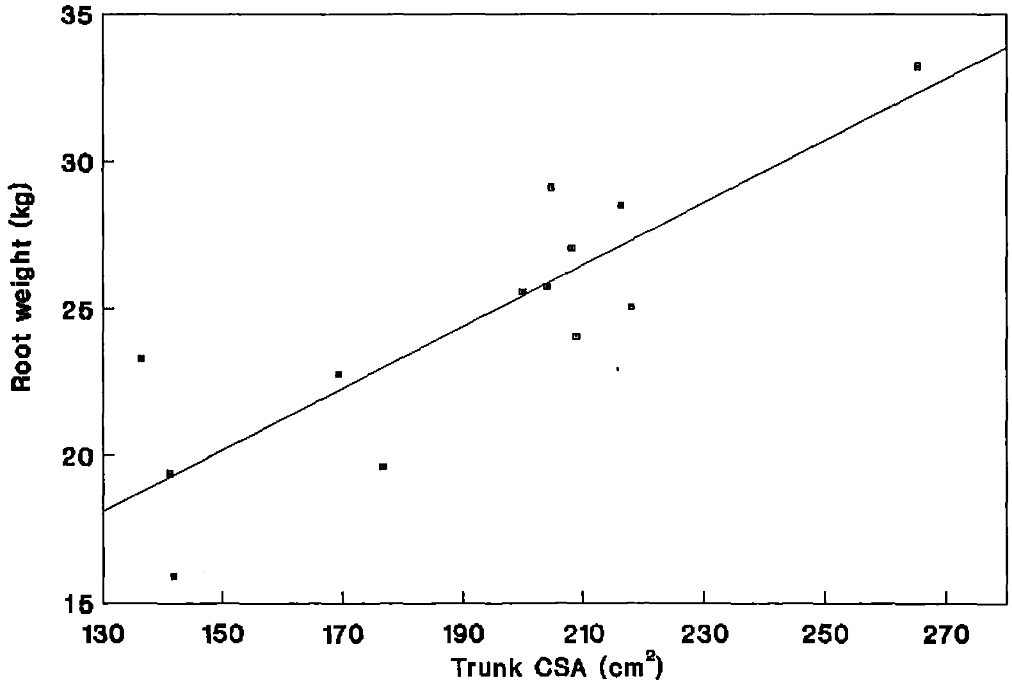

Figure A5.1 Relationship between root system weight and trunk CSA

Correlation of the trunk CSA of apple trees with the ratio of weight of above ground parts to root is shown in Figure A5.2. The ratios were concentrated between 3 and 4 but no clear correlation was found.

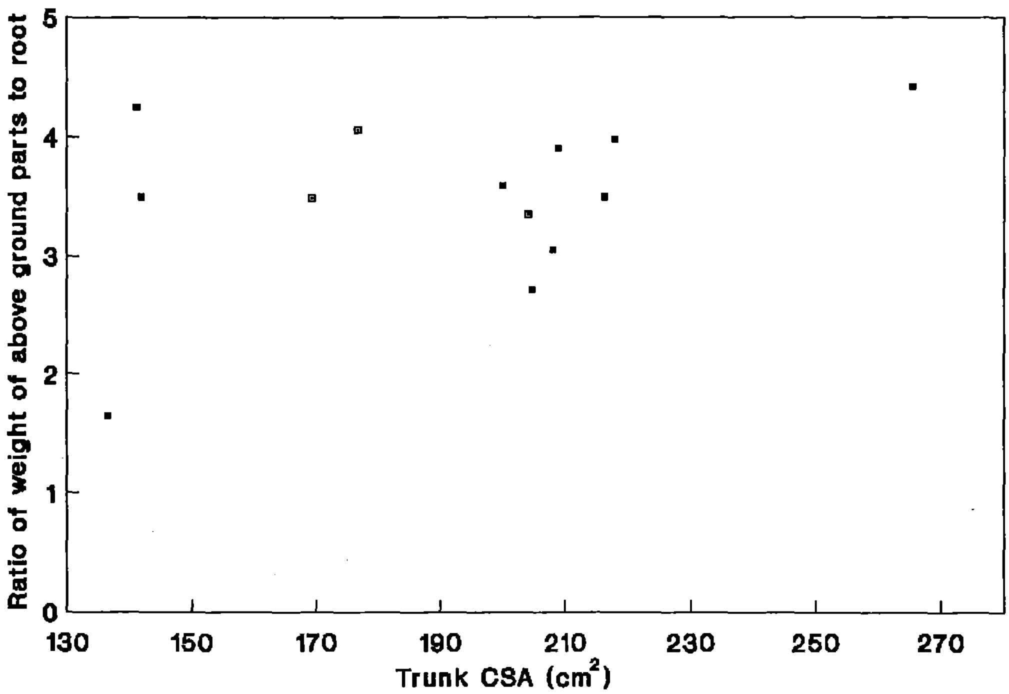

Figure A5.2 Relationship between the ratios of the weight of above ground parts to root of trees and trunk CSA

Appendix 6 % fruit in each count size (based on a standard deviation = 16% of the mean)

