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THE PATTERN OF SOIL WATER EXTRACTION BY

INDIVIDUAL KIWIFRUIT VINES

A thesis presented in partial fulfillment
of the requirements for the Master of Agricultural
Science in Soil Science at
Massey University

VALERIE OLGA SNOW

1987

ABSTRACT

In order to efficiently design and operate irrigation systems water balance studies are needed. To date few of these studies have been carried out on kiwifruit.

Detailed measurements of water extraction were made beneath two 7 year old kiwifruit vines. Under-vine covers were used on these vines to exclude rainfall and irrgation. Measurements of fruit size and leaf water potential were made on the two covered vines and on adjacent irrigated vines. In addition, solar radiation and air temperature were monitored in the orchard block. In concurrent studies, the root distribution of vines in the orchard were determined and heat pulse measurements of sapflow were made.

The water extraction pattern showed little variation with depth to the maximum depth of measurement (2.2 m). There was, however, considerable variation in extraction with horizontal distance away from the vine. This variation may be explained in terms of the root distribution. The soil volume may be divided into the zone of occupation, in which the soil is completely occupied by the plant roots, and the zone of exploration, which is the volume of soil in which there are a few roots but the soil is still largely unexplored. Within the zone of occupation, water is uniformly extracted despite variation in root density. Water appears to be extracted from the zone of exploration primarily by flow of water towards the zone of occupation, where the soil water potential is lower.

The fruit volume and leaf water potential measurements were used to indicate the onset of water-stress. At this time, soil water potential in the zone of occupation was between -40 and -50 kPa. The size of the reservoir of readily availible water was found to be at least 2.1 m^3 for 7 year old vines, and is projected to rise to a maximum of at least 6.5 m^3 in three or so years in this orchard. Whereas the vine canopy may, by management, mature in 3 years, the root system may take 10 years to mature, so irrigation requirements of young vines will be higher than for mature vines. This is contrary to common assumptions made in standard methods for designing horticultural irrigation systems and is due to

changes in the size of the reservoir rather than changes in the rate of water use.

When there is radial variation in water extraction it is important to take account of the variation when calculating volumes of water extracted from the soil. The rate of water use by the vines, as estimated by the water balance method and the heat pulse technique, was found to be considerably lower than that predicted by the equilibrium evapotranspiration rate. This may be due to experimental error, and further work is required to clarify this matter.

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The research presented in this thesis was a part of a larger investigation into the water economy of kiwifruit. People involved in this research have included Brent Clothier, Steve Green, Tom Sauer, Paul Gandar, Keith Hughes and Howard Nicholson. Thanks are specially due to Brent Clothier, Steve Green and Tom Sauer for assistance with some of the measurements presented in this thesis.

The orchard in which the research was carried out is owned and managed by John and Janice Carson. I thank them for making their orchard available and for their generosity and cooperation during the course of the field work.

The research was jointly funded by the Soil and Water Directorate, Ministry of Works and Development, Wanganui and the Plant Physiology Division, DSIR, Palmerston North. I was based at the latter institution for the duration of the degree and am grateful for the use of the facilities and for the swift action on the parts of the director, Jim Kerr, and Brent Clothier which allowed my involvement with the research programme.

Thanks to John Julian and Peter Menalda for the construction of the under-vine covers. Finally, I would like to thank Jim Watt (Soil Bureau, DSIR, Havelock North) and the SWAMP team who described the soil in the orchard and provided me with an advance copy of the results.

TABLE OF CONTENTS

ABSTRACT ii
ACKNOWLEDGEMENTS iv
TABLE OF CONTENTS v
LIST OF FIGURES vii
LIST OF TABLES x
LIST OF SYMBOLS xi

CHAPTER ONE

INTRODUCTION 1
1.1 Experimental Site Description 3
1.1.1 The Orchard 3
1.1.2 Soil Description 6

CHAPTER TWO

THE SPATIAL PATTERN OF WATER EXTRACTION AND ROOT DISTRIBUTION . . 12
2.1 Introduction 12
2.1.1 Why Measure Water Extraction? 12
2.1.2 How to Measure Water Extraction 13
2.1.3 Symmetry Considerations 13
2.1.4 Measuring Soil Water Content 14
2.1.5 Root Distributions 15
2.2 Methods 17
2.2.1 Under-vine Covers 17
2.2.2 Neutron Probe Measurements 18
2.2.2.1 Neutron Probe Theory 18
2.2.2.2 Access Tube Installation 19
2.2.2.3 Neutron Probe Calibration 21
2.2.2.4 Accuracy of the Neutron Probe Measurements 23
2.2.2.5 Drainage 25
2.2.3 Root Distribution 27
2.3 Results and Discussion 28
2.3.1 Water Extraction Patterns 28
2.3.2 Root Length Density Patterns 33
2.4 General Discussion 34
2.5 Conclusion 39

CHAPTER THREE

THE RESERVOIR OF AVAILABLE WATER 41
3.1 Introduction 41
3.2 Methods 46
3.2.1 Fruit Volume Measurements 47
3.2.2 Pressure Bomb Measurements 50
3.3 Results and Discussion 51
3.3.1 Fruit Volume Measurements 51
3.3.1.1 Irrigated Vines, 1985/86 Season 51
3.3.1.2 Non-irrigated Vines, 1985/86 Season 55
3.3.1.3 Irrigated Vines, 1986/87 Season 58
3.3.1.4 Non-irrigated Vines, 1986/87 Season 60
3.3.2 Leaf Water Potentials 61
3.4 The Lower Limit of Available Water 65
3.5 Recovery from Water Stress 73
3.6 Conclusions 75

CHAPTER FOUR

TEMPORAL PATTERNS OF WATER EXTRACTION 77
4.1 Introduction 77
4.1.2 Measurement and Estimation of Evapotranspiration in Orchards 80
4.2 Methods 81
4.2.1 Micrometeorological Measurements 81
4.3 Results and Discussion 82
4.4 Conclusions 88

CHAPTER FIVE

SUMMARY AND CONCLUSIONS 89
5.1 The Spatial Pattern of Water Extraction 89
5.2 The Size of the Reservoir of Available Water 91
5.3 Vine Water Requirements 92
5.4 Implications for Irrigation System Design and Operation . 93
5.5 Further Research Needs 97

BIBLIOGRAPHY

. 99

LIST OF FIGURES

Figure 1.1 Orchard location 4

Figure 1.2 Orchard block layout 5

Figure 1.3 Soil profile pit 7

Figure 1.4 Variation in soil bulk density (ρ_b) with depth . . . 8

Figure 1.5 Soil water rententivity 9

Figure 1.6 Water content of the Westmere silt loam at field capacity 11

Figure 2.1 Cover frame and skirt 17

Figure 2.2 Completed cover 17

Figure 2.3 Diagram of the layout of the under-tree cover and neutron probe access tube positions 20

Figure 2.4 Calibration of the neutron probe 22

Figure 2.5 Water content under vine A at 31/1/86, 7/3/86 and 08/04/86, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine 29

Figure 2.6 Water content under vine A at 5/12/86, 19/12/86 and 27/12/86, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine 30

Figure 2.7 Water content under vine A at 5/12/86, 19/12/86 and 27/12/86, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine 31

Figure 2.8 Water content under vine B at 5/12/86, 19/12/86 and 28/1/87, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine 32

Figure 2.9 The pattern of root distribution around 7 year old vines in J. Carson's orchard 35

Figure 2.10 Soil water deficit, (a) vine A 1985/86, (b) vine B 1985/86, (c) vine A 1986/87, (d) vine B 1986/87 36

Figure 3.1 Device for measureing fruit volume 48

Figure 3.2 Fruit volume for the 1985/86 season 52

Figure 3.3 Fruit growth rate, radiation and data for the 1985/86 season 56

Figure 3.4 Fruit volume for the 1986/87 season 59

Figure 3.5 Diurnal pattern of leaf water potential of the irrigated and coverd vines 63

Figure 3.6 Soil water content and potential at stress point . . . 69

Figure 3.7 Water content difference between "field capacity" and the "stress point" in the 1985/86 season (●) and the 1986/87 season (■) 71

Figure 4.1 Comparison of cumulative evapotranspiration estimated by the water balance technique on vine A (●) and vine B (■) and the equilibrium rate (———) in the 1985/86 season 83

Figure 4.2 Comparison of cumulative evapotranspiration estimated by the water balance technique on vine A (●) and vine B (■) and the equilibrium rate (———) in the 1986/87 season 84

Figure 4.3 Comparison of evapotranspiration estimated by the equilibrium rate (———) or the water balance technique when radial variation is ignored. Extraction at 0.5 (●) or 1 m (■) from vine B, 1985/86 season 87

LIST OF TABLES

Table 3.1 Miscellaneous Fruit Data 57

Table 3.2 Leaf Water Potential Results 62

Table 3.3 Monthly m^3 of irrigation water required under several combinations of reservoir size and rainfall regime . . 72

LIST OF SYMBOLS

		units
a	fitted constant	
b	fitted constant	
C_r	count rate	counts s^{-1}
E	rate of water vapourisation	mm day^{-1}
ET	rate of evapotranspiration	mm day^{-1}
k	hydraulic conductivity	m s^{-1}
NS	not significant	
NZDT	N. Z. daylight time	
R_n	net radiation	MJ m^{-2} day^{-1}
r	radius	m
s	slope of saturation vapour curve	mPa $°C^{-1}$
sd	standard deviation	
TDR	time doman reflectometry	
t	time	s
z	depth	m
γ	psychrometric constant	mPa C^{-1}
Δ	change with time	
ε	total error on θ	m^3 m^{-3}
ε_c	calibration error on θ	m^3 m^{-3}
ε_i	instrument error on θ	m^3 m^{-3}
ε_l	location error on θ	m^3 m^{-3}
ε_s	site error on θ	m^3 m^{-3}
θ	volumetric soil water content	m^3 m^{-3}
θ_m	measured value of θ	m^3 m^{-3}
θ_t	true value of θ	m^3 m^{-3}
λ	latent heat of vapourisation	MJ kg^{-1}
ρ_b	soil bulk density	Mg m^{-3}
ψ	soil water potential	kPa
ψ_l	leaf water potential	MPa
ω	gravimetric soil water content	kg kg^{-1}

CHAPTER ONE

INTRODUCTION

The knowledge of plant water requirements, and of the amount of water stored within the plant root zone, is important for the design and operation of irrigation systems, and for regional water allocation and planning. In the past, orchard irrigation systems have been designed and operated with little quantitative understanding of these factors. Estimates of orchard water requirements have been based on knowledge gained from New Zealand pastoral irrigation, and from expertise imported from other countries with more experience of horticultural irrigation. Unfortunately these countries tend to have significantly different climates to those found in New Zealand, and the technology has not always been adapted successfully to New Zealand conditions. The major technology transferred from pastoral to orchard irrigation has involved the use of micrometeorological techniques to estimate plant water requirements. These techniques had previously been demonstrated to work adequately for pastoral and arable crops grown in New Zealand (e.g. Clothier et al., 1982; Green et al., 1984). These micrometeorological equations were then applied to orchard conditions with little attempt to verify their applicability. There was also little consideration given to the potentially large storage of water within the root zone of orchard trees and vines.

That this situation has persisted is probably a reflection on the relatively low proportion of orchard establishment and running costs represented by irrigation, and also of the fact that under-watering can lead to dramatic and visible results, while the effects of over-irrigation are generally not visible. Compounding this is the general impression that water is not a commodity in short supply in New Zealand. Slowly these perceptions are changing. Under-irrigation has long been recognised as leading to under-sized fruit which have little value in today's markets. Over-irrigation increases costs through increasing irrigation expenses, leaching nutrients below the reach of the plant, so leading to

the need for increased fertilizer applications. It can also cause ground water quality problems. In severe cases, vine health may be adversely affected by water-logging. Inappropriate irrigation practices have also resulted from unsuccessful technology transfer. Examples of this may be found where irrigation systems have been designed with one or two drippers per plant. Irrigation systems designed in this manner have been successfully used to irrigate crops in arid climates. However, for orchard crops in New Zealand, too small a volume of soil may have been irrigated. The result was that large volumes of water were lost to drainage, or caused water-logging problems, while the plants remained water-stressed (Smith, 1983).

To improve the design and operation of irrigation systems, and to assess irrigation benefits includes; (i) the size of the reservoir of readily available water stored within reach of the plant roots, (ii) the rate at which the plant will extract this water, (iii) and the spatial pattern of water extraction.

The integration and application of this knowledge will help determine when irrigation should start, how much water to apply, how often it should be applied, and where the water should be applied. The size of the water reservoir and the spatial pattern of extraction will be dependent upon both soil and plant root factors. The rate of water use will be dependent on meteorological factors and canopy architecture. The nature of these dependencies, and how they may change with time, needs to be understood.

So, there is a need to understand how water extraction is related to soil and plant conditions, and how the plant root system may change with time. In this study spatial and temporal patterns of water extraction were measured around individual kiwifruit vines. The results are discussed, along with other available data obtained from plant-based measurements of water use, and spatial and temporal patterns of root growth.

1.1 Experimental Site Description.

1.1.1 The Orchard.

The orchard in which the trial was carried out is owned and managed by John and Janice Carson, and is on Lillybank Road, Westmere, in the Wanganui district. Fig. 1.1 shows the approximate location of the orchard. The surrounding area is predominantly devoted to arable and pastoral farming.

The particular block of the orchard in which the experimental work was carried out was planted, in the winter of 1980, with seedling Bruno rootstock, at a spacing of approximately 5x5 m. The rootstocks were grafted with a Hayward scion in August of 1981, and the vines were initially trained on a winged, T-bar trellis. In the winter of 1985, the T-bar trellis was converted to a pergola type, and the 1985/86 crop was the first to be produced on this trellis configuration. As a result of the change in trellising system, in the 1985/86 season (the first season in which experimental work was carried out), the kiwifruit canopy did not provide complete coverage until late in the season. In the following season, 1986/87, the vines were able to completely occupy the area available to them.

Originally the vines were irrigated with two drip emitters (4 l hr^{-1}) per vine. In November 1983, the drip system was converted to a microjet irrigation system. In the microjet system one emitter (40 l hr^{-1}) , which produced a wetted radius of 1.2 m, was installed underneath each vine. The irrigation scheduling system was to operate the system for 2.5 hours per day when irrigation was required. The requirement for irrigation was based on a subjective assessment of soil dryness.

Normal kiwifruit management practices operated both before, and during, the trial. Fig 1.2 shows a schematic diagram of the orchard block in which the research was carried out.

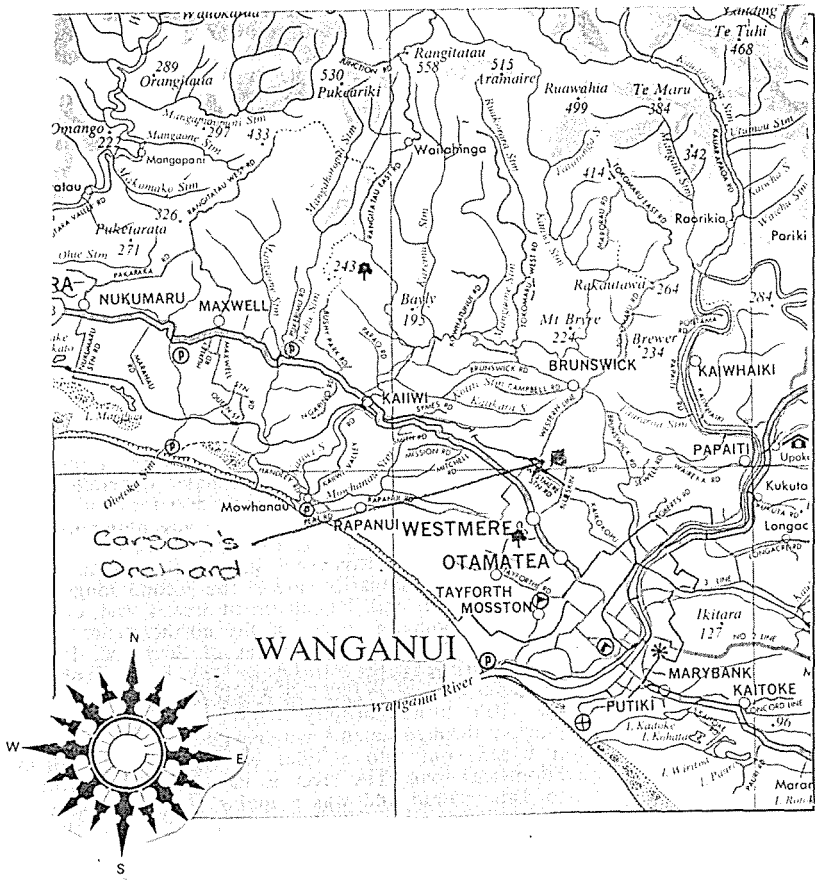

Figure 1.1 Orchard Location

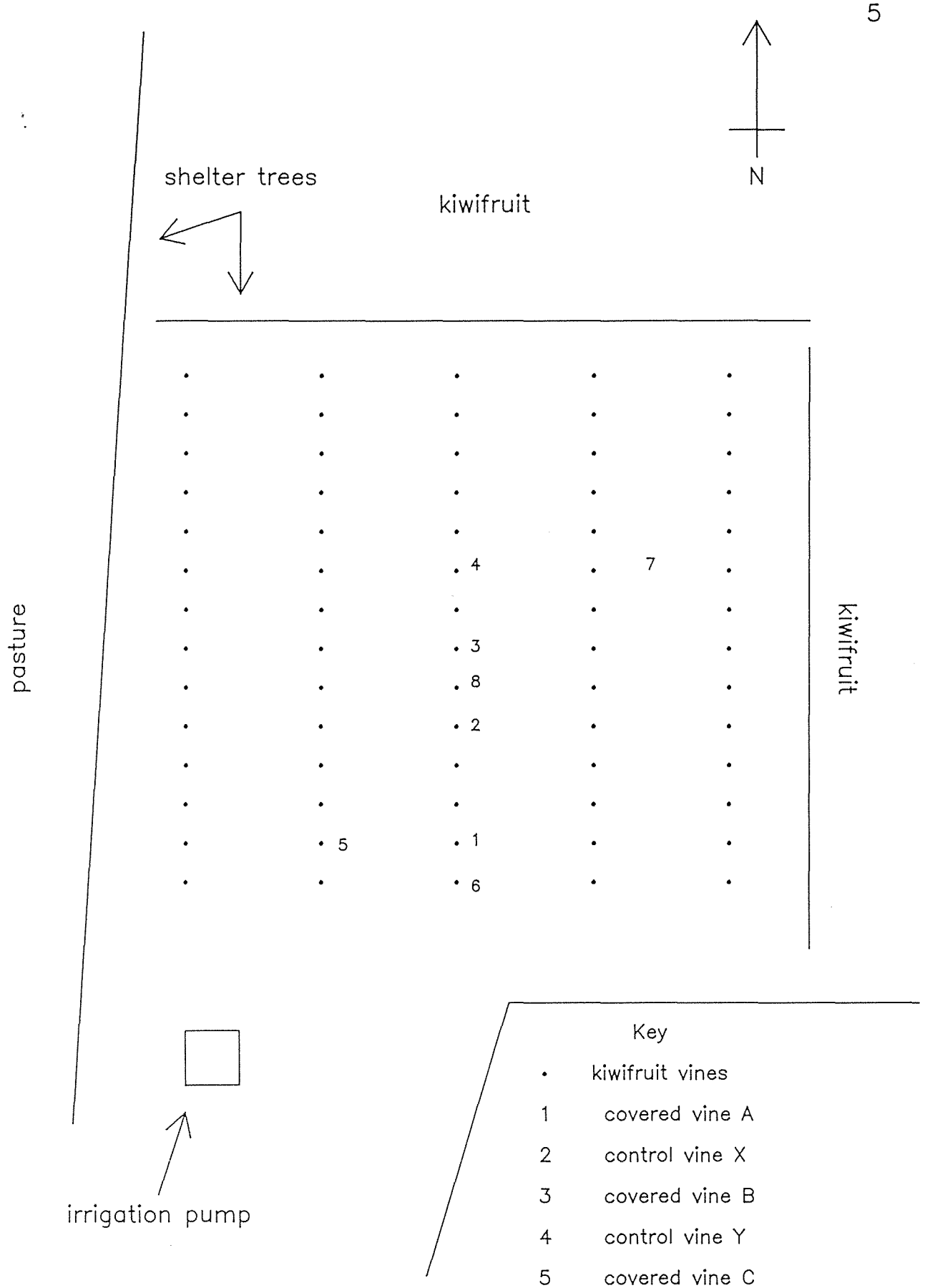

Figure 1.2 Orchard block layout

1.1.2 Soil Description.

The soil in the orchard is on the Westmere silt loam series. This soil series has been described by Cambell (1977) as being well-drained and moderately acid, but low in phosphorus. The soil has a deep, dark brown to black, friable, silt loam A horizon (0.25 m deep) with strongly-developed nut structure. The A horizon merges into a B horizon (from 0.25 m to greater than 1.5m) of brown to dark brown, friable to firm, clay loam, with moderately-developed blocky and nut structure. This overlies a similar, but somewhat firmer horizon, with weakly-developed blocky structure. This passes into a strong brown, sandy clay loam on sand. A more detailed description is given by Joe (1987), from a profile pit dug in the same orchard block as the experimental vines. This pit is shown in Fig. 1.3

Soil bulk density was found to range from a minimum of 1.02 Mg m^{-3} at 0.05 m, to a maximum of 1.34 Mg m^{-3} at 0.7 m. At depths greater than 0.7 m, bulk density decreased. The deepest measurement was taken at 1.15 m where the bulk density was 1.13 Mg m^{-3} (Joe, 1987). The bulk density data are presented in Fig. 1.4.

Water retention data for the soil are shown in Fig 1.5. Data are shown for two depths, 0.2 and 0.5 m, and were obtained from three different sources. Those points labelled "field data" refer to data collected by measuring soil water potential with a Soilmoisture Co. model 2900F "Quick Draw" tensiometer, then taking a soil sample to obtain volumetric water content. "Lab data" results from retentivity determined using either a Haines apparatus (-5 and -10 kPa), or a pressure plate (-100, -500 and -1500 kPa). Finally, the "SWAMP data" were taken from Joe (1987). The data, especially the "field data", show some scatter, this but this can be attributed to natural field variability. The "lab data" retention data for the two depths shown are similar, but the "SWAMP" data at the two depths diverge, especially at -1500 kPa. The reason for this divergence is not known, but it may be due to soil heterogeneity. However at potentials higher than -70 kPa, which is the region of interest in this study, the data collected from the three different sources agree well. Deeper in the profile, less water is stored above potentials of -40 kPa than at the two depths shown in Fig 1.5 (Joe, 1987).

Figure 1.3 Soil profile pit.

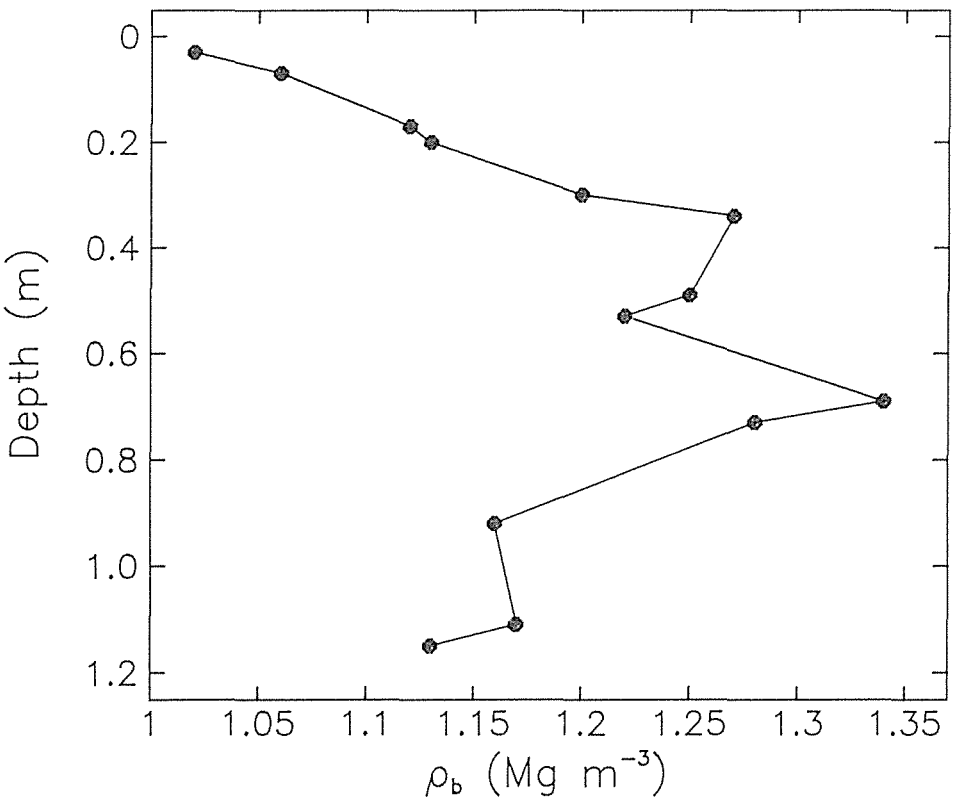

Figure 1.4 Variation in soil bulk density (ρ_b) with depth. Data from Joe (1987).

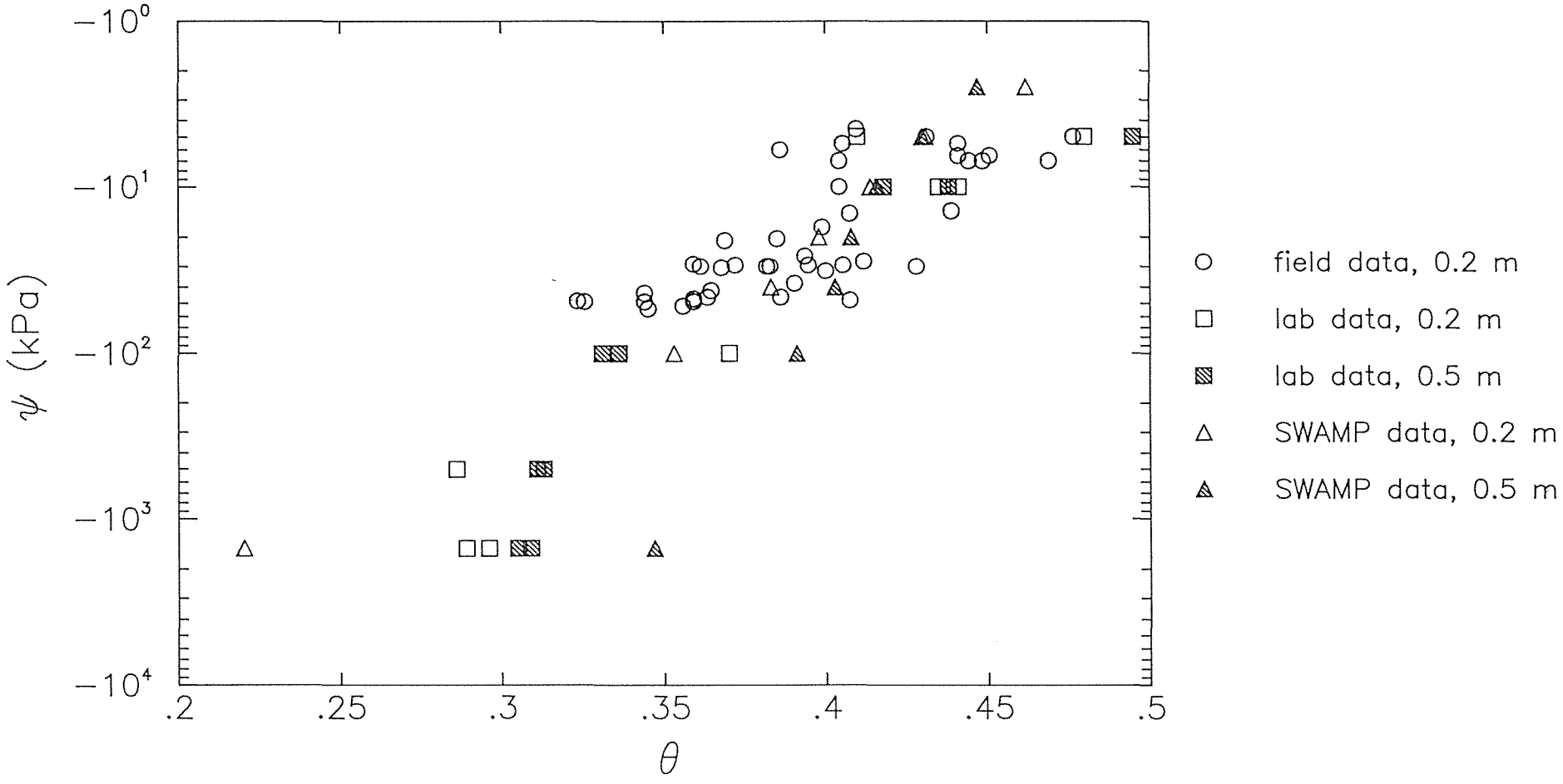

Figure 1.5 Soil water rententivity.

The water content of the soil at the so called "field capacity" is important as it sets the upper limit of water storage. Fig. 1.6 shows two profiles of water content with depth. The profile extending to 2.1 m deep was measured, using a neutron probe, on the 5th of December, 1986. The data shown are the means of four measurements, taken at 2 m along and across the row from each of the two vines. The soil 2 m from vine A had recieved rainfall and substantial volumes of irrigation water since early April of 1986, and yet was no wetter than the soil 2 m from vine B, which had recieved rainfall only from May onwards. If the soils had not reached field capacity, then one would expect the water content measured 2 m from vine A to be greater than that measured under vine B. Data from 2 m horizontally from the vine were used, as the soil at this distance had the lowest deficits at the end of the 1985/86 experimental period, and so were most likely to reach field capacity during the winter period. The water contents measured at 0.2 and 0.5 m are consistent with the -5 kPa water content data shown in Fig. 1.5. The other data shown on Fig. 1.6 is the -5 kPa water contents measured by Joe (1987). These data suggest a wetter field capacity than shown by the water content measurements taken on 5/12/86. This difference may be due to either soil heterogeneity or perhaps the soil at 2 m from the vines on 5/12/86 was not at field capacity. Without further measurements it is not possible to explain the reasons for the difference between the two data sets. The profiles measured in the field will be considered to indicate the field capacity of the soil. This is likely to underestimate the true field capacity.

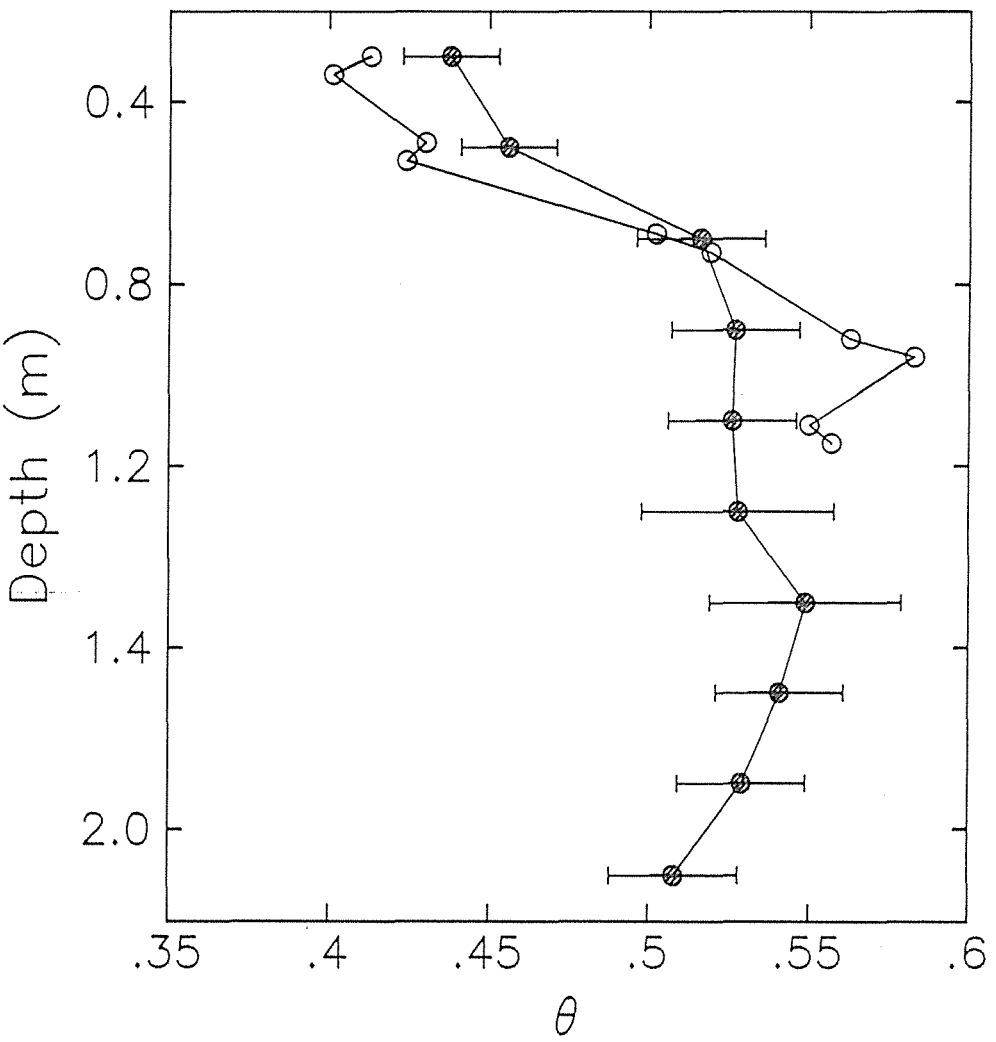

Figure 1.6 Water content of the Westmere silt loam at field capacity.