Mean fruit weight	216	198	175	163	150	138	125	113	100	88	80	72	64	56	48
90	44.48	31.15	12.48	8.34	2.93	0.60	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	39.29	31.37	13.93	10.26	4.11	0.99	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
94	34.50	31.01	15.13	12.19	5.51	1.56	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
96	30.12	30.15	16.03	14.05	7.10	2.33	0.20	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
98	26.18	28.89	16.63	15.75	8.84	3.34	0.35	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	22.66	27.34	16.91	17.22	10.66	4.59	0.58	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
102	19.55	25.57	16.91	18.42	12.48	6.08	0.92	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
104	16.81	23.69	16.65	19.31	14.23	7.78	1.39	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
106	14.43	21.75	16.18	19.88	15.86	9.67	2.02	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
108	12.36	19.81	15.52	20.14	17.29	11.68	2.81	0.38	0.01	0.00	0.00	0.00	0.00	0.00	0.00
110	10.56	17.93	14.74	20.11	18.49	13.75	3.79	0.61	0.01	0.00	0.00	0.00	0.00	0.00	0.00
112	9.02	16.13	13.86	19.82	19.44	15.82	4.95	0.93	0.02	0.00	0.00	0.00	0.00	0.00	0.00
114	7.70	14.44	12.92	19.31	20.10	17.83	6.29	1.37	0.04	0.00	0.00	0.00	0.00	0.00	0.00
116	6.57	12.86	11.95	18.61	20.50	19.70	7.77	1.96	0.07	0.00	0.00	0.00	0.00	0.00	0.00
118	5.60	11.42	10.99	17.77	20.63	21.39	9.37	2.70	0.13	0.00	0.00	0.00	0.00	0.00	0.00
120	4.78	10.10	10.04	16.83	20.52	22.85	11.05	3.62	0.21	0.00	0.00	0.00	0.00	0.00	0.00
122	4.08	8.91	9.13	15.82	20.19	24.06	12.77	4.73	0.33	0.00	0.00	0.00	0.00	0.00	0.00
124	3.48	7.84	8.26	14.76	19.68	24.99	14.47	6.02	0.50	0.01	0.00	0.00	0.00	0.00	0.00
126	2.97	6.89	7.44	13.70	19.01	25.63	16.13	7.49	0.74	0.02	0.00	0.00	0.00	0.00	0.00
128	2.54	6.04	6.68	12.64	18.21	25.99	17.68	9.13	1.06	0.03	0.00	0.00	0.00	0.00	0.00
130	2.17	5.29	5.98	11.60	17.33	26.09	19.11	10.90	1.47	0.05	0.00	0.00	0.00	0.00	0.00
132	1.86	4.63	5.34	10.61	16.38	25.94	20.36	12.79	2.00	0.09	0.00	0.00	0.00	0.00	0.00
134	1.60	4.04	4.76	9.66	15.39	25.57	21.43	14.75	2.65	0.14	0.00	0.00	0.00	0.00	0.00
136	1.37	3.53	4.23	8.77	14.39	25.00	22.30	16.75	3.44	0.21	0.01	0.00	0.00	0.00	0.00
138	1.18	3.09	3.75	7.94	13.39	24.27	22.96	18.74	4.36	0.31	0.01	0.00	0.00	0.00	0.00
140	1.01	2.69	3.33	7.16	12.40	23.40	23.40	20.69	5.43	0.46	0.02	0.00	0.00	0.00	0.00
142	0.87	2.35	2.95	6.45	11.44	22.43	23.64	22.55	6.63	0.64	0.04	0.00	0.00	0.00	0.00
144	0.75	2.05	2.61	5.80	10.52	21.38	23.68	24.29	7.97	0.89	0.07	0.00	0.00	0.00	0.00
146	0.65	1.79	2.30	5.20	9.64	20.27	23.54	25.88	9.42	1.20	0.10	0.00	0.00	0.00	0.00
148	0.56	1.57	2.04	4.66	8.81	19.13	23.23	27.29	10.97	1.58	0.15	0.00	0.00	0.00	0.00
150	0.49	1.37	1.80	4.17	8.04	17.98	22.77	28.50	12.60	2.04	0.22	0.01	0.00	0.00	0.00
152	0.42	1.20	1.59	3.73	7.31	16.83	22.19	29.51	14.29	2.60	0.32	0.01	0.00	0.00	0.00
154	0.37	1.05	1.40	3.33	6.64	15.71	21.50	30.30	16.00	3.24	0.45	0.02	0.00	0.00	0.00
156	0.32	0.92	1.24	2.97	6.02	14.61	20.73	30.87	17.70	3.97	0.63	0.02	0.00	0.00	0.00
158	0.28	0.81	1.09	2.65	5.45	13.54	19.89	31.22	19.38	4.80	0.84	0.04	0.00	0.00	0.00
160	0.25	0.71	0.97	2.36	4.92	12.53	19.00	31.37	21.01	5.71	1.11	0.06	0.00	0.00	0.00
162	0.22	0.62	0.85	2.11	4.45	11.56	18.08	31.32	22.56	6.71	1.45	0.09	0.00	0.00	0.00
164	0.19	0.55	0.76	1.88	4.01	10.64	17.14	31.09	24.00	7.77	1.85	0.13	0.00	0.00	0.00
166	0.17	0.48	0.67	1.67	3.61	9.78	16.19	30.69	25.32	8.90	2.33	0.18	0.00	0.00	0.00
168	0.15	0.42	0.59	1.49	3.26	8.97	15.25	30.15	26.51	10.08	2.88	0.26	0.00	0.00	0.00
170	0.13	0.37	0.52	1.33	2.93	8.22	14.32	29.47	27.54	11.28	3.52	0.36	0.01	0.00	0.00
172	0.11	0.33	0.46	1.18	2.64	7.51	13.41	28.69	28.42	12.51	4.24	0.48	0.01	0.00	0.00
174	0.10	0.29	0.41	1.06	2.37	6.87	12.53	27.81	29.13	13.73	5.04	0.64	0.02	0.00	0.00
176	0.09	0.26	0.37	0.94	2.13	6.27	11.68	26.85	29.68	14.94	5.92	0.84	0.03	0.00	0.00
178	0.08	0.23	0.33	0.84	1.92	5.71	10.86	25.84	30.07	16.12	6.89	1.08	0.04	0.00	0.00
180	0.07	0.20	0.29	0.75	1.73	5.20	10.09	24.78	30.29	17.25	7.92	1.37	0.06	0.00	0.00
182	0.06	0.18	0.26	0.67	1.55	4.74	9.35	23.69	30.36	18.32	9.01	1.72	0.09	0.00	0.00
184	0.06	0.16	0.23	0.60	1.40	4.31	8.66	22.58	30.29	19.31	10.15	2.13	0.12	0.00	0.00
186	0.05	0.14	0.20	0.54	1.26	3.92	8.00	21.47	30.08	20.23	11.34	2.60	0.17	0.00	0.00
188	0.04	0.13	0.18	0.48	1.13	3.56	7.39	20.36	29.74	21.05	12.56	3.14	0.23	0.00	0.00
190	0.04	0.11	0.16	0.43	1.02	3.24	6.82	19.27	29.29	21.77	13.79	3.75	0.31	0.00	0.00
192	0.04	0.10	0.15	0.39	0.92	2.94	6.28	18.20	28.74	22.39	15.02	4.43	0.42	0.00	0.00
194	0.03	0.09	0.13	0.35	0.82	2.67	5.78	17.15	28.10	22.90	16.25	5.18	0.54	0.00	0.00
196	0.03	0.08	0.12	0.31	0.74	2.43	5.32	16.13	27.39	23.31	17.45	5.99	0.70	0.01	0.00
198	0.03	0.07	0.10	0.28	0.67	2.20	4.89	15.15	26.61	23.61	18.62	6.88	0.89	0.01	0.00
200	0.02	0.07	0.09	0.25	0.60	2.00	4.49	14.20	25.78	23.80	19.74	7.82	1.11	0.01	0.00
202	0.02	0.06	0.08	0.23	0.55	1.82	4.12	13.30	24.90	23.90	20.80	8.83	1.38	0.02	0.00
204	0.02	0.05	0.08	0.20	0.49	1.65	3.78	12.44	23.99	23.89	21.79	9.88	1.70	0.03	0.00
206	0.02	0.05	0.07	0.18	0.44	1.50	3.47	11.62	23.06	23.80	22.71	10.98	2.06	0.04	0.00
208	0.02	0.04	0.06	0.16	0.40	1.36	3.18	10.84	22.12	23.62	23.54	12.11	2.48	0.06	0.00
210	0.01	0.04	0.06	0.15	0.36	1.24	2.92	10.10	21.17	23.36	24.29	13.26	2.96	0.08	0.00
212	0.01	0.04	0.05	0.13	0.33	1.13	2.67	9.40	20.22	23.03	24.94	14.43	3.50	0.11	0.00
214	0.01	0.03	0.05	0.12	0.30	1.03	2.45	8.75	19.28	22.64	25.50	15.61	4.10	0.14	0.00
216	0.01	0.03	0.04	0.11	0.27	0.93	2.25	8.13	18.35	22.18	25.96	16.78	4.76	0.19	0.00
218	0.01	0.03	0.04	0.10	0.24	0.85	2.06	7.56	17.44	21.68	26.32	17.93	5.49	0.25	0.00
220	0.01	0.02	0.03	0.09	0.22	0.77	1.89	7.02	16.54	21.14	26.59	19.07	6.29	0.32	0.00
222	0.01	0.02	0.03	0.08	0.20	0.70	1.73	6.51	15.67	20.55	26.76	20.17	7.15	0.41	0.00
224	0.01	0.02	0.03	0.07	0.18	0.64	1.59	6.04	14.83	19.94	26.85	21.22	8.07	0.51	0.00
226	0.01	0.02	0.03	0.07	0.17	0.59	1.45	5.60	14.02	19.31	26.84	22.23	9.04	0.64	0.00
228	0.01	0.02	0.02	0.06	0.15	0.53	1.33	5.19	13.23	18.66	26.75	23.18	10.08	0.79	0.00
230	0.01	0.01	0.02	0.06	0.14	0.49	1.22	4.81	12.48	17.99	26.59	24.06	11.16	0.97	0.00
232	0.01	0.01	0.02	0.05	0.13	0.44	1.12	4.45	11.75	17.32	26.35	24.88	12.29	1.18	0.01
234	0.00	0.01	0.02	0.05	0.11	0.41	1.03	4.12	11.06	16.64	26.04	25.62	13.45	1.42	0.01
236	0.00	0.01	0.02	0.04	0.10	0.37	0.94	3.82	10.40	15.97	25.67	26.29	14.65	1.69	0.01
238	0.00	0.01	0.01	0.04	0.10	0.34	0.87	3.53	9.77	15.30	25.25	26.88	15.88	2.01	0.02
240	0.00	0.01	0.01	0.04	0.09	0.31	0.80	3.27	9.18	14.63	24.78	27.38	17.12	2.37	0.02
242	0.00	0.01	0.01	0.03	0.08	0.28	0.73	3.03	8.61	13.98	24.26	27.80	18.37	2.77	0.03
244	0.00	0.01	0.01	0.03	0.07	0.26	0.67	2.80	8.08	13.34	23.71	28.14	19.62	3.21	0.04
246	0.00	0.01	0.01	0.03	0.07	0.24	0.62	2.59	7.57	12.71	23.12	28.40	20.87	3.71	0.06
248	0.00	0.01	0.01	0.02	0.06	0.22	0.57	2.40	7.09	12.10	22.51	28.58	22.10	4.25	0.07
250	0.00	0.01	0.01	0.02	0.06	0.20	0.52	2.22	6.64	11.51	21.87	28.68	23.32	4.85	0.10

% fruit in each count size (based on a standard deviation = 18% of the mean)

Mean fruit weight	216	198	175	163	150	138	125	113	100	88	80	72	64	56	48
90	45.09	28.06	12.15	9.27	4.11	1.21	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	40.46	28.09	13.20	10.89	5.36	1.82	0.18	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
94	36.14	27.71	14.03	12.44	6.75	2.60	0.31	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
96	32.17	26.98	14.63	13.86	8.23	3.58	0.50	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
98	28.54	25.97	14.99	15.12	9.75	4.76	0.79	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	25.25	24.75	15.13	16.16	11.27	6.12	1.18	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
102	22.29	23.38	15.07	16.98	12.73	7.63	1.69	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
104	19.64	21.90	14.83	17.56	14.08	9.27	2.35	0.37	0.01	0.00	0.00	0.00	0.00	0.00	0.00
106	17.27	20.38	14.43	17.90	15.28	10.99	3.14	0.58	0.01	0.00	0.00	0.00	0.00	0.00	0.00
108	15.18	18.86	13.91	18.02	16.31	12.74	4.09	0.87	0.03	0.00	0.00	0.00	0.00	0.00	0.00
110	13.33	17.35	13.30	17.93	17.14	14.47	5.17	1.26	0.05	0.00	0.00	0.00	0.00	0.00	0.00
112	11.69	15.89	12.62	17.66	17.77	16.13	6.38	1.77	0.09	0.00	0.00	0.00	0.00	0.00	0.00
114	10.26	14.50	11.90	17.23	18.18	17.68	7.69	2.42	0.15	0.00	0.00	0.00	0.00	0.00	0.00
116	9.00	13.18	11.15	16.68	18.40	19.08	9.08	3.20	0.23	0.00	0.00	0.00	0.00	0.00	0.00
118	7.89	11.95	10.39	16.02	18.43	20.31	10.51	4.14	0.36	0.01	0.00	0.00	0.00	0.00	0.00
120	6.92	10.80	9.64	15.29	18.29	21.33	11.95	5.23	0.53	0.01	0.00	0.00	0.00	0.00	0.00
122	6.08	9.74	8.91	14.51	17.99	22.15	13.37	6.46	0.76	0.03	0.00	0.00	0.00	0.00	0.00
124	5.34	8.77	8.20	13.69	17.57	22.76	14.73	7.83	1.07	0.04	0.00	0.00	0.00	0.00	0.00
126	4.69	7.89	7.53	12.85	17.04	23.15	16.00	9.31	1.46	0.07	0.00	0.00	0.00	0.00	0.00
128	4.13	7.09	6.89	12.02	16.42	23.33	17.17	10.89	1.95	0.11	0.00	0.00	0.00	0.00	0.00
130	3.63	6.36	6.29	11.20	15.73	23.33	18.20	12.53	2.54	0.17	0.01	0.00	0.00	0.00	0.00
132	3.20	5.70	5.73	10.40	15.00	23.15	19.09	14.21	3.24	0.26	0.01	0.00	0.00	0.00	0.00
134	2.83	5.11	5.22	9.63	14.23	22.82	19.83	15.89	4.06	0.37	0.02	0.00	0.00	0.00	0.00
136	2.50	4.57	4.74	8.89	13.45	22.34	20.40	17.55	4.99	0.53	0.04	0.00	0.00	0.00	0.00
138	2.21	4.10	4.30	8.19	12.66	21.76	20.82	19.16	6.03	0.72	0.06	0.00	0.00	0.00	0.00
140	1.95	3.67	3.90	7.53	11.88	21.07	21.07	20.68	7.18	0.97	0.10	0.00	0.00	0.00	0.00
142	1.73	3.29	3.53	6.91	11.11	20.32	21.18	22.10	8.41	1.28	0.14	0.00	0.00	0.00	0.00
144	1.54	2.94	3.19	6.33	10.37	19.50	21.15	23.40	9.72	1.65	0.21	0.01	0.00	0.00	0.00
146	1.37	2.64	2.89	5.79	9.65	18.64	20.99	24.55	11.10	2.09	0.30	0.01	0.00	0.00	0.00
148	1.22	2.36	2.61	5.29	8.96	17.75	20.71	25.55	12.51	2.60	0.41	0.02	0.00	0.00	0.00
150	1.08	2.12	2.36	4.83	8.31	16.85	20.33	26.39	13.95	3.18	0.56	0.03	0.00	0.00	0.00
152	0.97	1.90	2.13	4.41	7.69	15.95	19.87	27.06	15.39	3.84	0.75	0.04	0.00	0.00	0.00
154	0.86	1.71	1.93	4.02	7.10	15.05	19.32	27.56	16.81	4.57	0.98	0.07	0.00	0.00	0.00
156	0.77	1.53	1.74	3.67	6.55	14.17	18.72	27.91	18.20	5.37	1.26	0.10	0.00	0.00	0.00
158	0.69	1.38	1.58	3.34	6.04	13.31	18.07	28.09	19.52	6.24	1.60	0.14	0.00	0.00	0.00
160	0.62	1.24	1.43	3.04	5.56	12.48	17.38	28.13	20.77	7.15	2.00	0.19	0.00	0.00	0.00
162	0.56	1.12	1.29	2.77	5.12	11.68	16.66	28.02	21.94	8.11	2.47	0.27	0.01	0.00	0.00
164	0.50	1.01	1.17	2.52	4.70	10.91	15.93	27.79	23.00	9.10	3.00	0.36	0.01	0.00	0.00
166	0.45	0.91	1.06	2.30	4.32	10.18	15.19	27.44	23.95	10.12	3.59	0.48	0.02	0.00	0.00
168	0.41	0.82	0.96	2.09	3.97	9.48	14.45	26.98	24.79	11.15	4.26	0.63	0.03	0.00	0.00
170	0.37	0.74	0.87	1.91	3.64	8.82	13.71	26.44	25.50	12.17	4.98	0.81	0.04	0.00	0.00
172	0.33	0.67	0.79	1.74	3.34	8.20	12.98	25.81	26.09	13.18	5.78	1.04	0.06	0.00	0.00
174	0.30	0.61	0.71	1.58	3.07	7.61	12.27	25.12	26.55	14.17	6.62	1.30	0.08	0.00	0.00
176	0.27	0.55	0.65	1.44	2.81	7.07	11.58	24.37	26.89	15.12	7.52	1.61	0.11	0.00	0.00
178	0.25	0.50	0.59	1.31	2.58	6.55	10.91	23.58	27.11	16.03	8.47	1.97	0.15	0.00	0.00
180	0.23	0.45	0.54	1.20	2.37	6.07	10.26	22.75	27.21	16.88	9.45	2.39	0.20	0.00	0.00
182	0.21	0.41	0.49	1.09	2.17	5.62	9.64	21.90	27.20	17.67	10.46	2.86	0.27	0.00	0.00
184	0.19	0.37	0.44	1.00	1.99	5.21	9.05	21.04	27.08	18.39	11.49	3.38	0.36	0.00	0.00
186	0.17	0.34	0.40	0.91	1.83	4.82	8.49	20.17	26.87	19.04	12.53	3.96	0.46	0.01	0.00
188	0.16	0.31	0.37	0.83	1.68	4.46	7.95	19.29	26.58	19.61	13.56	4.60	0.59	0.01	0.00
190	0.14	0.28	0.34	0.76	1.54	4.12	7.44	18.42	26.20	20.10	14.59	5.30	0.75	0.01	0.00
192	0.13	0.26	0.31	0.70	1.41	3.81	6.96	17.56	25.75	20.52	15.59	6.05	0.94	0.02	0.00
194	0.12	0.24	0.28	0.64	1.30	3.53	6.50	16.72	25.24	20.85	16.57	6.84	1.16	0.02	0.00
196	0.11	0.22	0.26	0.59	1.19	3.26	6.07	15.89	24.68	21.09	17.51	7.69	1.42	0.03	0.00
198	0.10	0.20	0.24	0.54	1.10	3.01	5.67	15.09	24.06	21.27	18.40	8.57	1.72	0.05	0.00
200	0.09	0.18	0.22	0.49	1.01	2.79	5.29	14.30	23.41	21.36	19.24	9.49	2.07	0.06	0.00
202	0.09	0.17	0.20	0.45	0.93	2.58	4.93	13.55	22.73	21.38	20.02	10.43	2.46	0.09	0.00
204	0.08	0.15	0.18	0.42	0.86	2.38	4.60	12.82	22.03	21.34	20.74	11.40	2.90	0.11	0.00
206	0.07	0.14	0.17	0.38	0.79	2.21	4.29	12.12	21.30	21.23	21.39	12.38	3.39	0.15	0.00
208	0.07	0.13	0.15	0.35	0.73	2.04	3.99	11.44	20.57	21.06	21.98	13.37	3.93	0.20	0.00
210	0.06	0.12	0.14	0.32	0.67	1.89	3.72	10.80	19.82	20.84	22.49	14.35	4.53	0.25	0.00
212	0.06	0.11	0.13	0.30	0.62	1.75	3.47	10.19	19.07	20.56	22.92	15.33	5.18	0.32	0.00
214	0.05	0.10	0.12	0.27	0.57	1.62	3.23	9.60	18.33	20.24	23.29	16.30	5.88	0.40	0.00
216	0.05	0.09	0.11	0.25	0.53	1.50	3.01	9.04	17.59	19.88	23.58	17.24	6.63	0.50	0.00
218	0.05	0.09	0.10	0.23	0.49	1.39	2.80	8.51	16.86	19.49	23.80	18.15	7.43	0.62	0.00
220	0.04	0.08	0.09	0.22	0.45	1.29	2.61	8.01	16.14	19.06	23.95	19.03	8.27	0.76	0.01
222	0.04	0.07	0.09	0.20	0.42	1.19	2.43	7.54	15.43	18.61	24.03	19.87	9.16	0.93	0.01
224	0.04	0.07	0.08	0.18	0.38	1.11	2.27	7.09	14.74	18.13	24.04	20.66	10.09	1.12	0.01
226	0.03	0.06	0.07	0.17	0.36	1.03	2.11	6.66	14.07	17.64	23.99	21.40	11.05	1.33	0.01
228	0.03	0.06	0.07	0.16	0.33	0.95	1.97	6.26	13.41	17.14	23.89	22.09	12.04	1.58	0.02
230	0.03	0.05	0.06	0.15	0.31	0.89	1.83	5.88	12.78	16.62	23.73	22.73	13.06	1.86	0.03
232	0.03	0.05	0.06	0.14	0.28	0.82	1.71	5.52	12.16	16.09	23.52	23.30	14.10	2.18	0.03
234	0.03	0.05	0.06	0.13	0.26	0.76	1.59	5.19	11.57	15.57	23.26	23.82	15.15	2.53	0.04
236	0.02	0.04	0.05	0.12	0.24	0.71	1.49	4.87	11.00	15.04	22.96	24.27	16.20	2.93	0.06
238	0.02	0.04	0.05	0.11	0.23	0.66	1.39	4.57	10.45	14.51	22.62	24.66	17.26	3.36	0.08
240	0.02	0.04	0.04	0.10	0.21	0.62	1.29	4.30	9.93	13.98	22.24	24.99	18.32	3.83	0.10
242	0.02	0.04	0.04	0.09	0.20	0.57	1.21	4.03	9.42	13.46	21.83	25.25	19.37	4.35	0.12
244	0.02	0.03	0.04	0.09	0.18	0.53	1.13	3.79	8.94	12.95	21.40	25.45	20.40	4.90	0.15
246	0.02	0.03	0.04	0.08	0.17	0.50	1.05	3.56	8.48	12.44	20.94	25.60	21.41	5.50	0.19
248	0.02	0.03	0.03	0.08	0.16	0.46	0.98	3.34	8.03	11.94	20.46	25.69	22.39	6.15	0.24
250	0.02	0.03	0.03	0.07	0.15	0.43	0.92	3.13	7.61	11.46	19.97	25.72	23.34	6.83	0.29