○ data from Joe (1987)

⊘ profile at 5 Dec, 1986 with ± 1 sd error

CHAPTER TWO

THE SPATIAL PATTERN OF WATER EXTRACTION AND ROOT DISTRIBUTION

2.1 Introduction.

2.1.1 Why Measure Water Extraction?

The first step in a water balance study is often the measurement of the extraction of water from the soil. For several reasons, it is important to measure changes in water content in such a way that the temporal and spatial patterns of extraction, rather than merely the total amount of water extracted over some period, may be determined. Firstly, the spatial pattern may be used to examine the symmetry for the system being studied. The type of symmetry will have important implications for the calculation of changes in the volume of water in the root zone. When combined with a knowledge of the rooting pattern of the plants studied, of how the root system is likely to change with time, and of the soil physical properties, the knowledge gained from a water extraction study may be transferred to other environments. Or this may be used to predict behaviour in the same environment at some time in the future. Without knowing the pattern of water extraction and accessory information, any study will be specific to the site and time that the study was undertaken and will add little to the knowledge of the overall processes. This is one area where soil-based studies have an advantage over other studies, such as plant-based measurements. Plant-based measurements, e.g. excision experiments (e.g. Judd et al., 1986) or heat pulse studies (e.g. Edwards and Warrick, 1984), have the potential to provide detailed knowledge of plant water use when combined with atmospheric measurements, but leave other questions relating to irrigation scheduling unanswered.

2.1.2 How to Measure Water Extraction.

In water balance studies the prime motive is usually to quantify the plant component of water extraction. In an orchard there are many sources and sinks for water, all of which have the potential to affect the measured soil water content. These sources and sinks are; water uptake by plants other than the crop plant, drainage, evaporation from bare soil in the herbicide strip, and inputs of water from rainfall and irrigation. In order to isolate crop water extraction, the additional inputs and outputs must be accounted for. This may be achieved by either measuring them, or somehow excluding them. The exclusion of inputs, soil evaporation and non-crop water use is can be achieved by under-tree covers (e.g. Garnier *et al.*, 1986; Jones *et al.*, 1983). If it is not possible to prevent drainage, it must be independently measured (Chappaz, 1986; Garnier *et al.*, 1986).

The measurement of all input and output components of the system retains the system in its natural state, and may provide additional useful information, but additional sources of error are introduced in measuring these inputs and outputs. An example of this is the measurement of rainfall, rather than the exclusion of it (e.g. van Oostrum, 1985).

The exclusion of inputs and outputs may create an artificial situation, and this should be borne in mind when results are interpreted. For example, total water use in the orchard environment will be greater than that measured when under-tree covers are used, as water use by grasses and evaporation from soil has been excluded. The contribution of rainfall to the water economy of the natural system must also be considered.

2.1.3 Symmetry Considerations.

If one is interested only in the change in soil water content *per se*, then the symmetry of the system is not relevant. In most studies however the changes in water content will be used to calculate the volume of water extracted. Then the symmetry of the system is of importance.

Root systems of immature kiwifruit vines are likely to have root distributions which decrease in density with both horizontal and vertical

distance from the vine stem. Although older root systems may have more fully exploited the soil available to them, resulting in fairly uniform densities horizontally, root density may still fall with depth (Hughes et al., 1986). The age at which a root system may be considered to be mature will depend on soil properties, vine spacing, and vine management. For a vine spacing of 5 x 5 m it may take 10 years for the root system to lose horizontal variability (Hughes et al., 1986). Except for any flow of water into the root zone, the rooting pattern will define the shape and size of reservoir and the zone of water extraction. The pattern of water extraction within that zone may or may not follow root density, depending primarily on the hydraulic properties of the soil and properties of the roots.

Symmetry cannot be known precisely in advance. It is therefore important to choose sampling locations so that any symmetry may be detected, and allowed for, in subsequent calculations.

2.1.4 Measuring Soil Water Content.

There are many methods available for measuring the water content of soil. Each method has certain features which make it more or less suitable for a defined purpose. A method should be chosen for a study with full knowledge of the advantages and disadvantages associated with that method. Other factors which should be considered before choosing a particular method are the type of symmetry expected in the system and the degree of precision required.

Soil water content may be measured either on a volume basis, (θ), or on a weight basis, (ω). The two are related through the bulk density, (ρ_b, Mg m^{-3}). For water balance studies it is necessary to know the water content on a volume basis. The requirements of the method of water content measurement are that it be non-destructive, so that the water content may be measured sequentially at the same location, the soil structure and plant roots should not be disturbed by the measurements, the measurements should be quick to take, and preferably be on a volumetric basis. The first two criteria are the most important. The methods available which fit these requirements, and which are also suitable for use in the field are the neutron probe method and time-domain

reflectometry. Gravimetric sampling and tensiometry are inadequate.

The neutron probe method requires calibration for soil type, and measures the water content of a large soil volume, a sphere of perhaps 0.15 to 0.25 m radius (van Bavel et al., 1956). The time-domain reflectometry (TDR) method does not require calibration for individual soils, and samples the water content within approximately 40 mm of the wave guides (Soilmoisture Equipment Corp, 1986). If the neutron probe is to be used to measure the water content in the top 0.2 m or so of soil then a separate calibration is required. The TDR technique can successfully measure the water content near the soil surface but the only commercial device available limits measurements to a maximum of 1.2 m. The device provides the average water content to the depth of the wave guides, so to obtain a profile of water content with depth, several pairs of wave guides are required.

2.1.5 Root Distributions.

Although root length density studies are not an essential part of a water balance study it is desirable that a water balance study be accompanied by some quantitative assessment of the root distribution of the plant(s) studied. Root measurements will allow one to assess whether all the water taken up is likely to be a result of plant water extraction, and also to assess if all the water taken up by the plant is likely to have been measured. Root studies are also helpful when studying the reservoir size, because as the plant grows the root system will change and therefore so will the reservoir size. Knowledge of the root system and of soil properties will also assist in the transfer of knowledge from one environment to another by enabling study of the processes linking uptake of water from the soil by the roots.

2.2 Methods.

2.2.1 Under-Vine Covers.

In order to exclude rainfall and irrigation, and to prevent water use by plants other than the kiwifruit, under-vine covers were constructed. The overall size of the covered area was 8 m along the row by 6 m across the row. This allowed for at least a 1 m extension beyond the point half way

to the next vine. This overlap was to prevent any lateral flow caused by reduced water potentials under the covers resulting from vine water extraction.

The covers were constructed in three parts; the steel frame, the plastic roofing sheets, and the plastic canvas skirt.

The steel frame sloped down from a maximum height of 0.2 m near the vine to 0.1 m at a distance of 1 m from the vine at the edge of the herbicide strip (see Fig 2.1). The function of the frame was to support the plastic roofing and to provide attachment for the skirt.

The next step in the construction of the covers was the skirt. This extended from the steel frame to cover the 6 by 8 m area. The skirt was constructed from "Ripstop", a heavy-duty plastic canvas. The skirt was attached to the frame by turn-buttons and anchored at the outer edges by tent pegs. Zips were inserted at both ends for coverage around the trellis uprights, and in the centre of one side to allow access to the neutron access tubes placed across the row. This latter zip was covered with an extra layer of canvas to prevent water entry through the zip. The frame with the skirt attached is shown in Fig 2.1.

The other part of the covers was the central covering. This was constructed from "Lustrelite" plastic roofing. The sheets of roofing fitted under the ridge of the steel frame, and were held down at the outer edge of the frame by an extra length of steel tubing. The areas around the trellis uprights and the vine stem were made water-tight by attaching a polythene skirt to the poles or stem and attaching the outer edges to the cover. The finished cover is shown in Fig 2.2.

In the 1985/86 season the covers were installed on 22/1/86 and removed from vines A and B on 8/4/86 and 3/5/86 respectively. The covers were installed again on 5/12/86 for the 1986/87 season, and removed from vine A on 29/12/86 and from vine B on 17/3/87. Routine neutron probe measurements were, however, discontinued on 28/1/87. The cover removed from vine A was installed under a third vine, vine C, on 9/1/87. No neutron probe measurements were taken from under this vine.

Figure 2.1 Cover frame and skirt.

Figure 2.2 Completed cover.

2.2.2 Neutron Probe Measurements.

The scaler used was a Troxler Laboratories model 2601. The probe was a Troxler Laboratories model 104A with a 100 mCi Am:Be source. Measurements were taken approximately twice a week in the 1985/86 season and weekly in the 1986/87 season. The scaler was switched on for at least 15 min before any measurements were taken, to allow the electronics to warm up and stabilise. Before measurements were taken in each tube, four 15 s standard counts were taken with the probe in the shield. Two 15 s count measurements were then taken at each 0.2 m increment from 0.3 m to 2.1 m. The two 15 s counts offered the same degree of accuracy as one 30 s count, and also allowed some checking of the data against mis-typing. The counts were recorded in the field, on an Epson HX20 lap computer and were subsequently unloaded onto a VAX 11/780 computer.

2.2.2.1 Neutron Probe Theory.

The neutron probe measures the volumetric water content of a soil through three processes; the emission of fast neutrons, the thermalisation of the fast neutrons, and the detection and counting of these thermalised neutrons.

The fast neutron source consists of a radioactive nuclide and a target substance. The nuclide, normally either ^{226}Ra or ^{241}Am (IAEA, 1970), bombards the target substance, Be, with alpha particles. The bombarding radiation raises the Be to a higher energy level, the Be then decays with the emission of a fast neutron.

Thermalisation is the process by which a fast neutron loses energy until it reaches a thermal equilibrium with its surroundings. At this stage the neutron is said to be thermalised or slow. The element in soil most effective at thermalising neutrons is hydrogen. There are, however, other elements found in sufficient quantities in some soils to cause significant thermalisation. These elements include O, Si, Al, Fe, C, Mg (Wilson and Ritchie, 1977), B, Cl, and Ga (Nicolls et al., 1977). It should also be noted that not all hydrogen present in soils is associated with that water which may be removed by oven-drying. Hydrogen nuclei in bound water and structural hydrogen (e.g. in organic matter) can also thermalise

neutrons. Soil bulk density also affects fast neutron thermalisation.

Once a fast neutron becomes thermalised it diffuses through the soil until captured by a nucleus, either in the soil or probe detector. The probability of capture by the counting device, and thus of detection and contribution to the count rate, is related to the distance from the probe at which the neutron becomes thermalised. As the water content of the soil rises, so the distance the fast neutron is likely to travel before it becomes thermalised falls, and the probability of that neutron diffusing back to the probe for capture increases. Herein lies the water content dependence of the count rate.

The counting device consists of a compound, usually BF_3, efficient at capturing slow neutrons. Upon the capture of a slow neutron the detection compound releases a secondary charged particle which is in turn detected, amplified, and counted by associated electronic equipment.

2.2.2.2 Access Tube Installation.

Neutron probe access tubes (aluminium, ID=48mm) were installed to a depth of 2.2 m at 0.5 m intervals along and across the crop rows beneath two vines, A and B. The installation method was as follows. Firstly a pilot hole was drilled to 1 m with a powered screw auger. The hole was then enlarged and deepened to 2.2 m with a 48 mm diameter bucket auger. The aluminium access tubes were cut to length, checked for clearance with a dummy probe and sealed at both ends with 50 mm rubber bungs. The tube was then inserted in the augered hole. Access tubes placed along the crop row protruded from the soil surface by 0.1 m, while the tubes placed across the row were flush with the soil surface. When a measurement was to be taken in a tube flush with the surface, a 0.1 m extension was inserted in the top of the tube. The placement of the tubes is shown schematically in Fig 2.3.

In addition to the access tubes placed around the vines, four 1 m long tubes were placed nearby in the headland.

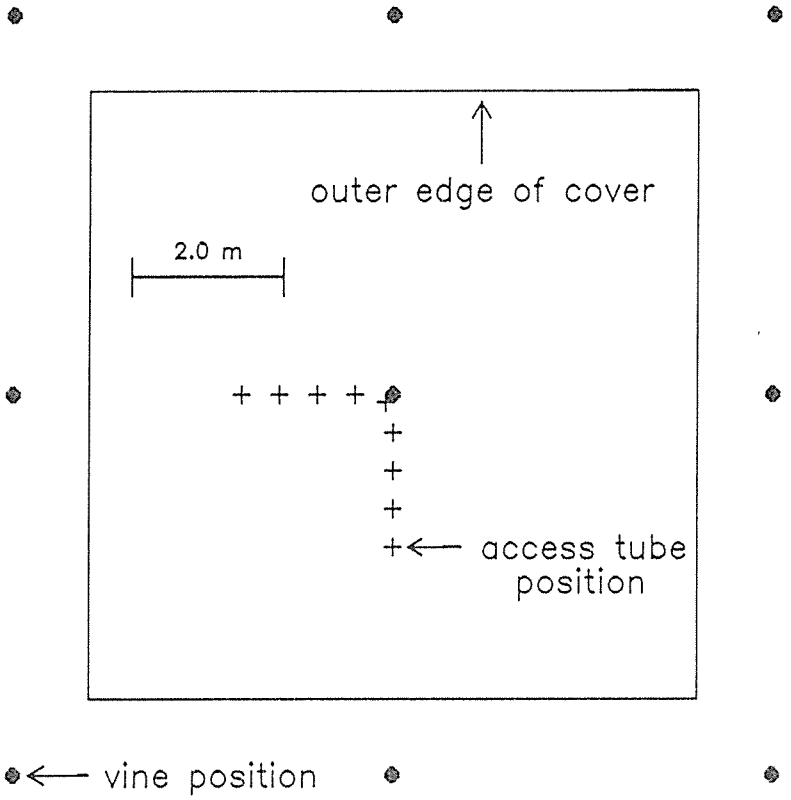

Figure 2.3 Diagram of the layout of the under–tree cover and neutron probe access tube positions.

2.2.2.3 Neutron Probe Calibration.

As different soils contain varying amounts of non-hydrogen elements capable of thermalising fast neutrons, of structural hydrogen, and of bound water, and also have different bulk densities, the neutron probe should have a corroborative calibration carried out for each soil in which it is used. The most common method of calibration is that of concurrent measurement of soil water content by the probe and some other independent method (IAEA, 1970). The calibration may be carried out either in the laboratory with repacked soil, or in the field. Successful laboratory calibration requires attention to the soil bulk density. Although this method may result in a more precise calibration, the calibration may contain significant bias. For these reasons field calibration is usually preferable.

The neutron probe was calibrated in the field at the end of the 1986/87 experimental period. In total, six tubes were used for the calibration, with samples taken at 9 depths within each tube. The calibration sites were the tubes located at 1.5 and 2.0 m along the row at covered vine A, 1.0 and 1.5 m along the row at covered vine B, and two further tubes located in the headland. The bulk density values needed to convert the gravimetric water content to a volumetric basis were obtained from Joe (1987) (see Section 1.2.2). Soil bulk density (calculated from the calibration samples) was the same in the headland area as within the orchard rows. Counts were taken at 0.1 m depth intervals, with the shallowest count being taken at 0.2 m and the deepest at 1.0 m. These counts were compared with soil samples taken with a 20 mm diameter corer auger within 0.3 to 0.5 m of the tube. Each soil sample was 0.1 m long, spanning the depth at which the count was taken.

The calibration data, a linear regression line through the data, and the factory calibration for the probe are shown in Fig 2.4. The error bar in the upper left hand corner of the figure shows the ± 3 standard deviation error (see Section 2.2.2.4) on the volumetric water content. The error bars on the regression line are also a three standard deviation error.

The regression line was found not to differ significantly from the factory calibration. The factory calibration;

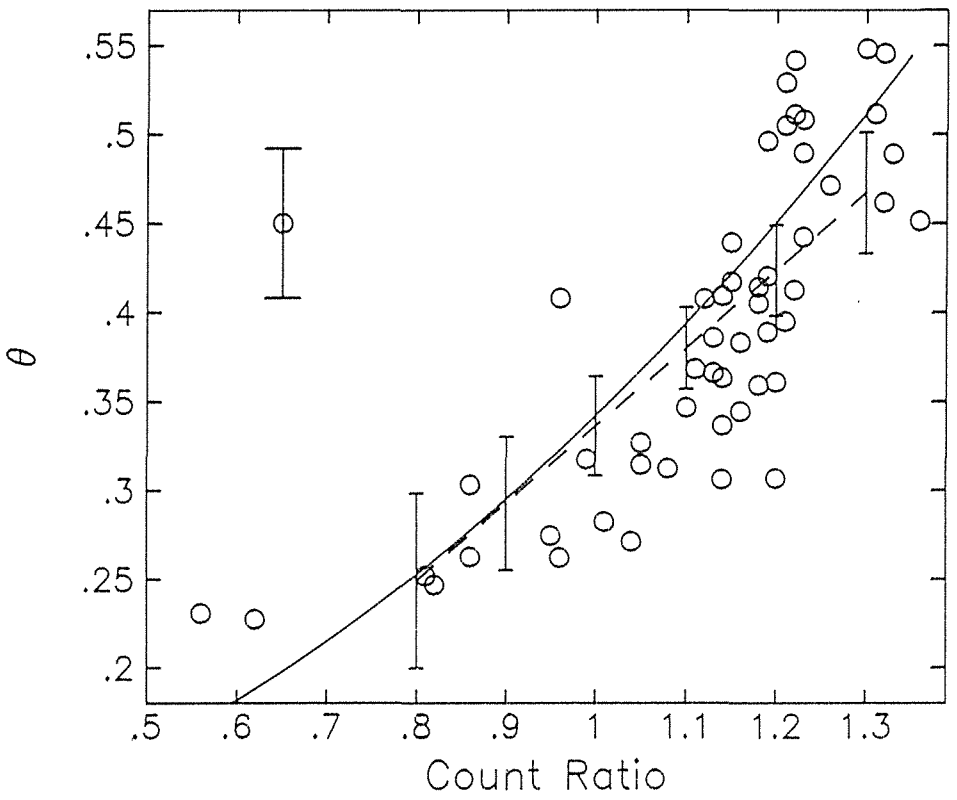

Figure 2.4 Calibration for the neutron probe. The vertical error bar in the top left corner shows the ± 3 standard deviation error on the θ data.