% fruit in each count size (based on a standard deviation = 20% of the mean)

Mean fruit weight	216	198	175	163	150	138	125	113	100	88	80	72	64	56	48
90	45.58	25.50	11.68	9.82	5.16	2.00	0.25	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	41.40	25.42	12.44	11.14	6.37	2.78	0.42	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
94	37.48	25.04	13.02	12.37	7.66	3.72	0.65	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
96	33.85	24.41	13.41	13.46	8.97	4.81	0.97	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00
98	30.50	23.57	13.63	14.38	10.26	6.05	1.39	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100	27.43	22.57	13.68	15.13	11.51	7.41	1.93	0.34	0.01	0.00	0.00	0.00	0.00	0.00	0.00
102	24.63	21.47	13.59	15.69	12.66	8.85	2.58	0.52	0.02	0.00	0.00	0.00	0.00	0.00	0.00
104	22.09	20.29	13.36	16.07	13.69	10.34	3.36	0.78	0.03	0.00	0.00	0.00	0.00	0.00	0.00
106	19.79	19.07	13.02	16.26	14.58	11.84	4.26	1.12	0.06	0.00	0.00	0.00	0.00	0.00	0.00
108	17.72	17.83	12.60	16.29	15.32	13.31	5.26	1.56	0.09	0.00	0.00	0.00	0.00	0.00	0.00
110	15.87	16.61	12.10	16.17	15.90	14.72	6.36	2.12	0.15	0.00	0.00	0.00	0.00	0.00	0.00
112	14.20	15.41	11.56	15.92	16.32	16.03	7.53	2.79	0.24	0.01	0.00	0.00	0.00	0.00	0.00
114	12.71	14.25	10.98	15.55	16.57	17.23	8.74	3.60	0.36	0.01	0.00	0.00	0.00	0.00	0.00
116	11.37	13.15	10.38	15.10	16.68	18.28	9.97	4.52	0.53	0.02	0.00	0.00	0.00	0.00	0.00
118	10.18	12.10	9.78	14.57	16.65	19.17	11.20	5.57	0.75	0.03	0.00	0.00	0.00	0.00	0.00
120	9.12	11.11	9.17	13.98	16.49	19.90	12.40	6.73	1.04	0.06	0.00	0.00	0.00	0.00	0.00
122	8.17	10.19	8.57	13.35	16.22	20.45	13.55	7.99	1.40	0.09	0.00	0.00	0.00	0.00	0.00
124	7.33	9.33	7.99	12.70	15.86	20.85	14.62	9.33	1.84	0.13	0.01	0.00	0.00	0.00	0.00
126	6.58	8.53	7.43	12.03	15.43	21.07	15.60	10.73	2.38	0.20	0.01	0.00	0.00	0.00	0.00
128	5.91	7.79	6.90	11.36	14.92	21.15	16.47	12.17	3.01	0.29	0.02	0.00	0.00	0.00	0.00
130	5.31	7.12	6.39	10.69	14.37	21.09	17.23	13.62	3.73	0.41	0.03	0.00	0.00	0.00	0.00
132	4.78	6.49	5.91	10.04	13.79	20.90	17.86	15.06	4.55	0.56	0.05	0.00	0.00	0.00	0.00
134	4.30	5.92	5.46	9.40	13.18	20.59	18.37	16.47	5.46	0.76	0.08	0.00	0.00	0.00	0.00
136	3.88	5.40	5.03	8.79	12.55	20.19	18.75	17.82	6.45	1.00	0.12	0.00	0.00	0.00	0.00
138	3.50	4.93	4.64	8.20	11.92	19.70	19.01	19.10	7.52	1.30	0.18	0.01	0.00	0.00	0.00
140	3.16	4.49	4.27	7.64	11.29	19.15	19.15	20.29	8.65	1.65	0.26	0.01	0.00	0.00	0.00
142	2.86	4.10	3.93	7.11	10.66	18.53	19.18	21.37	9.83	2.06	0.35	0.02	0.00	0.00	0.00
144	2.59	3.74	3.62	6.60	10.05	17.88	19.10	22.33	11.05	2.53	0.48	0.03	0.00	0.00	0.00
146	2.35	3.41	3.32	6.13	9.46	17.19	18.93	23.17	12.28	3.06	0.64	0.04	0.00	0.00	0.00
148	2.13	3.11	3.06	5.68	8.88	16.48	18.68	23.88	13.53	3.66	0.84	0.07	0.00	0.00	0.00
150	1.94	2.84	2.81	5.27	8.33	15.76	18.36	24.46	14.75	4.31	1.07	0.09	0.00	0.00	0.00
152	1.76	2.60	2.58	4.88	7.80	15.03	17.97	24.91	15.95	5.02	1.36	0.13	0.00	0.00	0.00
154	1.61	2.37	2.37	4.51	7.30	14.31	17.53	25.23	17.11	5.77	1.69	0.19	0.01	0.00	0.00
156	1.46	2.17	2.18	4.18	6.82	13.59	17.04	25.43	18.21	6.57	2.08	0.26	0.01	0.00	0.00
158	1.34	1.98	2.01	3.86	6.37	12.89	16.52	25.51	19.25	7.40	2.52	0.34	0.01	0.00	0.00
160	1.22	1.82	1.84	3.57	5.94	12.20	15.96	25.47	20.21	8.26	3.02	0.45	0.02	0.00	0.00
162	1.12	1.66	1.70	3.30	5.54	11.53	15.39	25.34	21.09	9.13	3.57	0.59	0.03	0.00	0.00
164	1.02	1.53	1.56	3.06	5.16	10.89	14.81	25.11	21.87	10.01	4.18	0.76	0.04	0.00	0.00
166	0.94	1.40	1.44	2.83	4.81	10.26	14.21	24.80	22.56	10.89	4.85	0.96	0.06	0.00	0.00
168	0.86	1.29	1.32	2.61	4.48	9.67	13.61	24.41	23.15	11.76	5.56	1.19	0.09	0.00	0.00
170	0.79	1.18	1.22	2.42	4.17	9.10	13.02	23.95	23.64	12.61	6.31	1.47	0.12	0.00	0.00
172	0.73	1.09	1.12	2.24	3.88	8.55	12.43	23.43	24.04	13.43	7.11	1.78	0.16	0.00	0.00
174	0.67	1.00	1.04	2.07	3.61	8.04	11.85	22.87	24.33	14.22	7.94	2.15	0.22	0.00	0.00
176	0.62	0.92	0.96	1.92	3.36	7.55	11.28	22.27	24.53	14.96	8.79	2.56	0.29	0.00	0.00
178	0.57	0.85	0.88	1.77	3.13	7.08	10.72	21.63	24.65	15.65	9.67	3.01	0.38	0.01	0.00
180	0.53	0.78	0.82	1.64	2.91	6.65	10.18	20.97	24.67	16.30	10.55	3.52	0.48	0.01	0.00
182	0.49	0.72	0.75	1.52	2.71	6.23	9.66	20.29	24.61	16.88	11.44	4.07	0.61	0.01	0.00
184	0.45	0.67	0.70	1.41	2.52	5.84	9.16	19.59	24.48	17.40	12.33	4.66	0.76	0.02	0.00
186	0.42	0.62	0.65	1.31	2.34	5.47	8.67	18.89	24.28	17.87	13.21	5.31	0.94	0.02	0.00
188	0.39	0.57	0.60	1.21	2.18	5.13	8.21	18.18	24.01	18.27	14.07	5.99	1.16	0.03	0.00
190	0.36	0.53	0.55	1.13	2.03	4.81	7.76	17.48	23.69	18.60	14.91	6.71	1.40	0.05	0.00
192	0.34	0.49	0.51	1.05	1.89	4.50	7.33	16.78	23.31	18.87	15.71	7.46	1.68	0.06	0.00
194	0.31	0.46	0.48	0.97	1.76	4.22	6.93	16.09	22.89	19.08	16.48	8.24	2.00	0.08	0.00
196	0.29	0.42	0.44	0.90	1.64	3.95	6.54	15.41	22.43	19.23	17.21	9.05	2.36	0.11	0.00
198	0.27	0.39	0.41	0.84	1.53	3.70	6.18	14.74	21.93	19.32	17.89	9.88	2.77	0.14	0.00
200	0.26	0.37	0.38	0.78	1.43	3.47	5.83	14.09	21.41	19.36	18.52	10.72	3.21	0.19	0.00
202	0.24	0.34	0.36	0.73	1.33	3.25	5.50	13.46	20.86	19.34	19.09	11.57	3.70	0.24	0.00
204	0.22	0.32	0.33	0.68	1.24	3.04	5.18	12.84	20.29	19.27	19.62	12.42	4.24	0.30	0.00
206	0.21	0.30	0.31	0.63	1.16	2.85	4.89	12.24	19.71	19.16	20.08	13.26	4.82	0.38	0.00
208	0.20	0.28	0.29	0.59	1.09	2.67	4.61	11.67	19.12	19.00	20.49	14.10	5.44	0.47	0.00
210	0.18	0.26	0.27	0.55	1.01	2.50	4.34	11.11	18.52	18.80	20.85	14.92	6.10	0.58	0.00
212	0.17	0.24	0.25	0.51	0.95	2.35	4.09	10.58	17.92	18.56	21.14	15.72	6.80	0.70	0.01
214	0.16	0.22	0.23	0.48	0.89	2.20	3.86	10.06	17.32	18.30	21.37	16.50	7.54	0.85	0.01
216	0.15	0.21	0.22	0.45	0.83	2.07	3.64	9.57	16.72	18.00	21.56	17.25	8.32	1.02	0.01
218	0.14	0.20	0.20	0.42	0.78	1.94	3.43	9.09	16.12	17.68	21.68	17.96	9.13	1.21	0.02
220	0.13	0.18	0.19	0.39	0.73	1.82	3.23	8.64	15.53	17.33	21.75	18.64	9.96	1.43	0.02
222	0.13	0.17	0.18	0.37	0.68	1.71	3.04	8.21	14.95	16.97	21.78	19.28	10.82	1.68	0.03
224	0.12	0.16	0.17	0.35	0.64	1.60	2.87	7.79	14.38	16.59	21.75	19.87	11.70	1.96	0.04
226	0.11	0.15	0.16	0.32	0.60	1.51	2.70	7.40	13.82	16.20	21.68	20.42	12.60	2.27	0.05
228	0.11	0.14	0.15	0.30	0.56	1.42	2.55	7.02	13.27	15.79	21.57	20.92	13.50	2.61	0.07
230	0.10	0.13	0.14	0.29	0.53	1.33	2.40	6.67	12.74	15.38	21.42	21.38	14.42	2.99	0.09
232	0.10	0.13	0.13	0.27	0.50	1.25	2.27	6.33	12.22	14.96	21.23	21.79	15.33	3.40	0.11
234	0.09	0.12	0.12	0.25	0.47	1.18	2.14	6.00	11.72	14.53	21.00	22.14	16.25	3.85	0.14
236	0.09	0.11	0.12	0.24	0.44	1.11	2.02	5.69	11.23	14.11	20.75	22.45	17.15	4.33	0.17
238	0.08	0.11	0.11	0.22	0.41	1.04	1.91	5.40	10.75	13.68	20.46	22.71	18.04	4.85	0.21
240	0.08	0.10	0.10	0.21	0.39	0.98	1.80	5.12	10.29	13.26	20.16	22.92	18.92	5.41	0.26
242	0.07	0.09	0.10	0.20	0.37	0.93	1.70	4.86	9.85	12.83	19.82	23.08	19.78	5.99	0.32
244	0.07	0.09	0.09	0.19	0.34	0.87	1.60	4.61	9.42	12.42	19.47	23.20	20.61	6.62	0.39
246	0.07	0.08	0.09	0.18	0.32	0.82	1.51	4.38	9.01	12.00	19.10	23.27	21.42	7.28	0.46
248	0.06	0.08	0.08	0.17	0.31	0.78	1.43	4.15	8.62	11.59	18.72	23.30	22.19	7.97	0.55
250	0.06	0.08	0.08	0.16	0.29	0.73	1.35	3.94	8.24	11.19	18.32	23.29	22.93	8.68	0.66

% fruit in each count size (based on a standard deviation = 22% of the mean)

Mean fruit weight	216	198	175	163	150	138	125	113	100	88	80	72	64	56	48
90	45.98	23.35	11.15	10.07	6.01	2.87	0.52	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	42.17	23.20	11.70	11.15	7.14	3.76	0.78	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
94	38.59	22.83	12.11	12.11	8.28	4.78	1.12	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
96	35.24	22.27	12.37	12.94	9.41	5.91	1.56	0.29	0.01	0.00	0.00	0.00	0.00	0.00	0.00
98	32.14	21.56	12.49	13.63	10.49	7.13	2.10	0.45	0.02	0.00	0.00	0.00	0.00	0.00	0.00
100	29.27	20.73	12.48	14.16	11.49	8.41	2.75	0.67	0.03	0.00	0.00	0.00	0.00	0.00	0.00
102	26.63	19.81	12.37	14.55	12.39	9.72	3.49	0.97	0.06	0.00	0.00	0.00	0.00	0.00	0.00
104	24.22	18.84	12.16	14.79	13.18	11.03	4.34	1.35	0.09	0.00	0.00	0.00	0.00	0.00	0.00
106	22.01	17.84	11.86	14.89	13.85	12.31	5.26	1.82	0.15	0.00	0.00	0.00	0.00	0.00	0.00
108	20.00	16.82	11.50	14.86	14.38	13.53	6.26	2.40	0.23	0.01	0.00	0.00	0.00	0.00	0.00
110	18.16	15.81	11.09	14.72	14.78	14.67	7.30	3.09	0.35	0.01	0.00	0.00	0.00	0.00	0.00
112	16.50	14.81	10.65	14.49	15.06	15.71	8.38	3.89	0.50	0.02	0.00	0.00	0.00	0.00	0.00
114	14.99	13.84	10.17	14.17	15.21	16.62	9.46	4.79	0.71	0.04	0.00	0.00	0.00	0.00	0.00
116	13.63	12.91	9.68	13.78	15.24	17.41	10.53	5.78	0.97	0.06	0.00	0.00	0.00	0.00	0.00
118	12.39	12.01	9.18	13.34	15.17	18.06	11.56	6.87	1.30	0.10	0.01	0.00	0.00	0.00	0.00
120	11.27	11.16	8.69	12.86	15.01	18.58	12.55	8.03	1.70	0.15	0.01	0.00	0.00	0.00	0.00
122	10.26	10.36	8.19	12.34	14.77	18.95	13.46	9.24	2.18	0.21	0.02	0.00	0.00	0.00	0.00
124	9.35	9.60	7.71	11.81	14.46	19.20	14.30	10.50	2.74	0.31	0.03	0.00	0.00	0.00	0.00
126	8.52	8.89	7.24	11.26	14.09	19.32	15.05	11.77	3.39	0.42	0.04	0.00	0.00	0.00	0.00
128	7.77	8.23	6.79	10.71	13.67	19.33	15.71	13.04	4.11	0.58	0.07	0.00	0.00	0.00	0.00
130	7.10	7.61	6.35	10.16	13.21	19.23	16.26	14.29	4.91	0.77	0.10	0.00	0.00	0.00	0.00
132	6.49	7.04	5.94	9.62	12.73	19.04	16.71	15.50	5.78	1.00	0.15	0.01	0.00	0.00	0.00
134	5.93	6.51	5.55	9.09	12.23	18.76	17.06	16.66	6.72	1.28	0.21	0.01	0.00	0.00	0.00
136	5.43	6.01	5.18	8.57	11.72	18.41	17.31	17.75	7.71	1.61	0.29	0.02	0.00	0.00	0.00
138	4.98	5.56	4.83	8.07	11.20	17.99	17.46	18.76	8.74	1.99	0.39	0.03	0.00	0.00	0.00
140	4.57	5.13	4.50	7.59	10.68	17.53	17.53	19.68	9.81	2.42	0.53	0.04	0.00	0.00	0.00
142	4.19	4.75	4.19	7.13	10.16	17.02	17.51	20.50	10.89	2.90	0.69	0.06	0.00	0.00	0.00
144	3.86	4.39	3.90	6.70	9.66	16.48	17.41	21.22	11.98	3.44	0.89	0.09	0.00	0.00	0.00
146	3.55	4.06	3.63	6.28	9.16	15.92	17.24	21.84	13.06	4.02	1.12	0.12	0.00	0.00	0.00
148	3.27	3.75	3.38	5.89	8.68	15.33	17.01	22.34	14.12	4.65	1.40	0.17	0.01	0.00	0.00
150	3.01	3.47	3.14	5.52	8.21	14.74	16.73	22.74	15.15	5.32	1.73	0.23	0.01	0.00	0.00
152	2.78	3.22	2.92	5.16	7.76	14.14	16.40	23.04	16.13	6.03	2.10	0.31	0.01	0.00	0.00
154	2.57	2.98	2.72	4.83	7.33	13.54	16.03	23.23	17.07	6.76	2.51	0.41	0.02	0.00	0.00
156	2.38	2.76	2.53	4.52	6.91	12.95	15.62	23.33	17.94	7.51	2.98	0.53	0.03	0.00	0.00
158	2.20	2.56	2.36	4.23	6.52	12.37	15.19	23.34	18.75	8.28	3.49	0.68	0.05	0.00	0.00
160	2.04	2.37	2.19	3.96	6.14	11.79	14.74	23.27	19.48	9.05	4.05	0.85	0.07	0.00	0.00
162	1.89	2.20	2.04	3.70	5.78	11.23	14.27	23.12	20.14	9.82	4.65	1.06	0.09	0.00	0.00
164	1.76	2.05	1.90	3.46	5.44	10.68	13.79	22.89	20.72	10.58	5.30	1.30	0.12	0.00	0.00
166	1.63	1.90	1.77	3.24	5.12	10.16	13.30	22.61	21.22	11.32	5.97	1.58	0.17	0.00	0.00
168	1.52	1.77	1.65	3.03	4.82	9.65	12.81	22.27	21.64	12.04	6.68	1.90	0.22	0.00	0.00