——— factory calibration

— — - linear regression line and errors.

$$\theta = 0.0813 + 0.0268\ C_r + 0.234\ C_r^2 \qquad (2.1)$$

where θ is the volumetric water content ($m^3\ m^{-3}$) and C_r is the count ratio (i.e. the count rate in the soil / the count rate in the shield), was used in all subsequent analysis.

2.2.2.4 Accuracy of the Neutron Probe Measurements.

Before any calculations are made with the measured water content values the error on these values should be estimated. The measured water content, θ_m, may differ from the true water content, θ_t, as described by the following equation;

$$\theta_m = \theta_t + \varepsilon \qquad (2.2)$$

where;

$$\varepsilon = \varepsilon_c + \varepsilon_i + \varepsilon_s + \varepsilon_l \qquad (2.3)$$

where ε is the error on an individual measurement of water content, ε_c is the calibration error, ε_i is the instrument error, ε_s is the site error, and ε_l the location error.

The calibration error is a result of imperfect calibration of the neutron probe for the soil used in the experiment. This may occur if some form of bias arises during the calibration, or if effects due to soil variability are not separated out during calibration and subsequent application of the calibration.

The location error is the error arising from the depth location of the probe within the access tube. The importance of siting the probe at the same depth for each measurement will depend upon the water content gradients within the sphere of influence, which is itself a function of the probe, soil water content and other physical and chemical properties.

The site error will depend on how representative the measurement site is of the volume of soil in which it is assumed to estimate the water

content. There are two components to this error, a random error due to the selection of the position for the access tube, and the the error introduced by the heterogeneity of the experimental site.

The instrument error is that associated with the neutron probe itself. It arises from errors in the timing mechanism and from the random nature of radioactive decay. In modern instruments the timing error is likely to be small. The error due to radioactive decay will therefore dominate this term.

The total error (ε) can be sub-divided into its constituent parts, and each error term quantified (Sinclair and Williams, 1977). However such a detailed error analysis is not required for water balance applications. When only the total error is required, it is possible to find the error using an analysis of variance (ANOVA). An ANOVA was carried out using the SAS general linear models procedure with the vines, orientation (i.e. either along or across the row), horizontal distance from the vine, depth and measurement date as factors. All possible interactions were included in the model, and initially the 1985/86 and the 1986/87 data sets were analysed separately. Preliminary analysis showed no difference, as regards the error mean square or the significant factors, between the data collected in the two seasons, so the two data sets were bulked. The large data sets (4000 measurements in 1985/86) combined with the large number of factors and interactions would have consumed large amounts of computer processor time. To prevent this, five measurement dates (1000 data points) were selected to form a smaller data set on which to carry out the ANOVA.

The ANOVA on the θ data showed that all factors and most interactions were significant. The error mean square was 0.00019, indicating that the error on θ was 0.014 $m^3\ m^{-3}$.

Although the parameter $\Delta\theta$ (i.e. the difference in water content between samplins) arises as the difference between two θ measurements, as the $\Delta\theta$ value is calculated from two θ estimates measured at the same location, it is not appropriate to simply use transmission of error formulae to calculate the error on $\Delta\theta$. This is because when the two estimates of θ are measured at the same location, some of the components of the variance

(see Eqn. 2.3) change. Specifically, the calibration error is likely to decrease as only the slope is important for the calculation of $\Delta\theta$, while the instrument and location errors will increase just because there is an extra measurement involved. Most significant however, is a usually large decrease in the site error. As a result, the variation in $\Delta\theta$ is usually much less than in θ. Vachaud et al. (1985) attributed the decrease in variance in $\Delta\theta$, as compared with θ, to much of the variance in θ being due to variation in the amount of water stored in the soil below the permanent wilting point. When $\Delta\theta$ is calculated this variance is not included.

In order to find the error on $\Delta\theta$ another ANOVA was carried out, this time on the variable $\Delta\theta$ rather than θ. The model was the same as described above. The ANOVA on $\Delta\theta$ showed that of the main effects, only measurement date and distance from the vine were significant. More importantly, orientation and the depth of measurement were not significant effects. The error on $\Delta\theta$ was estimated to be 0.011 $m^3\ m^{-3}$.

The error on the calculation of the volume of water stored in the root zone will be discussed in chapter 4.

2.2.2.5 Drainage.

Drainage may be defined as the loss of water below the depth of interest, in this case 2.2 m. The equation describing unsaturated flow of water for one-dimensional vertical flow may be written as;

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[k(\theta)\left(\frac{\partial\psi}{\partial z} + 1 \right) \right] \qquad (2.4)$$

where t is time (s), z is distance (m, +ve downwards), k is the hydraulic conductivity of the soil (m s^{-1}), and ψ is the matric potential of the soil. It may be seen that drainage, $\partial\theta/\partial t$, is influenced by the slope of the matric potential profile, gravity, and the hydraulic conductivity of the soil.

Hydraulic conductivity has a strongly non-linear dependence on water content. The nature of the dependence of is such that, between satiation and "field capacity" ($P \simeq -5$ kPa), $k(\theta)$ may vary by three or more orders of magnitude. Thus, at potentials below field capacity, the hydraulic

conductivity, and therefore $\partial\theta/\partial t$, becomes very small. Because of this it is often possible to assume that drainage is negligible in water balance studies in which inputs of irrigation or rainfall are prevented. If drainage is fast in the initial stages of the study then the soil water potential, quickly falls to a potential at which drainage is a small proportion of the total water balance. On the other hand, if drainage is negligible to start with, and if no water is added to the system, the rate of drainage cannot increase and so it will remain unimportant.

The above discussion suggests that in the worst case drainage will be important only at the beginning of a water balance study, provided that there are no inputs of water to the system. Further, if the water balance has been dominated by plant extraction for some time before the start of the experimental period, the drainage will not even be important in the initial stages of the study.

Let us now examine the relative magnitudes of rainfall and evapotranspiration in the weeks immediately preceding the experimental periods. The cumulative evapotranspiration, as estimated by the Priestley-Taylor equation (measured in the orchard by an Algin ET meter; see Section 4.2.1), for the three weeks prior to the 1985/86 experimental period was 113 mm. The rainfall measured for the same period (at the Wanganui airport, about 10 km from the orchard) was 77 mm. On the day immediately prior to the installation of the covers there was 1.6 mm of rain recorded; the next most recent rainfall was 10 days earlier when 13.7 mm of rain fell. Although the rainfall at the airport may not be an accurate measure of that received at the orchard, it is a good first approximation. So, in the three weeks before the covers were installed, evaporation is estimated to have exceeded rainfall by approximately 36 mm.

Evapotranspiration data are available for only 7 days immediately prior to the 1986/87 experimental period. Over this week estimated cumulative evapotranspiration was 30 mm, while rainfall was 15 mm. Furthermore, for the month prior to the start of the experimental period rainfall totalled 43 mm. Evapotranspiration over the period would have been considerably higher than the rainfall. The most recent rainfall occurred 4 days before the covers were installed, and was 2.6 mm.

The meteorological data suggest that drainage was probably negligible prior to both study periods and support the interpretation of the data that changes in water content of the soil will be as a result of water uptake by the kiwifruit alone.

2.2.3 Root Distribution.

Root length densities are expressed as a root length per unit volume of soil. The absorbing root surface area would be a more appropriate measure but surface area is difficult to measure and as most of the roots involved in water uptake are found to lie within only a small range of diameters; length is well correlated with the surface area.

Samples for root length density were taken 4 times during the experimental period, as part of the kiwifruit root survey by a team of from Plant Physiology Division, DSIR. The sampling times were May, September, and December, 1986, and February 1987. The vines sampled were not the experimental vines, except on the final occasion when three cores were taken from covered vine A. The sampling method and scheme have been previously described by Hughes et al. (1986) and so will only briefly be described here.

Soil from the top 1 m was sampled with a 46 mm diameter corer driven into the soil by a modified, engine-powered concrete breaker. The corer and soil core were then extracted using a tripod and winch. Soil between 1 and 2 m was sampled similarly, but using a 36 mm diameter corer. From each core, 8 to 10, 0.1 m long samples were extracted from known depths within the core. The kiwifruit roots were then extracted from the core using a semi-automatic root washer. Root length was measured from these subsamples using a Comair Root Length Scanner.

2.3 Results and Discussion.

2.3.1 Water Extraction Patterns.

The soil water content profiles found under vine A and B at the start, approximately middle, and end of the 1985/86 and 1986/87 experimental periods are shown in Figs 2.5-2.8. Water contents are shown for each of the five radial distances from the vine that were monitored. The water content shown is the mean of the measurements along and across the row. The horizontal error bar shown is the ± 1 standard deviation error on an individual θ measurement.

It should be noted that there is significant water extraction at both 2 m horizontally and vertically from the vine. It may therefore be assumed that beyond these measurement points there has been some additional water extraction which has not been measured.

The symmetry of water extraction is important, as the failure to recognise the appropriate symmetry and take it into account when calculating volumes of water may lead to large errors. If, for example, the symmetry is spherical then equal changes in water content at different radial distances from the vine will translate to different volumes of water. A small change in water content at some distance from the vine may indicate a greater volume of water extraction then a larger change in water content closer to the vine.

The symmetry of water extraction should depend mostly on the symmetry of the root system. This may however be distorted by variability in soil hydraulic properties. Other studies (Gandar and Hughes, 1987) have found that kiwifruit vines initially have a bowl-shaped symmetry (more accurately described as an ellipsoid). As the vine matures and the roots occupy all of the space available to them, there ceases to be any root length density variation in the horizontal direction, but the density still falls with increasing depth. The kiwifruit root system density then is found to be three-dimensional in immature vines but tending toward root density variation in the vertical direction only as the vines mature. In vines spaced 5 m apart, maturity is thought to occur after about ten years.

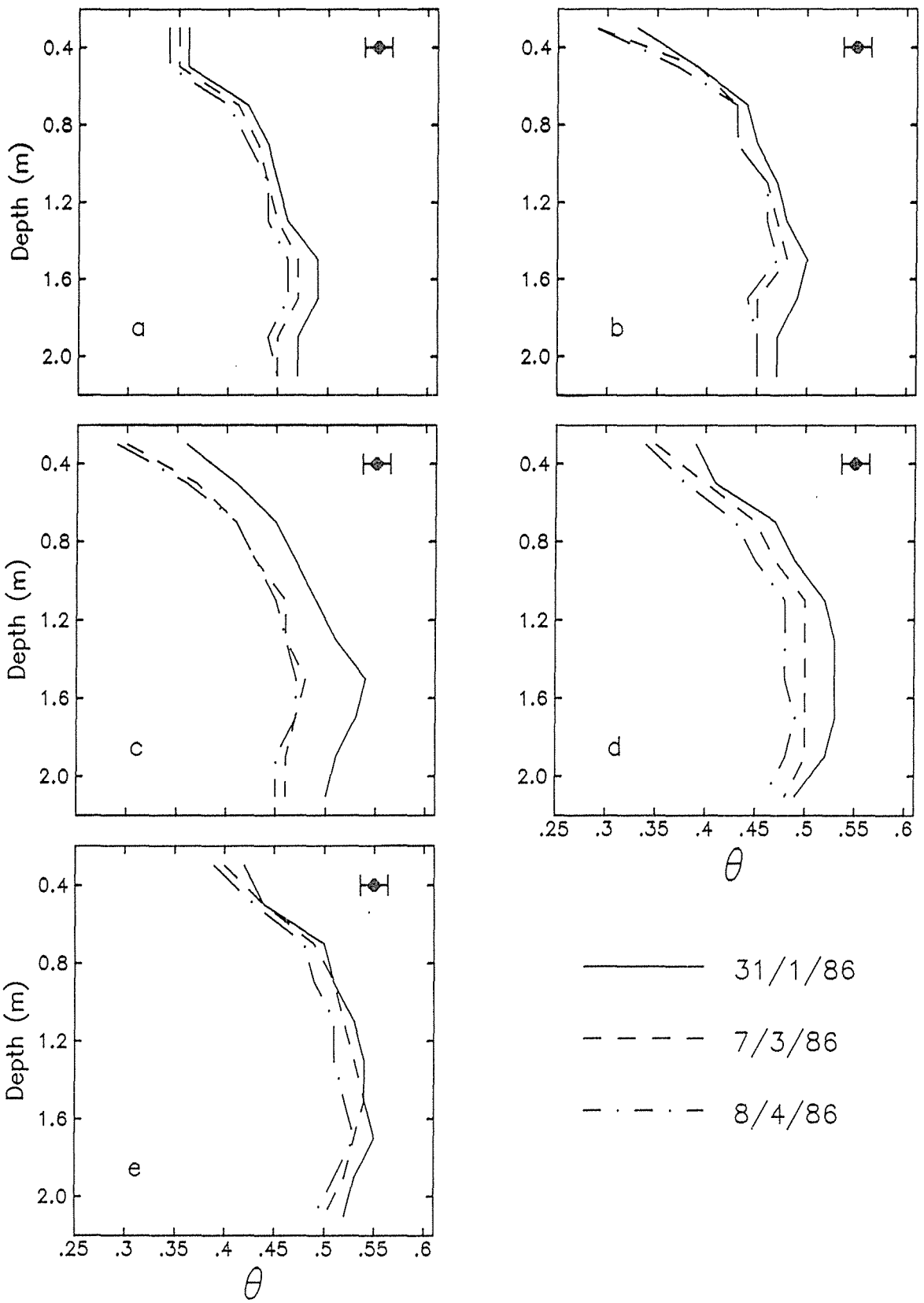

Figure 2.5 Water content under vine A at 31/1/86, 7/3/86 and 08/04/86, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine. The error bar shows the ± 1 sd error on θ.

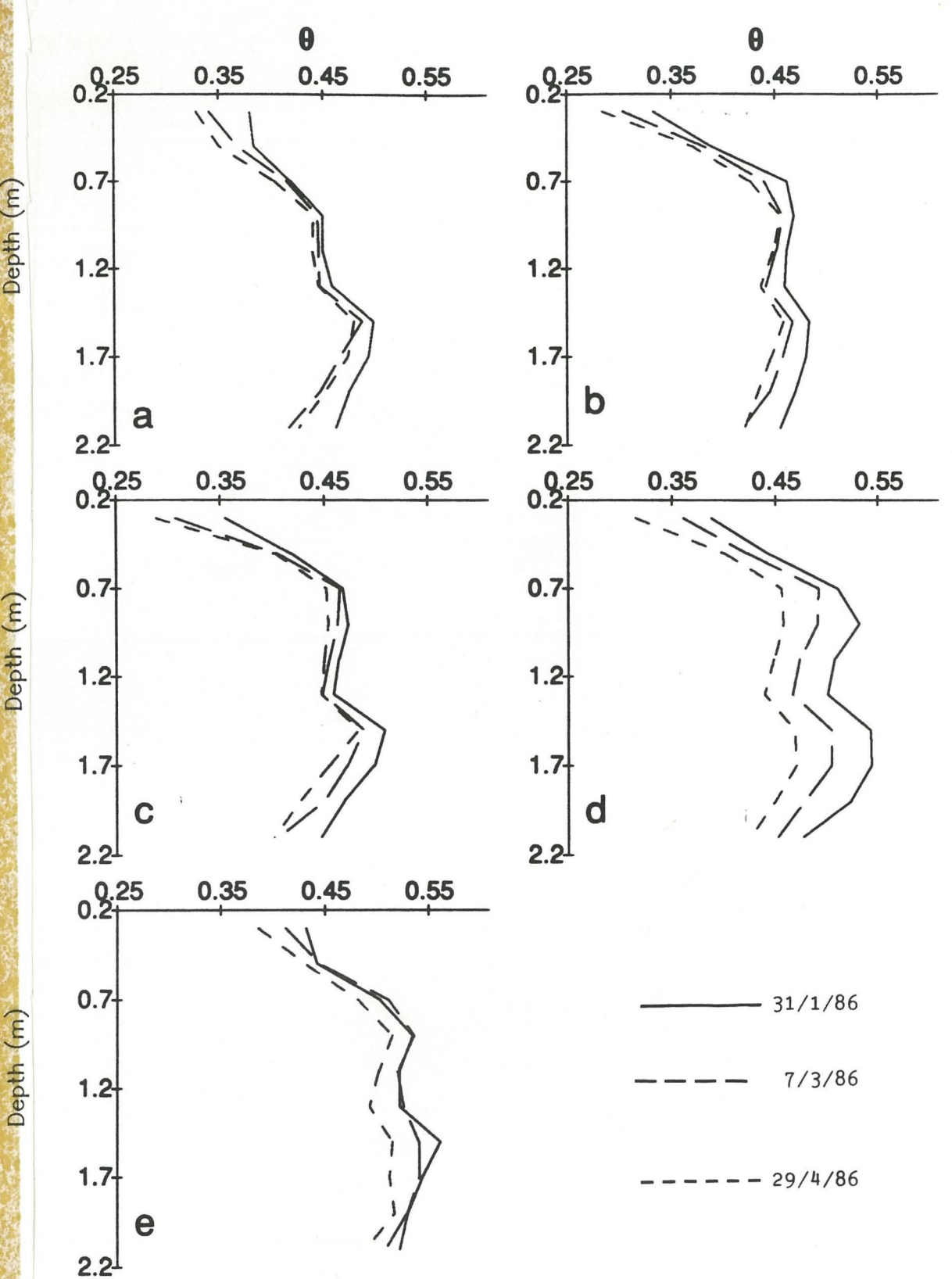

Figure 2.6 Water content under vine A at 31/1/86, 7/3/86 and 29/4/86, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0 m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine.