170	1.42	1.65	1.54	2.83	4.53	9.15	12.32	21.88	21.98	12.74	7.42	2.25	0.29	0.00	0.00
172	1.32	1.53	1.44	2.65	4.26	8.68	11.83	21.44	22.24	13.39	8.18	2.65	0.37	0.01	0.00
174	1.23	1.43	1.34	2.48	4.01	8.23	11.35	20.97	22.42	14.02	8.95	3.09	0.47	0.01	0.00
176	1.15	1.33	1.25	2.32	3.77	7.80	10.87	20.47	22.53	14.59	9.72	3.57	0.60	0.01	0.00
178	1.08	1.24	1.17	2.18	3.54	7.38	10.41	19.95	22.58	15.13	10.50	4.08	0.74	0.02	0.00
180	1.01	1.16	1.10	2.04	3.33	6.99	9.95	19.40	22.55	15.61	11.28	4.64	0.91	0.03	0.00
182	0.94	1.08	1.02	1.91	3.13	6.61	9.51	18.84	22.47	16.04	12.05	5.23	1.11	0.04	0.00
184	0.89	1.01	0.96	1.79	2.95	6.26	9.08	18.27	22.32	16.43	12.80	5.85	1.34	0.06	0.00
186	0.83	0.95	0.90	1.68	2.77	5.92	8.66	17.69	22.13	16.76	13.53	6.51	1.60	0.07	0.00
188	0.78	0.89	0.84	1.58	2.61	5.60	8.26	17.11	21.89	17.04	14.23	7.19	1.89	0.10	0.00
190	0.73	0.83	0.79	1.48	2.45	5.29	7.87	16.53	21.60	17.26	14.91	7.89	2.22	0.13	0.00
192	0.69	0.78	0.74	1.39	2.31	5.01	7.50	15.95	21.28	17.44	15.55	8.61	2.59	0.17	0.00
194	0.65	0.73	0.69	1.31	2.17	4.73	7.14	15.38	20.92	17.57	16.15	9.34	3.00	0.21	0.00
196	0.61	0.69	0.65	1.23	2.05	4.48	6.80	14.81	20.54	17.65	16.71	10.08	3.44	0.27	0.00
198	0.58	0.65	0.61	1.15	1.93	4.23	6.47	14.25	20.13	17.69	17.23	10.82	3.92	0.33	0.00
200	0.55	0.61	0.58	1.09	1.82	4.00	6.16	13.70	19.69	17.69	17.70	11.57	4.44	0.42	0.00
202	0.52	0.57	0.54	1.02	1.71	3.79	5.86	13.17	19.24	17.64	18.13	12.31	4.99	0.51	0.01
204	0.49	0.54	0.51	0.96	1.62	3.58	5.57	12.65	18.77	17.56	18.51	13.03	5.58	0.62	0.01
206	0.46	0.51	0.48	0.91	1.52	3.39	5.30	12.14	18.30	17.45	18.85	13.75	6.20	0.75	0.01
208	0.44	0.48	0.45	0.85	1.44	3.21	5.03	11.64	17.81	17.30	19.13	14.44	6.86	0.90	0.01
210	0.41	0.45	0.43	0.81	1.36	3.03	4.79	11.16	17.32	17.12	19.37	15.12	7.55	1.07	0.02
212	0.39	0.42	0.40	0.76	1.28	2.87	4.55	10.70	16.82	16.92	19.57	15.77	8.26	1.26	0.03
214	0.37	0.40	0.38	0.72	1.21	2.72	4.33	10.25	16.33	16.69	19.72	16.39	8.99	1.48	0.03
216	0.35	0.38	0.36	0.68	1.14	2.58	4.11	9.81	15.83	16.44	19.83	16.98	9.75	1.72	0.04
218	0.34	0.36	0.34	0.64	1.08	2.44	3.91	9.39	15.34	16.17	19.89	17.54	10.52	1.99	0.06
220	0.32	0.34	0.32	0.60	1.02	2.31	3.72	8.99	14.85	15.88	19.92	18.06	11.31	2.29	0.07
222	0.30	0.32	0.30	0.57	0.97	2.19	3.53	8.60	14.36	15.58	19.90	18.54	12.11	2.62	0.09
224	0.29	0.30	0.29	0.54	0.92	2.08	3.36	8.23	13.89	15.27	19.85	18.99	12.91	2.98	0.12
226	0.28	0.29	0.27	0.51	0.87	1.97	3.20	7.87	13.42	14.94	19.77	19.40	13.71	3.37	0.15
228	0.26	0.27	0.26	0.49	0.82	1.87	3.04	7.53	12.95	14.61	19.66	19.76	14.51	3.79	0.18
230	0.25	0.26	0.24	0.46	0.78	1.77	2.89	7.20	12.50	14.27	19.51	20.09	15.31	4.24	0.22
232	0.24	0.25	0.23	0.44	0.74	1.68	2.75	6.88	12.06	13.93	19.34	20.38	16.10	4.72	0.27
234	0.23	0.23	0.22	0.41	0.70	1.60	2.62	6.58	11.63	13.58	19.14	20.63	16.88	5.23	0.33
236	0.22	0.22	0.21	0.39	0.67	1.52	2.49	6.29	11.21	13.23	18.92	20.83	17.64	5.77	0.39
238	0.21	0.21	0.20	0.37	0.63	1.44	2.37	6.01	10.80	12.88	18.68	21.00	18.38	6.35	0.47
240	0.20	0.20	0.19	0.35	0.60	1.37	2.26	5.75	10.40	12.53	18.42	21.14	19.10	6.94	0.56
242	0.19	0.19	0.18	0.34	0.57	1.30	2.15	5.49	10.02	12.18	18.14	21.23	19.79	7.57	0.66
244	0.18	0.18	0.17	0.32	0.54	1.24	2.05	5.25	9.64	11.83	17.85	21.29	20.46	8.22	0.77
246	0.18	0.17	0.16	0.30	0.52	1.18	1.95	5.02	9.28	11.49	17.54	21.32	21.10	8.89	0.90
248	0.17	0.17	0.15	0.29	0.49	1.12	1.86	4.80	8.93	11.15	17.23	21.31	21.71	9.59	1.05
250	0.16	0.16	0.15	0.28	0.47	1.07	1.77	4.59	8.59	10.81	16.90	21.27	22.28	10.30	1.21

% fruit in each count size (based on a standard deviation = 24% of the mean)

Mean fruit weight	216	198	175	163	150	138	125	113	100	88	80	72	64	56	48
90	46.31	21.52	10.61	10.13	6.66	3.75	0.88	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	42.81	21.33	11.01	10.99	7.67	4.69	1.24	0.24	0.01	0.00	0.00	0.00	0.00	0.00	0.00
94	39.51	20.97	11.29	11.75	8.67	5.73	1.68	0.37	0.02	0.00	0.00	0.00	0.00	0.00	0.00
96	36.42	20.47	11.46	12.38	9.62	6.84	2.22	0.56	0.03	0.00	0.00	0.00	0.00	0.00	0.00
98	33.53	19.85	11.51	12.89	10.51	7.99	2.84	0.81	0.05	0.00	0.00	0.00	0.00	0.00	0.00
100	30.85	19.15	11.47	13.28	11.32	9.15	3.56	1.13	0.09	0.00	0.00	0.00	0.00	0.00	0.00
102	28.37	18.37	11.35	13.54	12.03	10.31	4.35	1.54	0.14	0.00	0.00	0.00	0.00	0.00	0.00
104	26.07	17.56	11.15	13.68	12.63	11.44	5.20	2.04	0.21	0.01	0.00	0.00	0.00	0.00	0.00
106	23.96	16.72	10.89	13.72	13.12	12.52	6.11	2.63	0.32	0.01	0.00	0.00	0.00	0.00	0.00
108	22.02	15.86	10.58	13.66	13.51	13.52	7.05	3.31	0.46	0.02	0.00	0.00	0.00	0.00	0.00
110	20.23	15.01	10.23	13.51	13.79	14.43	8.01	4.09	0.65	0.04	0.00	0.00	0.00	0.00	0.00
112	18.60	14.17	9.86	13.29	13.96	15.25	8.97	4.95	0.89	0.06	0.00	0.00	0.00	0.00	0.00
114	17.10	13.35	9.46	13.01	14.04	15.95	9.91	5.90	1.18	0.10	0.01	0.00	0.00	0.00	0.00
116	15.73	12.55	9.05	12.68	14.03	16.54	10.82	6.91	1.54	0.15	0.01	0.00	0.00	0.00	0.00
118	14.47	11.78	8.63	12.30	13.94	17.02	11.68	7.98	1.97	0.22	0.02	0.00	0.00	0.00	0.00
120	13.32	11.04	8.22	11.89	13.77	17.38	12.48	9.08	2.47	0.30	0.03	0.00	0.00	0.00	0.00
122	12.28	10.34	7.80	11.46	13.55	17.63	13.21	10.21	3.04	0.42	0.05	0.00	0.00	0.00	0.00
124	11.32	9.68	7.39	11.01	13.28	17.78	13.87	11.34	3.68	0.57	0.08	0.00	0.00	0.00	0.00
126	10.44	9.05	6.99	10.55	12.96	17.83	14.45	12.47	4.39	0.75	0.11	0.01	0.00	0.00	0.00
128	9.64	8.46	6.61	10.09	12.60	17.79	14.94	13.57	5.17	0.96	0.16	0.01	0.00	0.00	0.00
130	8.91	7.90	6.24	9.63	12.22	17.67	15.34	14.63	6.00	1.23	0.23	0.01	0.00	0.00	0.00
132	8.24	7.38	5.88	9.17	11.81	17.48	15.66	15.64	6.87	1.53	0.31	0.02	0.00	0.00	0.00
134	7.63	6.89	5.54	8.73	11.39	17.22	15.90	16.58	7.79	1.88	0.42	0.03	0.00	0.00	0.00
136	7.07	6.43	5.21	8.29	10.96	16.91	16.06	17.46	8.73	2.28	0.55	0.05	0.00	0.00	0.00
138	6.55	6.01	4.90	7.86	10.53	16.55	16.14	18.26	9.69	2.72	0.71	0.07	0.00	0.00	0.00
140	6.08	5.61	4.61	7.45	10.09	16.15	16.15	18.97	10.66	3.20	0.90	0.10	0.00	0.00	0.00
142	5.65	5.24	4.33	7.05	9.66	15.72	16.10	19.59	11.63	3.73	1.14	0.15	0.01	0.00	0.00
144	5.26	4.89	4.07	6.67	9.23	15.27	15.99	20.13	12.58	4.30	1.40	0.20	0.01	0.00	0.00
146	4.89	4.57	3.82	6.31	8.81	14.79	15.83	20.58	13.50	4.90	1.71	0.27	0.01	0.00	0.00
148	4.56	4.27	3.59	5.96	8.40	14.31	15.62	20.93	14.40	5.52	2.06	0.35	0.02	0.00	0.00
150	4.25	3.99	3.37	5.63	8.00	13.81	15.36	21.21	15.25	6.18	2.46	0.46	0.03	0.00	0.00
152	3.97	3.73	3.17	5.32	7.61	13.31	15.08	21.39	16.05	6.85	2.89	0.59	0.05	0.00	0.00
154	3.71	3.49	2.97	5.02	7.24	12.81	14.76	21.50	16.80	7.53	3.37	0.74	0.06	0.00	0.00
156	3.47	3.27	2.79	4.74	6.88	12.31	14.41	21.54	17.49	8.21	3.88	0.92	0.09	0.00	0.00
158	3.24	3.06	2.63	4.47	6.53	11.81	14.05	21.50	18.12	8.90	4.43	1.13	0.12	0.00	0.00
160	3.04	2.87	2.47	4.22	6.20	11.33	13.67	21.40	18.68	9.57	5.01	1.37	0.16	0.00	0.00
162	2.85	2.69	2.32	3.98	5.89	10.85	13.27	21.25	19.18	10.24	5.63	1.65	0.21	0.00	0.00
164	2.67	2.52	2.18	3.75	5.58	10.39	12.87	21.03	19.61	10.88	6.27	1.96	0.28	0.01	0.00
166	2.51	2.37	2.05	3.54	5.29	9.93	12.46	20.77	19.97	11.50	6.93	2.30	0.35	0.01	0.00
168	2.36	2.22	1.93	3.34	5.02	9.49	12.05	20.47	20.27	12.10	7.60	2.68	0.45	0.01	0.00
170	2.22	2.09	1.82	3.15	4.76	9.07	11.64	20.13	20.50	12.66	8.29	3.10	0.56	0.02	0.00
172	2.09	1.96	1.71	2.98	4.51	8.65	11.23	19.76	20.66	13.18	8.98	3.55	0.70	0.02	0.00
174	1.97	1.85	1.61	2.81	4.28	8.26	10.82	19.36	20.77	13.67	9.68	4.04	0.85	0.03	0.00
176	1.86	1.74	1.52	2.66	4.05	7.88	10.42	18.93	20.82	14.12	10.37	4.55	1.04	0.05	0.00
178	1.76	1.64	1.43	2.51	3.84	7.51	10.03	18.49	20.82	14.53	11.05	5.10	1.25	0.06	0.00
180	1.66	1.54	1.35	2.37	3.64	7.16	9.64	18.03	20.76	14.89	11.72	5.67	1.48	0.08	0.00