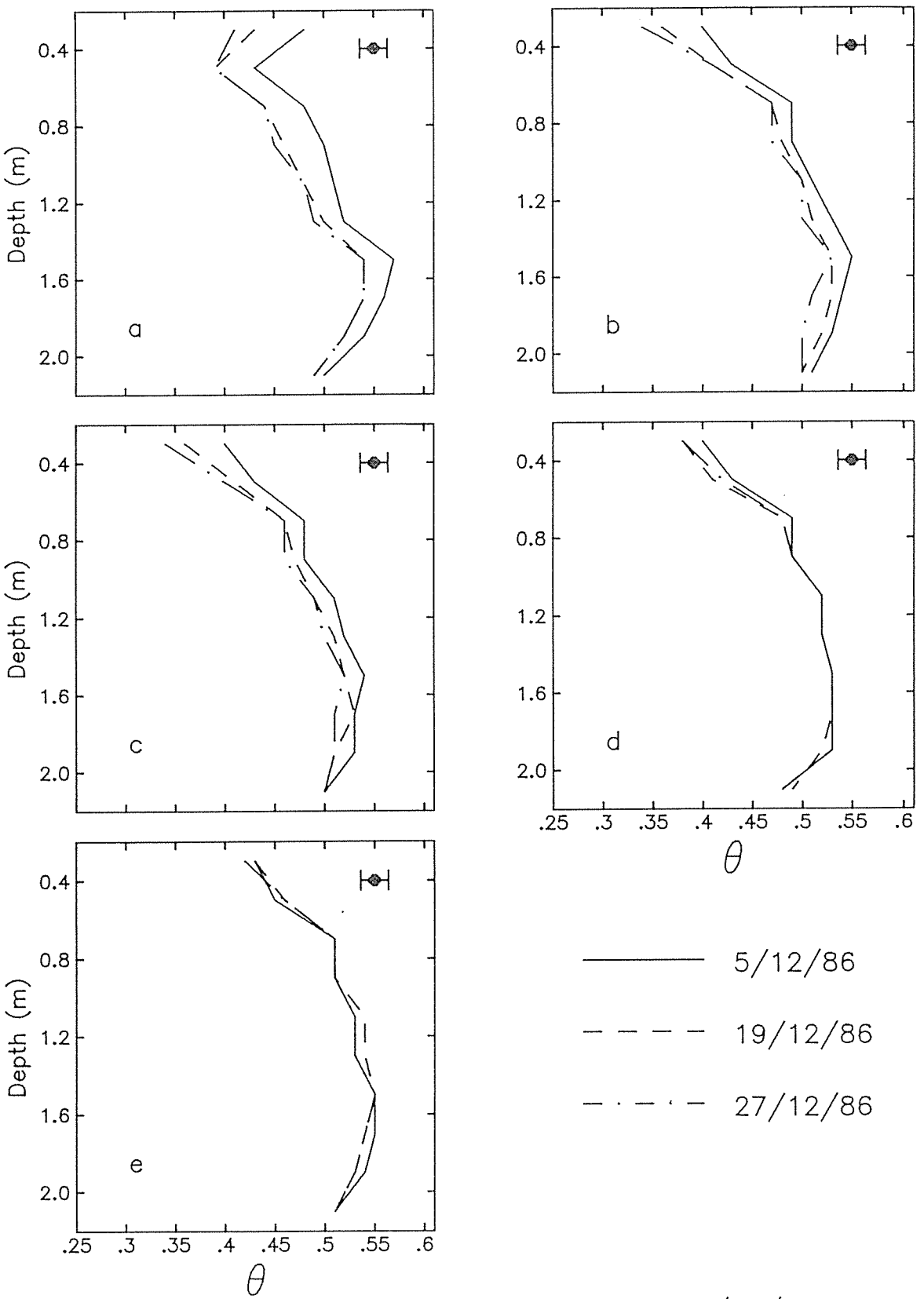

Figure 2.7 Water content under vine A at 5/12/86, 19/12/86 and 27/12/86, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine. The error bar shows the ± 1 sd error on θ.

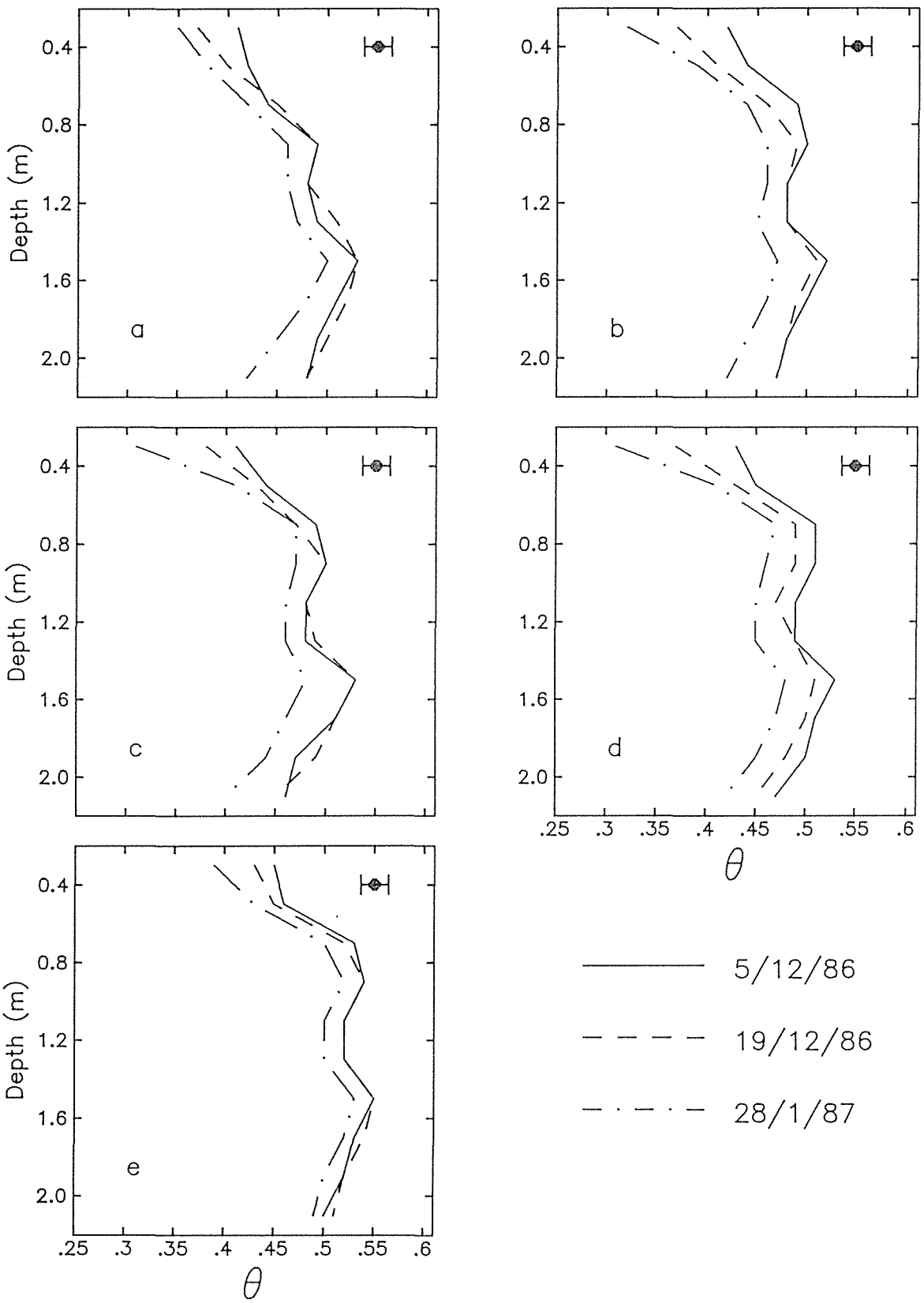

Figure 2.8 Water content under vine B at 5/12/86, 19/12/86 and 28/1/87, (a) 0m from vine, (b) 0.5m from vine, (c) 1.0m from vine, (d) 1.5 m from vine, (e) 2.0 m from vine. The error bar shows the ± 1 sd error on θ.

In order to calculate the volume of water stored within the root-zone from the water extraction data, it is desirable to determine the simplest form of symmetry which will fit the data, and then exploit this symmetry to simplify the calculations. The simplest form of symmetry which may apply to the water extraction data is one-dimensional, in which θ or $\Delta\theta$ may change only with depth. This type of symmetry may be ruled out simply by looking at the data (see for example Fig. 2.6). It can be seen that there is a marked variation in θ and with $\Delta\theta$ with horizontal distance from the vine. Therefore one-dimensional symmetry varying only with depth can be ruled out. The next most simple type of one-dimensional symmetry is spherical. This symmetry can also be ruled out as the variation in θ or $\Delta\theta$ with depth is less than the variation with horizontal distance. For example, if spherical symmetry could be applied, then the change in water content at 2 m depth should be the same as at 2 m horizontally from the vine. Obviously this is not the case.

The next level of complexity is two-dimensional symmetry. There are several types of two-dimensional symmetry, but the one most likely to apply to water extraction around an isolated vine is cylindrical symmetry. Cylindrical symmetry allows θ or $\Delta\theta$ to vary with horizontal radial distance from the vine and with depth. If the θ data show variation with orientation around the vine as well as with depth and horizontal distance, then a three-dimensional analysis, with orientation as the third dimension, is appropriate. As the $\Delta\theta$ data show no effect of orientation, two-dimensional cylindrical symmetry was assumed when the soil water data were analysed.

2.3.2 Root Length Density Patterns.

Plant root systems are highly variable. Measured root densities ranged from 0 km m^{-3}, to a maximum of 17 km m^{-3}. The frequency distribution of the densities was highly skewed, so that the mean density was 1.2 km m^{-3} but the median value was 0.6 km m^{-3}.

The root length density data is expressed in km m^{-3}. Ten km m^{-3} is numerically equal to 1 cm cm^{-3} and may be visualised as a 1 cm cube of soil with one root growing through it. The data are presented diagramatically in Fig. 2.9. Horizontal radial distance is displayed on

the ordinate, and depth on the abscissa. Each sampling position is indicated by a circle. If that sample contained roots at a density of greater than 10 km m^{-3} a filled circle appears, and if the root length density was found to be greater than 0 but less than 10 km m^{-3} a half-filled circle appears. The root density data span a period of 10 months and show no systematic change with time (K. A. Hughes, pers. comm.).

In the Carson's orchard, the root length density showed relatively little variation with depth. It is probable that there were substantial densities of roots below the maximum 2.0 m depth sampled. In contrast, there was a marked variation in root density with horizontal distance. Closer to the vine than 1.4 m most of the samples taken contained roots. Few roots were found beyond 2.5 m, and this may be considered to be the horizontal extent of the root zone. The root zone may then be sub-divided into two regions, one which is more-or-less completely occupied by roots, and a second in which the soil has only been scantily explored. The former region will be referred to as the zone of occupation and the latter as the zone of exploration. Note the similar terminology, but slightly different definitions, to those in Gandar and Hughes (1987).

2.4 General Discussion

The detailed pattern of water extraction around an individual vine is shown in Figs 2.5-2.8. Fig 2.10 shows the cumulative change in water content with time, relative to the assumed "field capacity" for the five horizontal radial distances from the vine that were measured. Note that the soil may not have been at field capacity when the covers were installed. As there is no evidence of variation in extraction with depth, the water contents shown represent the average observed at the distance indicated.

From these graphs it appears that in the 1985/86 season the water found within 1.0 m of the vine stem is uniformly available to the plant. It is possible that during the earlier stages of drying the water closer to the vine tends to be extracted first. Data for the very early stages of water extraction are not available so that this point cannot be investigated further. However, as preferential extraction of water close to the vine

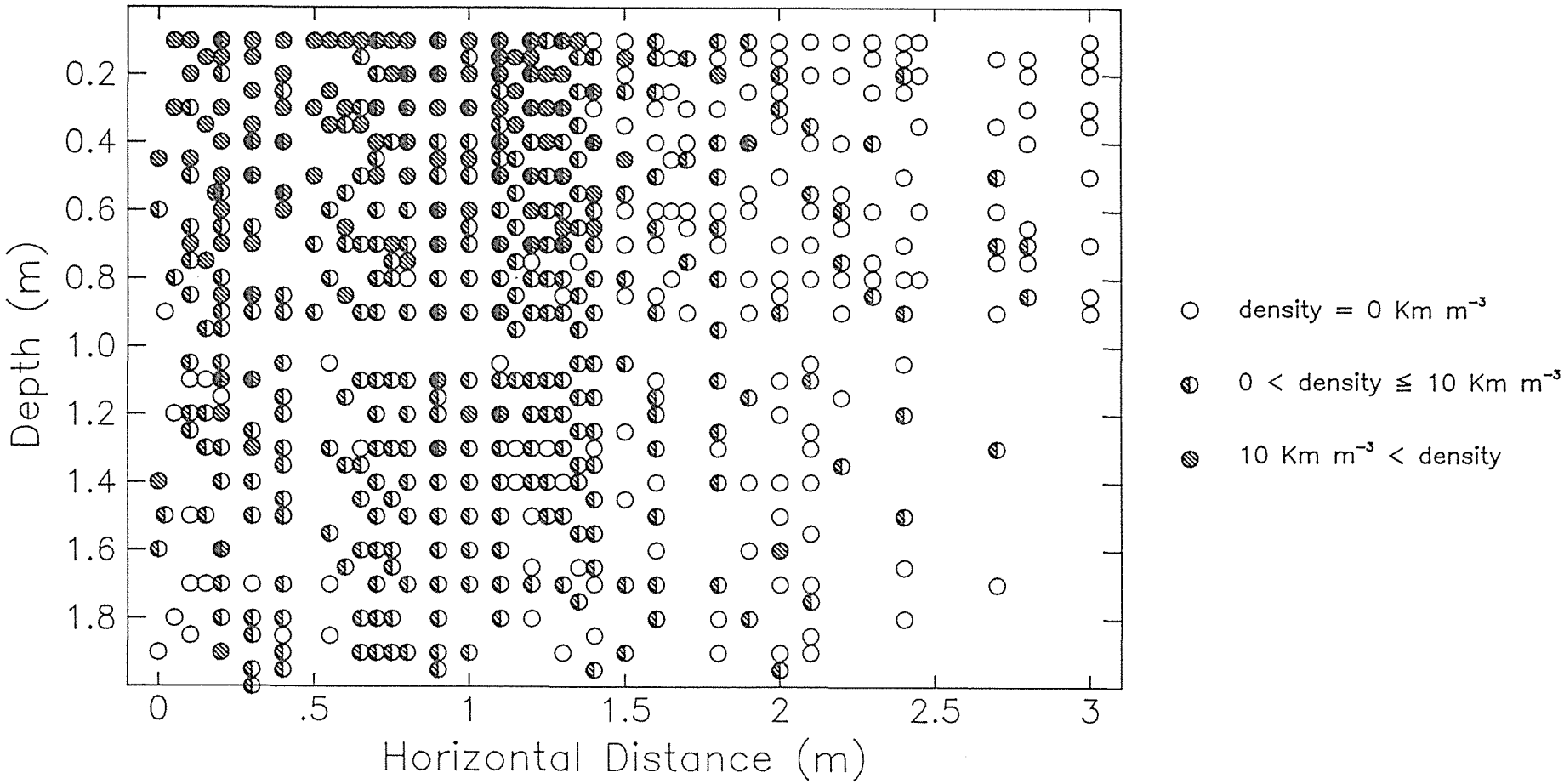

Figure 2.9 The pattern of root distribution around 7 year old vines in J. Carson's orchard.