182	1.57	1.45	1.27	2.24	3.45	6.82	9.26	17.56	20.66	15.22	12.36	6.27	1.75	0.11	0.00
184	1.48	1.37	1.20	2.12	3.27	6.50	8.89	17.08	20.51	15.49	12.99	6.88	2.05	0.14	0.00
186	1.41	1.29	1.14	2.00	3.10	6.19	8.53	16.59	20.33	15.73	13.59	7.52	2.39	0.18	0.00
188	1.33	1.22	1.07	1.90	2.94	5.90	8.19	16.11	20.11	15.92	14.16	8.16	2.75	0.23	0.00
190	1.26	1.16	1.02	1.79	2.79	5.62	7.85	15.62	19.85	16.08	14.70	8.82	3.15	0.28	0.00
192	1.20	1.09	0.96	1.70	2.65	5.35	7.52	15.13	19.57	16.19	15.21	9.48	3.58	0.35	0.00
194	1.14	1.03	0.91	1.61	2.51	5.10	7.21	14.65	19.26	16.27	15.68	10.14	4.05	0.43	0.01
196	1.08	0.98	0.86	1.53	2.39	4.86	6.90	14.17	18.93	16.30	16.11	10.80	4.55	0.53	0.01
198	1.03	0.93	0.82	1.45	2.27	4.63	6.61	13.69	18.58	16.31	16.51	11.46	5.07	0.64	0.01
200	0.98	0.88	0.77	1.37	2.15	4.41	6.33	13.23	18.21	16.28	16.87	12.10	5.63	0.77	0.01
202	0.93	0.83	0.73	1.30	2.04	4.20	6.06	12.77	17.83	16.22	17.18	12.73	6.22	0.92	0.02
204	0.89	0.79	0.70	1.24	1.94	4.00	5.80	12.32	17.44	16.13	17.46	13.35	6.83	1.08	0.03
206	0.85	0.75	0.66	1.17	1.85	3.81	5.55	11.89	17.04	16.02	17.70	13.94	7.46	1.27	0.03
208	0.81	0.71	0.63	1.11	1.76	3.63	5.31	11.46	16.63	15.88	17.90	14.52	8.12	1.48	0.04
210	0.77	0.68	0.60	1.06	1.67	3.46	5.08	11.04	16.22	15.72	18.06	15.07	8.79	1.72	0.06
212	0.74	0.65	0.57	1.01	1.59	3.30	4.86	10.64	15.80	15.53	18.19	15.59	9.48	1.97	0.07
214	0.71	0.61	0.54	0.96	1.51	3.15	4.65	10.25	15.39	15.33	18.28	16.08	10.18	2.26	0.09
216	0.68	0.58	0.51	0.91	1.44	3.00	4.45	9.87	14.97	15.12	18.34	16.55	10.89	2.57	0.12
218	0.65	0.56	0.49	0.87	1.37	2.87	4.26	9.50	14.56	14.89	18.36	16.98	11.61	2.91	0.14
220	0.62	0.53	0.46	0.83	1.31	2.74	4.08	9.14	14.14	14.64	18.35	17.38	12.32	3.27	0.18
222	0.59	0.51	0.44	0.79	1.25	2.61	3.90	8.79	13.73	14.39	18.32	17.75	13.04	3.67	0.22
224	0.57	0.48	0.42	0.75	1.19	2.49	3.74	8.46	13.33	14.12	18.25	18.09	13.75	4.09	0.26
226	0.55	0.46	0.40	0.72	1.13	2.38	3.58	8.14	12.93	13.85	18.16	18.39	14.46	4.53	0.32
228	0.52	0.44	0.38	0.68	1.08	2.27	3.42	7.82	12.54	13.57	18.05	18.66	15.15	5.01	0.38
230	0.50	0.42	0.37	0.65	1.03	2.17	3.28	7.52	12.15	13.29	17.91	18.89	15.84	5.51	0.45
232	0.48	0.40	0.35	0.62	0.99	2.08	3.14	7.24	11.77	13.00	17.76	19.09	16.51	6.03	0.54
234	0.46	0.39	0.34	0.59	0.94	1.99	3.01	6.96	11.40	12.71	17.58	19.26	17.16	6.58	0.63
236	0.45	0.37	0.32	0.57	0.90	1.90	2.88	6.69	11.04	12.42	17.39	19.40	17.79	7.15	0.74
238	0.43	0.35	0.31	0.54	0.86	1.82	2.76	6.43	10.68	12.12	17.18	19.51	18.40	7.74	0.86
240	0.41	0.34	0.29	0.52	0.82	1.74	2.64	6.18	10.34	11.83	16.95	19.59	18.98	8.35	1.00
242	0.40	0.32	0.28	0.50	0.79	1.66	2.53	5.95	10.00	11.54	16.71	19.64	19.54	8.98	1.15
244	0.38	0.31	0.27	0.48	0.75	1.59	2.43	5.72	9.67	11.25	16.47	19.66	20.08	9.62	1.32
246	0.37	0.30	0.26	0.46	0.72	1.52	2.33	5.50	9.35	10.96	16.21	19.65	20.58	10.28	1.51
248	0.36	0.29	0.25	0.44	0.69	1.46	2.23	5.29	9.04	10.67	15.94	19.62	21.06	10.95	1.71
250	0.35	0.27	0.24	0.42	0.66	1.40	2.14	5.09	8.74	10.38	15.67	19.57	21.51	11.63	1.94

Appendix 7 Papers presented at conferences based on this thesis

THIELE, G.F.; ZHANG, J. The dynamic apple tree system: relationships to aid management strategies. *Acta Horticulturae* 313:249-256, 1992. Third International Symposium on Computer Modelling in Fruit Research and Orchard Management, Palmerston North, New Zealand, 11 - 14 February 1992.

ZHANG, J.; ROWE, R.N; THIELE, G.F. Apple tree branch sampling. Paper presented to the NZIAS/NZSHS Convention, Lincoln University, 25 - 28 August, 1992.

ZHANG, J.; THIELE, G.F. The dynamic apple system: pomological and climatic relationships. *Acta Horticulturae* 313:107-114, 1992. Third International Symposium on Computer Modelling in Fruit Research and Orchard Management, Palmerston North, New Zealand, 11 - 14 February 1992.

Appendix 8 Lincoln University Horticulture Apple Model (LUHAM)

The computer program for the model used in this thesis is named LUHAM. It is available with the written permission of the Head of the Department of Horticulture, Lincoln University or his nominee. It may not be used or copied without permission.