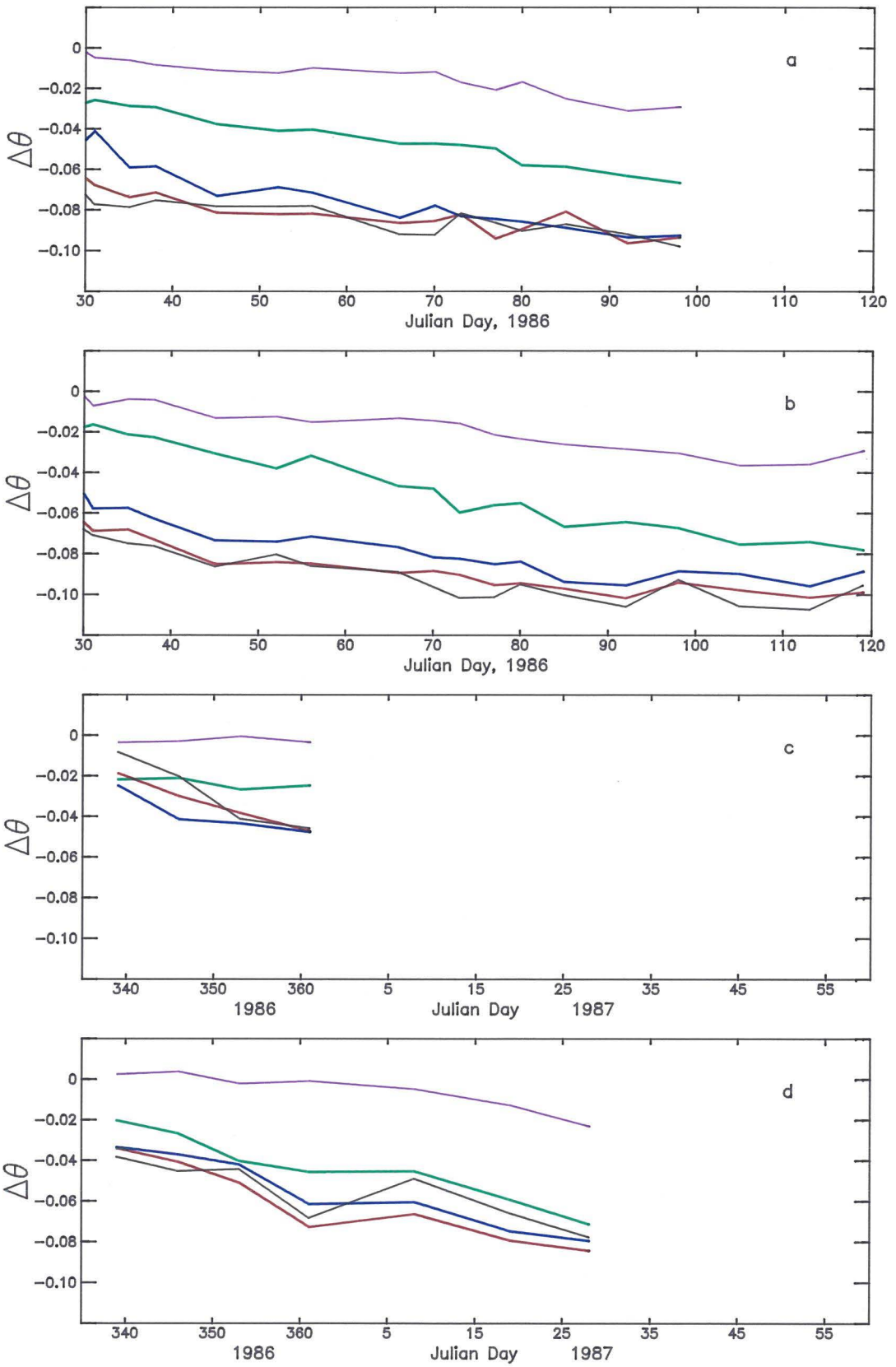

Figure 2.10 Soil water deficit, (a) vine A 1985/86, (b) vine B 1985/86, (c) vine A 1986/87, (d) vine B 1986/87.

— 0 m, — 0.5 m, — 1 m, — 1.5 m, — 2 m.

is mostly a function of root hydraulic resistance, with a more pronounced variation in extraction with distance associated with plants with high root resistances, and as kiwifruit have remarkably low root resistances (M^{c}Aneney and Judd, 1983), little preferential uptake would be expected within the zone of occupation. The water content at 1.5 m from the vine is more slowly reduced by vine, particularly at first, but by the end of the 120 day experimental period in 1985/86 the decrease in water content 1.5 m from the vine is not greatly different to that closer to the vine. The water 2.0 m from the vine is even more slowly extracted, the change in water content at 2.0 m being approximately half that of the other distances by the end of the experimental period. The same general pattern is repeated in the 1986/87 data, with the water at 1.5 m from the vine perhaps being more readily extracted than it was during the previous season.

The data presented in Figs. 2.5 to 2.8 show little variation in water extraction with depth. This is partially because water content was not monitored to the maximum depth of extraction. The actual pattern of extraction with depth is likely to be similar to that observed with horizontal distance, i.e. more-or-less constant to the maximum depth of rooting, then decreasing with depth due to some uptake by pioneering sparse roots, and upward flow into the zone of occupation.

Figure 2.10 shows the rooting distribution found in the orchard at four samplings between May 1986 and Feb 1987. From this it can be seen that the root density had started to drop 1.3 m away horizontally from the vine and that the root length density 2.0 m away was quite low. The combination of root data and water content data suggest that the water extraction observed at 2.0 m, and maybe at 1.5 m, was due, in part at least, to lateral flow into the zone of occupation rather than by direct uptake kiwifruit roots.

The water extraction within 1.0 m horizontally of the stem is more or less uniform, despite the increase in root length density closer to the stem. The same is true vertically. Although there are roots present at depth, the highest densities are found within 0.8 m of the surface. Water extraction was however more or less constant with depth, over the 2.2 m measured. This observation is consistent with the findings of M^{c}Aneney

and Judd (1983) that the hydraulic conductivity of kiwifruit roots was very high. These high conductivities imply that the water potential at all points in the root system may be almost equal. This being the case, then as long as the root length density is high enough to exploit the available water (this root density will be a function of the soil hydraulic properties) then water extraction should be even within that zone.

This effect may be illustrated using Gardner's (1960) theory of cylindrical flow to a single root. The root distribution may be idealised as a matrix of straight parallel roots spaced evenly at the required root density. Using the D and k functions provided in Gardner's (1960) paper, and water use and rooting volumes relevant to kiwifruit, it is possible to model the relationship between root density and the bulk soil water potential required to supply water to the vine at a given rate. It may be shown, using Gardner's equation (4), that if root length density is reduced from 10 km m^{-3} to 1 km m^{-3} it will be necessary to increase the bulk soil water potential by only 8 kPa to maintain the flux of water to the root. In terms of water content this change is only of the order of 0.01 m^3 m^{-3}. The lower root density is close to the median value while the higher density is approximately the 80^{th} percentile value of the root densities measured in kiwifruit. This analysis is illustrative only, as Gardner's theory assumes constant D and k functions and measured data are not available in this study. But it does illustrate how root densities may not be highly correlated with water uptake.

In the water uptake experiments of Herkelrath et al. (1977a), a wide range of root densities (33 to 252 km m^{-3}) resulted in the soil eventually being dried by water uptake to approximately the same water content at all depths and root densities. In Herkelrath's experiments however the water was preferentially taken up near the soil surface before deeper layers were dried out. The vertical variation in water uptake shown by Herkelrath et al. (1977a) is likely to be extreme because water flow between soil layers was physically prevented. Nevertheless, this phenomenon has been noted by other authors (e.g. Garnier et al., 1986, in peaches). Also in the data of Van Oostrum (1985) there is some evidence of preferential uptake from the upper soil layers during the early stages of drying. However some of this may have been due to evaporation from the

bare soil or to uptake by plants other than the kiwifruit. Herkelrath et al. (1977a) attributed the preferential uptake near the surface to high root densities allowing faster depletion of water near the surface. In the present study the change in root density with depth was not as great as that in Herkelrath's experiment. Also the potential for redistribution of water within the soil profile to smooth out vertical differences is greater in the current study than in Herkelrath's experiment. These two factors, coupled with the coarseness and timing of neutron probe measurements, may explain why no pattern of differential uptake with depth was noted in the present study.

There have been few studies of changes in water content around individual orchard trees, and fewer still around kiwifruit vines. Both van Oostrum (1985) and Prendergast et al. (1987) found some change in water extraction with radial distance from the vine. Their measurements were, however, not detailed enough to determine what type of extraction pattern existed. M^{c}Auliffe (1985) preformed a more detailed study on 4 and 5 year old vines in the same orchard as the present study. He found that there was significant extraction 1.0 m from the vine but little change in water content further than 1.0 m from the vine horizontally. The data presented in this thesis were collected 2 and 3 years after M^{c}Auliffe's study and found significant extraction to 1.5 m, with less extraction at 2.0 m.

Hughes et al. (1986) also sampled root length density in the orchard a year before M^{c}Auliffe's (1983) study. At this time the vines were 3 years old, and most of the roots were found within 1.0 m of the vine horizontally. Hughes et al. (1986) found the roots were concentrated in the top 1.0 m of the soil in 1984 and M^{c}Auliffe (1985) found significant extraction to only 1 m deep in 1983. By 1986/87 the roots were found to have grown to at least 2.0 m depth and the present study has found significant water extraction to this depth. These results indicate that as the plant matures and the root system grows, the volume of soil capable of supplying water to the vine increases accordingly. The consequences of this will be considered in more detail in Chapter 3.

2.5 Conclusion

The pattern of water extraction around 7 and 8 year-old kiwifruit vines on the Westmere silt loam was found to have cylindrical symmetry to a depth of 2.2 m. Below this depth, at the maximum depth of rooting, the symmetry is likely to change. Water extraction was relatively constant with depth to at least 2.2 m and uniform to 1.0 m radially. Water stored 1.5 m horizontally from the vine stem was more slowly extracted than that within 1.0 m of the vine, while water 2.0 m from the vine was even more slowly extracted. In the second season of measurement (8 year old vines) there was some evidence that the water stored at 1.5 m was more readily extracted than in the previous season.

The observed water extraction patterns were closely associated with the presence or absence of roots, but showed poor correlation with the measured root distribution patterns. The poor correlation is likely to be a result of low root resistances and relativly high soil conductivities.

The limit of measurement was 2.2 m deep and 2.0 horizontally from the vine. Significant extraction was found at the extremeties suggesting that water was extracted from greater distances from the vine horizontally and vertically.

CHAPTER THREE

THE RESERVOIR OF AVAILABLE WATER

This chapter is concerned with the determination of the size of the reservoir of available water, that is the volume of water which may be extracted by the kiwifruit vine without incurring any penalty in terms of fruit growth. Although the size of the reservoir has little effect on strategy once irrigation has commenced, it is a major determinant of when irrigation must commence, or whether it is needed at all.

3.1 Introduction.

When operating an irrigation system, the grower's aim is usually to maximise the return from the crop. In a high value crop, such as kiwifruit, where irrigation accounts for a relatively small proportion of the cost of production. But it may have a major impact on the yield and quality, so the aim of irrigation scheduling is to optimise the yield and quality of fruit. To quote Taylor (1965), "irrigation should take place while the soil water potential is still high enough that the soil can, and does, supply water fast enough to meet the local atmospheric demands without placing the plants under a stress that would reduce yield or quality of the harvested crop". The amount of water which may be removed below field capacity by the crop roots is the reservoir of available water. A rider to the quote from Taylor (1965) is that irrigation should not take place at such a high water potential that substantial amounts of water are lost to deep drainage. Drainage losses are undesirable, as they increase costs due to the need to apply extra water to compensate for the drainage loss, and by leaching of nutrients. The leached nutrients may have environmental consequences such as the pollution of ground water.

In combination with rainfall and the rate of water use by the vine, the size of the reservoir determines whether the crop would benefit from irrigation. For this reason it is important to know the size of the reservoir to help determine whether irrigation is economically

advantageous, and to decide when irrigation should commence.

The size of the reservoir is set by a complex of factors involving the soil, plant and atmosphere. Nor is the reservoir size constant, it may exhibit fluctuations on both a short-term (between days) and a long-term (between years) bases. The reservoir size is set crudely by the volume of the soil explored by the plant roots, and the amount of water stored in the soil between field capacity and the matric potential to which the plant roots can extract water. Other factors which may be important are flow into the volume of soil explored by the roots, and the rate at which the water is required by the plant. Another factor which may be important is the degree of water stress the plant can withstand before suffering reductions in marketable yield. This factor varies between species and may also vary with the physiological stage of the plant.

Historically there have been two opposite and extreme views of the availability of water to plants. One view was that all water stored in the soil between field capacity and the permanent wilting point was readily-available to the plant (Veihmeyer and Hendrickson, 1955). On the other hand, Thornthwaite and Mather (1955) were of the opinion that there was a linear decline in "availability" of water such that the relative availability of water fell from 100% at field capacity to 0% at the permanent wilting point.

The opposing views were, partially at least, reconciled by the theoretical work of Gardner (1960) and the experimental work of Denmead and Shaw (1962). Gardner (1960) solved the equation for flow of water through the soil to a single root, assuming constant soil-water diffusivity. He showed that as the flux of water to the root increased, the water potential at the root surface decreased for a given potential in the bulk soil. Thus, as the transpirational demand rises, the bulk soil water potential at which the plant cannot extract sufficient water to meet its need rises.

The two opposing views, discussed above, of the availability of water to the plant arose from experimental work carried out under different regimes of atmospheric demand for water. The above discussion of water availability is in terms of the transpiration rate of plants at different

levels of soil moisture in relation to well-watered plants. However the parameter of more concern in the present case is the growth of fruit, rather than of water use per se. Transpiration may be considered to be governed by the ease with which water vapour molecules diffuse out of the stomata, while photosynthesis (and by implication fruit growth) is governed by the ease with which CO_2 molecules diffuse into the stomata. The two properties are not necessarily well related (Cowan and Troughton, 1971).

Numerous authors have described the flow of water through the soil and plant to the atmosphere using the analogy of a resistance network (e.g. Cowan, 1965). Using this approach, the loss of water from the leaves to the atmosphere causes the water potential in the leaves to fall, thus encouraging the flow of water from the roots to the leaves. In this manner a gradient of water potential is set up through the plant. The magnitude of the water potential in the leaves is determined by a number of factors, but if it is assumed that there is no active intervention by the plant itself, it is determined by the balance between the supply of water from the lower regions of the plant and the demand for water by the atmosphere. The water potential in the roots will be higher than that in the leaves but lower than that in the soil adjacent to the roots.

As the plant extracts water, the soil dries and the soil water potential drops. To extract additional water, at the same rate as from wetter soil, the water potential in the roots, and therefore the leaves, must fall. This process will continue until eventually the leaf water potential falls to such an extent that other physiological processes (e.g. fruit growth) begin to suffer.

First let us consider the processes associated with the plant, which affect the reservoir size. At the onset of water stress, the leaf is at a certain critical leaf water potential which has, in some manner, been propagated down to the root surface. The water potential at the root surface induces uptake, and therefore flow, from the surrounding soil. Thus the soil around an individual root has a water potential which is low near the root surface and rises to some more-or-less constant value in the bulk soil away from the root. The pattern of water potential around the isolated root was solved for the constant soil water diffusivity case by

Gardner (1960).

Various authors have discussed, or obtained, values for many of the components of soil and plant resistances; e.g. root radial resistance (Michel 1977, Taylor and Keppler 1975), and root axial resistance (Rowse and Barnes 1979, Landsberg and Fowkes 1978), etc... Often the conclusion they arrived at when trying to link resistances together was that either the soil or root resistance was higher than it was often assumed or measured to be. Depending on the perspective of the author(s) involved, the other resistance was blamed for the discrepancies in the data. One explanation postulated was that there was an additional contact resistance in the transfer of water between the soil in close proximity and the root surface to the root itself. Huck and Hillel (1983) proposed that there may be a vapour gap between the root and soil, caused by the root shrinking away from the soil. Root shrinkage has been observed (Huck et al., 1969), but at soil water potentials less than -500 kPa. This does not explain the high resistance still present at soil water potentials above -500 kPa. Herkelrath (1977b) found, in laboratory experiments, that the resistance began to rise at around -10 kPa and postulated that at potentials lower than this, soil water began to retreat into the small cracks and corners created by adjoining soil particles, and in doing so left ever-increasing areas of root surface in contact with air rather than water. The retreat of water away from parts of the root surface would effectively decrease the absorbing area of the roots, and so account for the observed increase in resistance.

If the critical leaf water potential for yield reduction was constant, then due to fluctuating atmospheric demand, the water potential of the bulk soil would vary with weather conditions. In order to supply an increased demand, the flux of water through the soil to the roots must increase, thus causing a greater difference in water potential between bulk soil and root surface. This effect will occur within and between days. Thus, during times of high transpirational demand, even though the leaf water potential may be the same as at times with low transpirational demand, the soil water potential to which the roots can dry the soil will be lower, because of the greater head loss between the bulk soil and the plant roots incurred at higher rates of water loss.

So then, for a given leaf water potential and transpirational demand the plant will be able to reduce the water potential of the soil to a certain level. A stress point will be defined as the soil water potential at which the plant can no longer remove water without causing undesirably low leaf water potentials. The amount of water available to the plant will be the amount of water stored in the soil explored by the roots between field capacity and the stress point, plus any water which may flow into the root zone from unexplored soil during soil water extraction. The amount of water stored in the soil between field capacity and the stress point, is a function of the pore size distribution in the soil, and can be estimated from the water retentivity curve. The importance of flow into the root zone will be dependent on soil hydraulic properties, the geometry, and the volume of unexplored soil relative to the rooted soil.

The volume of soil explored by the roots will largely determine the size of the reservoir. Kiwifruit are planted at wide spacings and so may take 10 or more years to explore the soil available to them (Hughes et al. 1986, Clothier et al. 1986). The wide spacing, and especially the potential for deep rooting (Greaves 1985, Hughes et al. 1986), implies that a kiwifruit vine may be able to call upon a large volume of readily-available water.

The leaf water potential below which fruit growth is adversely affected has not been extensively researched. Van Oostrum (1985) found that irrigated vines had pre-dawn leaf water potentials of around -0.05 MPa, falling to -0.5 MPa at solar noon on a hot, cloudless day. Stomatal conductance was found to decrease if leaf water potential fell below -0.6 MPa. This figure is far higher than the reported range of critical leaf water potentials for stomatal closure for several species (Ritchie and Hinckley, 1975). Van Oostrum (1985) found that if pre-dawn leaf water potential was above -0.14 MPa, wilting was unlikely to occur during the day. Pre-dawn leaf water potential of -0.14 to -0.65 MPa led to vines wilting during the day but recovering at night. If the pre-dawn leaf water potential fell below -0.65 MPa, incomplete nocturnal recovery occurred. In another study (Judd et al., 1987) indicated that if pre-dawn leaf water potential fell below 0.1 MPa kiwifruit vines were stressed.

The point at which the kiwifruit vine becomes stressed does not correspond to a constant soil water potential but will vary with the prevailing conditions. Also the volume of water which may be extracted between field capacity and the onset of stress will vary markedly with vine age.

3.2 Methods.

The general pattern and symmetry of water extraction was discussed in Chapter 2. This section is concerned with the calculation of volumes of water extracted from, or stored within, the root zone.

The water content and root length density distributions measured, as described in Chapter 2, were also used in the determination of the reservoir of water stored within the root zone of the kiwifruit. The discussion of errors associated with these measurements in the previous chapter is also relevant. However the error on the calculation of volumes of water stored in the soil needs further discussion.

First consider the error in the calculation of a volume of water. In Section 2.2.2.4 it was concluded that θ varied significantly with depth and that the error on an individual estimate of θ was 0.014 $m^3\ m^{-3}$. The estimate of θ in each of the 50, 0.2 m thick, annuli is the mean of two measurements, so the error on θ in each annulus is 0.031 $m^3\ m^{-3}$. To calculate the volume of water, the water content in each annulus is multiplied by the volume of the annulus, and the resultant products summed. The error in the volume of water is calculated similarly, using the variance of the water content estimate of the annulus rather than the water content itself. Thus, the error in the volume of water in the root zone (that is the volume of soil 2.2 m deep and within a radius of 2.25 m horizontally from the vine) may be calculated to be $\pm$ 0.1 m^3.

The change in water content was found not to vary significantly with depth and to have an error of 0.011 $m^3\ m^{-3}$ (see Section 2.2.2.4). The error calculation for the volume of water extracted is similar to that for a volume of water stored but there are 20 estimates of $\Delta\theta$ within each of the 5 annuli. The error may be calculated to be $\pm$0.07 m^3.

3.2.1. Fruit Volume Measurements.

In order to determine the reservoir of water readily-available to the kiwifruit, and to assess the impact of withholding water from the vine on the economic yield, fruit volumes on the covered vines and two irrigated vines were measured.

In January of 1986, 12 fruit from each of the vines to be covered (vines a and B) and two further vines close by (control vines X and Y) were tagged for measurement of fruit volume change through the season. (See Fig. 1.3 for the position of the vines in the orchard block.) The fruit volume measurements were commenced on the 28th of January and carried out approximately twice a week until harvest. The fruit volume was measured by the displacement technique. The measurement vessel was a perspex tube with a graduated tube connected to one side (see Fig 3.1). The device allowed measurements to be taken to the nearest 2 ml. The method was to read the water level, the fruit was then immersed until the calyx was just covered and the water level read again. A bubble level attached to the base allowed the device to be kept perpendicular. There were some air bubbles trapped by the hairs on the fruit, but as the volume of these bubbles was more or less constant with time and as they were of small volume compared with the volume of the fruit, they caused little error.

In addition to the normal sampling of the same 12 fruit on the vines, a sample of 100 fruit/vine was measured on 11/4/86 on a once only basis. This mass sampling was to assess if the rather small sample of 12 fruit was representative of the population of fruit on the vine.

Fruit volume is affected by fruit loading, canopy structure and the efficiency of pollination, as well as vine water relations. To help account for these effects, the numbers of fruit and leaves on each vine were counted in early April of 1986. After the final fruit volume measurement the sample fruit were picked for subsequent counting of the number of seeds per fruit to assess pollination effects.

The seeds were extracted by allowing the fruit to become over-ripe, removing the skin and forcing the remaining pulp through a sieve with water. The seeds were then recovered from the sieve and dried. The

Figure 3.1 Device for measureing fruit volume.

end-product of this extraction process was the dried seeds, contaminated by some flakes of central core and septa. The amount of material contaminating the seeds varied from fruit to fruit. Each kiwifruit contains approximately 900 to 1600 seeds. To count this many seeds by hand takes approximately 30 min and considerable errors are inevitable. In order to shorten the counting time and reduce error a subsample of 200 seeds were counted and weighed. Care was taken to ensure that the subsample contained a representative amount of debris as well as seed. The total weight of the seeds was taken and the number of seeds calculated from the ratio of the weights. On eight fruit, chosen to span the range of sizes encountered, all the seeds, as well as the sub-sample were counted. The correlation between the calculated number of seeds and the counted number of seeds was 0.998 (n=8). The largest discrepancy was 24 seeds. Due to the difficulty of counting large numbers of seeds, and the associated errors, this magnitude of error was considered to be acceptable. The time taken for the subsampling method was approximately 5 min per fruit as opposed to 30 min when all the seeds were counted.

In the 1986/87 season an effort was made to ensure that all the fruit chosen started with the same initial fruit size. Before flowering, 20 shoots per vine were selected which were terminal shoots of approximately 5 nodes length, with 3 to 6 flower buds of even bud development between and within shoots. The flowers were monitored so that the day of opening was recorded and the flowers artificially pollinated. Sufficient flowers opened between the 4th and 7th of December to allow 10 canes per vine with at least three flowers per cane. A week after flowering was complete, the number of flowers per canes was reduced to 3. By 29/12/86 flower abscission had finished and the number of fruit was reduced to 2 on each of the 10 canes per vine. Using the standard deviations measured in the previous year, significant differences should have been in the order of 1 size class.

Fruit volumes were measured using the same system as in the 1985/86 season. The first measurement was at 29/12/86, and subsequent measurements were taken at approximately weekly intervals. By the end of the season the number of tagged fruit per vine had been reduced to 2 fruit on each of 9 canes.

3.2.2 Pressure Bomb Measurements.

In the 1986/87 season it was decided to measure leaf water potential to monitor vine water relations. Pressure bomb design and use has been described fully by Ritchie and Hinckley (1975) and so will only briefly be discussed here. The leaves chosen for pressure bomb measurements were fully expanded leaves in full sunlight. The chosen leaf was sealed in a plastic bag and severed from the vine with a scalpel blade, at approximately 20 mm from the point of attachment to the cane. The severed leaf and plastic bag were then inserted in the pressure bomb and the pressure slowly increased, at approximately 0.05 MPa per second, until the balancing point was reached. The time taken between severing the leaf and reaching the balancing point was between 60 and 90 seconds, depending on both the distance of the vine from the pressure bomb and the pressure required to equalise the leaf water potential. The sampling scheme was to measure the leaf water potential of the covered vines between measurements taken on irrigated vines. On day 9 of 1987 a third vine, vine C, was chosen and a cover installed under it. Leaf water potentials only were measured on this vine.

To distinguish when the leaf water potential of the covered vines started to fall below that of the irrigated vines, the data from the irrigated vines were fitted with a parabola of the form;

$$\psi_l = a + b\ t^2 \qquad (3.1)$$

where ψ_l is the leaf water potential (MPa), t is time (hrs) and a and b are fitted parameters. The parabola was fitted using a regression. The parabola fitted the data reasonably well (a typical R^2 was 60%), as in most cases all the measurements were taken on one side of solar noon (when leaf water potential usually reaches a minimum). On one occasion the diurnal pattern of leaf water potential was measured and to get a reasonable fit in this case the following equation was used;

$$\psi_l = a + b\ (t - 15.6)^2. \qquad (3.2)$$

The value 15.6 MPa was the observed minimum leaf water potential of the irrigated vines.

The parabola fitted to the irrigated vines was then used to interpolate reference leaf water potentials at the time at which leaf water potentials on the covered vines had been taken. The deviation in the ψ_l of the covered vines, from the reference of the irrigated vines, was calculated and subjected to a t-test to see if they were significantly different from 0. In a few cases (generally corresponding to times when there were either very few measurement points or there was intermittent cloud) the parabola did not fit well. In these cases the data set was discarded.

3.3 Results and Discussion.

3.3.1 Fruit Volume Measurements.

3.3.1.1 Irrigated Vines, 1985/86 Season.

The fruit volume data for the 1985/86 season are shown in Fig 3.2. The shape of the fruit volume curve is that of a single-sigmoid rather than the double sigmoid observed by Lees (1982), Hopping (1976b) and Grant and Ryugo (1984b) or the triple-sigmoid found by Pratt and Reid (1974). The fruit volume of the control vines rose from approximately 60 ml at 50 days after peak flowering, to between 100 and 105 ml at harvest. These volumes are similar to those measured by van Oostrum (1985) in the Bay of Plenty, but higher than the volumes calculated (from measured length and diameter) by Pratt and Reid (1974). Although weight (in g) and volume (in ml) are approximately numerically equal during most of the fruit development (van Oostrum, 1985), the weights reported by Hopping (1976b) and Grant and Ryugo (1984b) are lower than the volumes measured here.

The fruit volumes measured on the two control vines are significantly different to each other from Julian day 76 onwards. By harvest this difference averaged 10.5 ml, approximately 1 size class difference. Factors affecting fruit size include pollination efficiency, date of flowering, position of the fruit on the vine, lighting regime, water and nutrient relations and crop loading. In addition, it is possible that the small number of fruit sampled (11) may not have been a representative sample of the population.

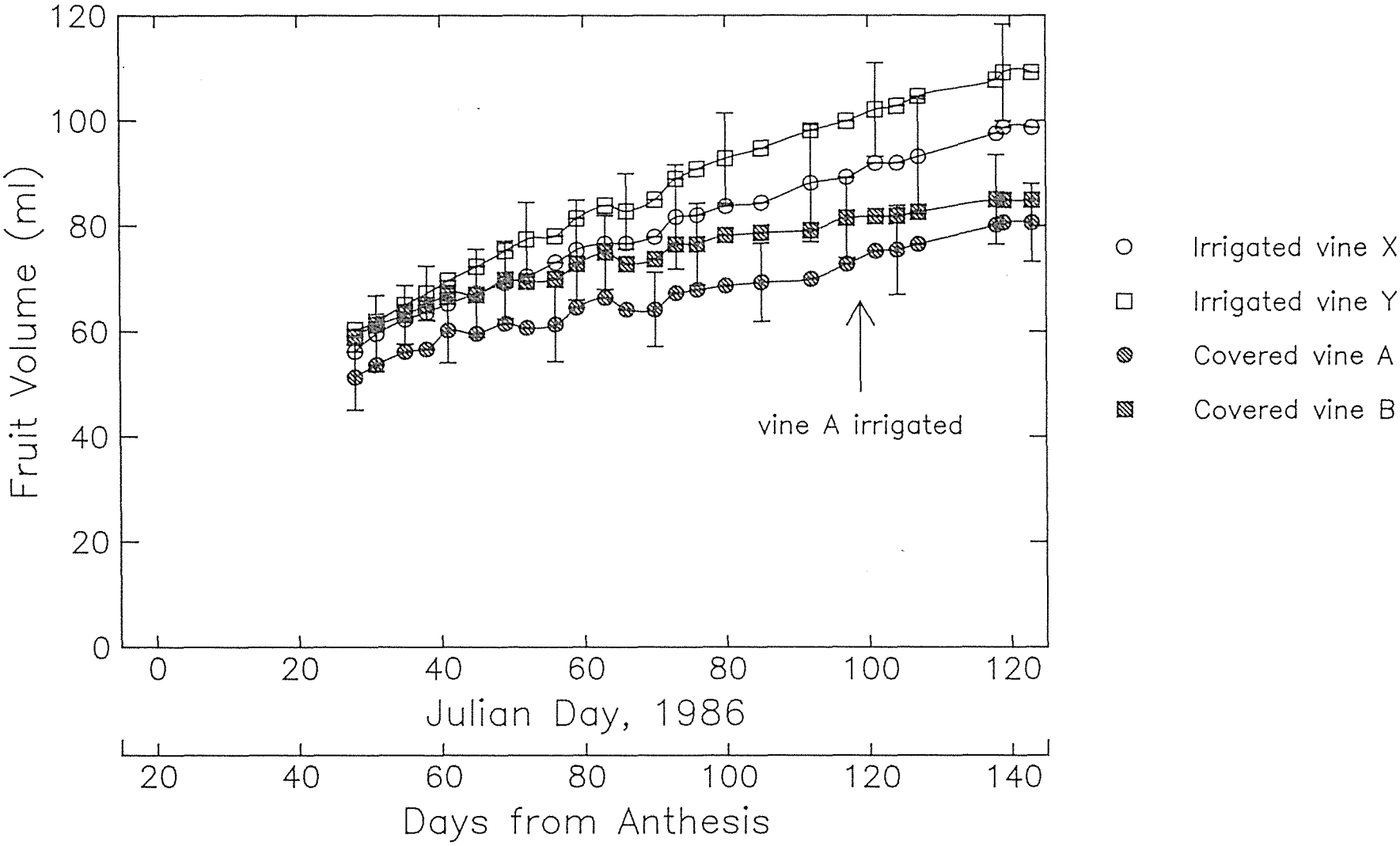

Figure 3.2 Fruit volume for the 1985/86 season.

The error bars show ± 1 standard deviation.

The fruit of control vines X and Y differed in size by an average of 4.2 ml at 50 days after peak flowering. Cell division in kiwifruit slows down at 30 days from pollination, and is complete by 50 days (Hopping, 1976b), so the fruit size at 50 days is determined largely by the number of cells. Further increases in fruit size are by cell expansion only. Therefore low cell number may affect fruit growth in the future, and result in low fruit volumes at harvest. Although the initial difference in fruit volume is not statistically significant, the difference may become significant as the fruit matures.

The individual flowering dates of the fruit sampled in the 1985/86 season was not known as the fruit were selected in January. It must be assumed that there were no differences in water or nutrient relations between the control vines (although such differences are possible due to rootstock variability). The lighting regime of the vines was not visibly different. The crop loading of the two vines was, however, quite different. Control vine X had 1184 fruit, and these fruit had an average volume of 91.9 ml in the first week of April. at this time control vine Y had 756 fruit with a mean volume of 102.1 ml. On kiwifruit growing in Hawkes Bay that were a year younger than these vines, a difference in fruit number of the order observed in the control vines led to a difference in fruit weight of 8-14 g, depending on the amount of cane on the vine (Cooper and Marshall, 1987). This difference is similar to that observed in this study.

Another factor known to affect fruit size is the number of seeds in the fruit (Hopping, 1976a). The mean seed number in the fruit of control vine X was 1149, and of control vine Y, 1278. These numbers are significantly different. In Hopping's (1976a) trial a difference in seed number of this magnitude caused a 15 g difference in fruit weight at harvest.

A sample of 12 fruit from a total of 700-1200 is only about 1% of the total crop and may not be representative. In order to assess whether the samples were representative, a mass sampling of 100 fruit per vine was carried out. Only in control vine X was there a significant difference between the sample of 12 and the larger sample. In this case the difference was significant to the 1% level. The sample of 12 had a mean volume 5.2 ml higher than the sample of 100. If the sample of 100 is assumed to be a more accurate estimate of the mean fruit size of the

population of fruit on the vine than the original sample of 12, then the real difference in fruit size between control vines X and Y is greater than that indicated by the routine measurements.

These factors, fruit number and seed number, help explain the differences between the mean fruit sizes measured on the irrigated vines. Although this analysis will help in the design of future experiments, it does not help with the analysis of this experiment. Three ways of dealing with the problem were investigated. The first was to select fruit from the sample of 11 with initial fruit sizes which lay within a defined, narrow range. This option has been used successfully (van Oostrum, 1985) by choosing fruit sizes which initially differed over only 2 ml. This proved not to be possible in this trial, due to the large differences between the initial sizes of the fruit.

The second option investigated involved examining the growth rates of the fruit rather than the absolute sizes. Although this method introduces additional noise into the system (for example an error in a reading on one date will affect the growth rate measurement on two occasions) it lessens the effect of initial size. The factors which set the initial size are however not completely screened out. The third option is to use relative growth rate, that is the ratio of the growth rate to the initial size. Using relative growth rate helps screen out historical effects, but involves yet another calculation with subsequent loss of degrees of freedom.

The growth rate of the two control vines was significantly different only between 100 and 105 days after anthesis. When relative growth rate was used significant differences were found between 93 and 96, and 107 and 121 days after anthesis. Thus the use of the relative growth rate, shows no advantage over absolute growth rate so growth rate was used in subsequent analysis, with the average of the two control vines used for comparison with covered vines.

The fruit growth did not proceed in a smooth fashion, but at times showed marked "dips" in volume growth. These dips were evident in both the irrigated and covered vines but were a little more accentuated in the covered vines. The two most marked dips (starting at Julian days 52 and

63) correspond to times when there has been a period (5-10 days) of low solar radiation and temperature (see Fig 3.3). Overall fruit growth appears not to be well correlated with solar radiation.

3.3.1.2 Non-irrigated Vines, 1985/86 Season.

As can be seen from Fig 3.2, by harvest-time the fruit sampled on the two covered vines were substantially smaller than the fruit sampled on either of the irrigated vines. The fruit of covered vine A were smaller than the fruit of the irrigated vines at the time that the covers were installed. Possible reasons for the difference in fruit size have already been discussed in Sections 3.1 and 3.3.1.1. Covered vine A had the largest number of fruit (1231) and a seed count comparable to that of control vine X (see Table 3.1). As a 4.2 ml difference in initial size subsequently led to significant differences of fruit size in the control vines, the differences in size between the control vines and covered vine A cannot be attributed to the lack of water alone.

When fruit growth rate is used to indicate differences between irrigated and non-irrigated vines, then the fruit growth on the covered vine B is lower than that of the irrigated vines on four occasions. These occasions are 61-65, 69-72, 86-94, and 105-112 days from anthesis. The first two occasions coincide with periods when the fruit growth of covered vine A has also decreased, while the fourth occurred after vine A had been irrigated. It is interesting to note that on no occasion were successive measurements of fruit growth significantly different. If the decrease in fruit growth was due to the onset of an unrelieved water stress then one would expect fruit growth to remain low. Judd and M^{c}Aneney (1986) hypothesised that once a kiwifruit vine has experienced water stress, the fruit growth approaches zero until the stress is relieved. After water is applied the growth resumes at a rate comparable to that found in vines which had not been water stressed. This pattern was not observed in the current study.

Control vine Y and covered vine B have similar initial fruit sizes, crop loading and seed numbers. All other things being equal then the fruit from these 2 vines should be comparable. This would allow the fruit volume to be used as the comparative measure. Fruit size is probably the

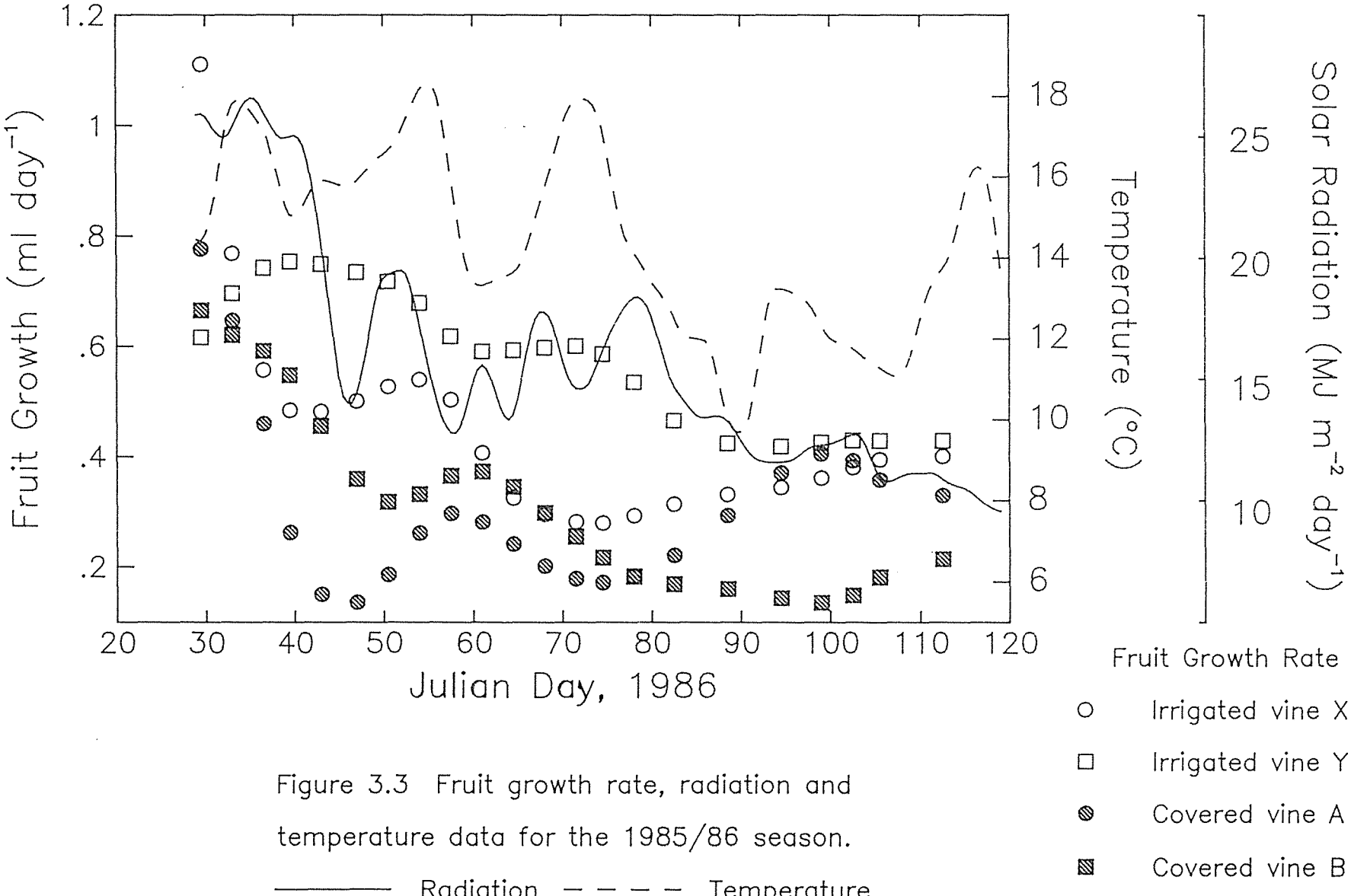

Figure 3.3 Fruit growth rate, radiation and temperature data for the 1985/86 season.

Table 3.1 Miscellaneous Fruit Data.

	Mean (sd)			
	Covered A *	Control X	Covered B	Control Y
Initial Volume 22/1/86 (ml)	51.3 (6.2) a	56.2 (8.4) ab	59.2 (5.5) bc	60.4 (7.0) bc
Final Volume 3/5/86 (ml)	80.6 (7.4) a	98.7 (12.2) b	84.9 (7.8) a	109.1 (9.2) c
Volume at 11/4/86 (ml)	75.3 (7.5) a	91.9 (11.3) b	81.9 (8.0) a	102.1 (8.9) c
Sample of 100	69.9 (16.8) a	76.4 (13.0) a	81.8 (13.1) a	97.0 (15.8) b
Difference **	NS	1%	NS	NS
Fruit Number	1231	1184	714	756
Seed Number	1166 (117)	1149 (90)	1224 (100)	1278 (117)

The letters refer to the numbers immediately above. Different letters indicate a significant difference across the row. * Covered vine A had been irrigated since 8/4/86. ** The difference refers to the comparison between the sample of 12 and the sample of 100. NS = not significant. The level of significance of the differences between samples was calculated using a t-test.

best measure as it is both an integrative parameter and the parameter which eventually sets the return to the grower. Slightly decreased fruit growth can lead to significantly reduced fruit volumes, therefore fruit volume should be a more sensitive parameter than growth rate. The fruit of vine B were significantly smaller than the fruit of control vine Y on Julian day 52 (72 days after anthesis, 30 days after the covers were installed). The fruit growth rate had been significantly different once, some 9 days earlier.

The main purpose of measuring fruit growth was to indicate the onset of water stress. Due to the difficulties with comparisons between vines, this proved difficult. However, as mentioned before, vines Y and B have similar properties and may therefore be compared. Fruit size on these two vines were significantly different on Julian day 52. At this time there had been one and two prior instances of decreased fruit growth (relative to growth in the irrigated vines) in vines A and B respectively. During this time fruit growth had not been consistently lower in the covered vines. From this, it appears that there was enough water stored in the soil profile at the time the vines were covered to allow growth to proceed for 30 days, at a rate comparable to the irrigated vines, Thus, water contents measured under vine B on Julian day 52 should indicate the lower limit of readily available water.

3.3.1.3 Irrigated Vines, 1986/87 Season.

The fruit size data for the 1986/87 season are shown in Fig 3.4. In this year the fruit were chosen so they were pollinated within 4 days of each other at the peak of flowering, and there were only 2 fruit on each determinate cane of 5 to 7 nodes. These restrictions were enforced to ensure the the sampled fruit were comparable between vines.

As with the 1985/86 data, the fruit show a single sigmoid growth curve. This is in contrast to the findings of several other authors also working on kiwifruit. The separation between the phases 1 and 2 is quite distinct at 61 days from anthesis, similar to the break found by Pratt and Reid (1974), Hopping (1976b) and van Oostrum (1985). There is some evidence that a second phase of increased growth may have commenced at 107 days from anthesis, but additional measurements would be needed to confirm

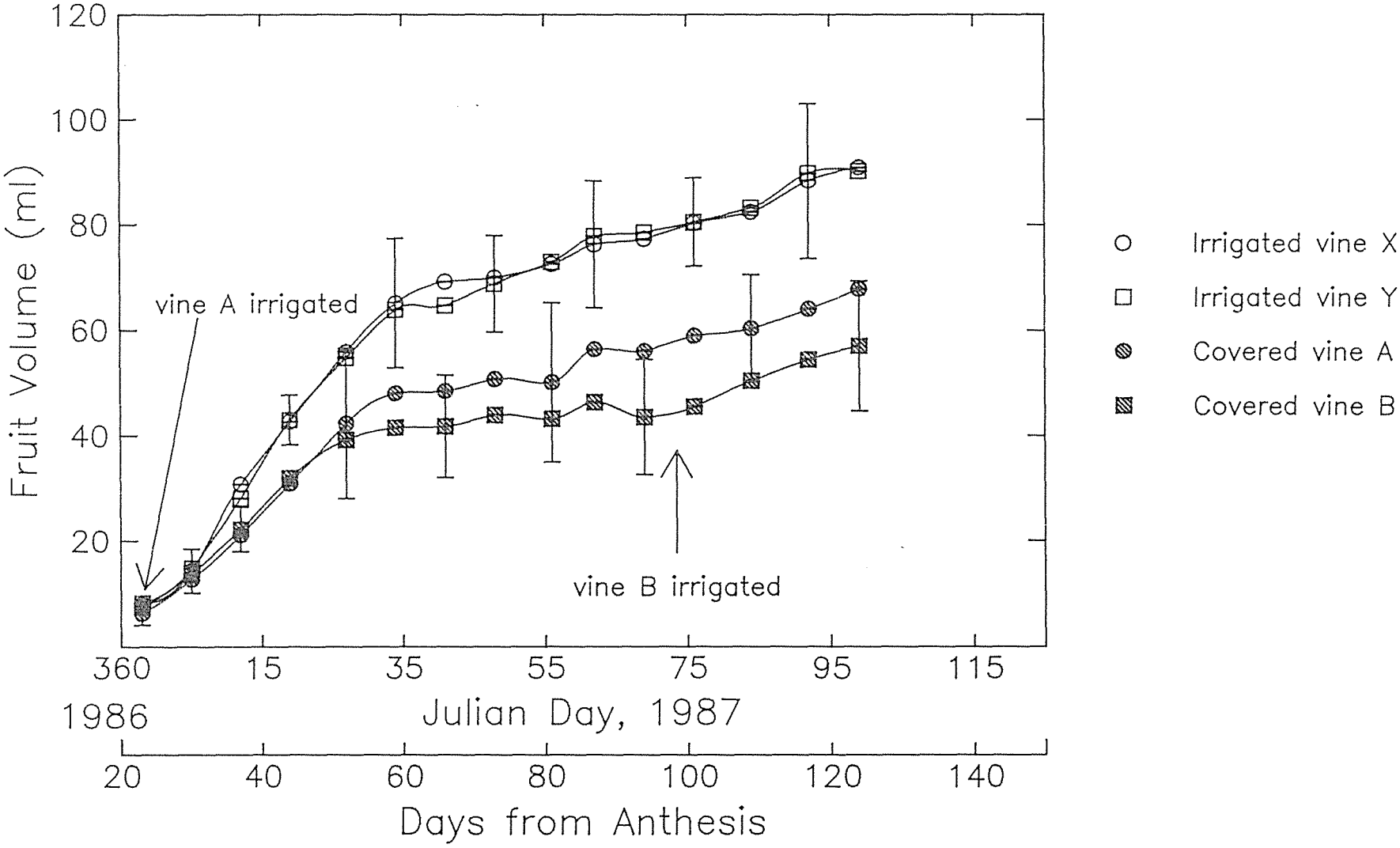

Figure 3.4 Fruit volume for the 1986/87 season.

The error bars show ± 1 standard deviation.

this.

The fruit sizes on the 2 control vines followed each other closely and were never significantly different. This is probably a result of the selection of the fruit at flowering.

3.3.1.4 Non-irrigated Vines, 1986/87 Season.

Due to the excellent agreement between the fruit of the control vines in the 1986/87 season, comparisons between vines are easy to make. The initial fruit size of the control vines and covered vine B are within 0.6 ml of each other. The smallest initial fruit size was in vine A (6.3 ml) and the largest in control Y (8.2 ml). The initial size of the fruit of vine A was 1.8 ml lower than that of the controls. The low volumes may well have been a result of lack of water, as the vines had been covered some 24 days before the first fruit volume measurements were taken. These differences are not significant.

The fruit size of covered vine B were significantly different from that of the control vines on Julian day 17 of 1987, 45 days after the covers were installed.

Covered vine A showed symptoms of water stress early in the 1986/87 experimental period, and so was irrigated on Julian day 363 of 1986. Despite the fact that the vine had been well-irrigated from 29/12/86, the fruit volumes of vine A did not become significantly greater than those measured on covered vine B until day 34 of 1987, over a month after the vine A had been irrigated. Although vine A had shown signs of water stress considerably earlier than vine B (see Section 3.3.2), fruit size on vine A was not more severely affected than on vine B.

Again, as noted in the 1985/86 season, fruit growth has not conformed to the grow/no grow hypothesis of Judd and M^{c}Aneney (1986). The fruit of vine B continued to grow, at a slightly reduced rate compared with the irrigated vines, for approximately 25 days after leaf water potentials of vine B first fell below that of the irrigated vines (see Section 3.3.2). After the period of slightly reduced growth the fruit still continued to grow, but at a greatly reduced rate, until irrigation was resumed. After

vine B was irrigated there is some indication of compensatory growth.

3.3.2 Leaf Water Potentials.

The pressure bomb results are summarised in Table 3.2. Fig. 3.5 shows a diurnal pattern of leaf water potential measured in irrigated and non-irrigated kiwifruit vines. The mean difference between the leaf water potential of the non-irrigated and irrigated vines is only an indication of the degree of water stress the vine is under, as the deviation will depend not only on the degree of stress, but also on the the time of day the measurements were taken, and on the conditions that the vine experienced at the time of measurement. The maximum deviations will be found on stressed vines at around solar noon on hot sunny days with a low vapour pressure deficit.

The data shown in Fig 3.5 were taken on a hot sunny day in late February. although the first measurements were not taken until 7:30 in the morning, (NZDT), these early morning measurements will be fairly indicative of the pre-dawn leaf water potential as the leaves were shaded and dew-covered, resulting in little transpiration. On this day the first measurements taken on the irrigated vines and vine A (which had been irrigated 2 months previously) were approximately -0.07 MPa, and on the covered vine B -0.3 MPa. Although measurements on vine C were not taken until later on in the morning, at that time they were comparable to those taken on vine B. These early morning leaf water potential measurements agree with the finding of K. J. M^{c}Aeneny (pers. comm.) that non-stressed vines have pre-dawn leaf water potentials greater than -0.1 MPa. Water-stressed vines develop lower leaf water potentials during the day, recover more slowly at night, and do not reach the same night-time leaf water potential as irrigated vines.

The leaf water potentials measured on vine A were found to be significantly lower than those of the irrigated vines from the first measurement date, 7 days after the covers were installed. At this time vine B still had normal leaf water potentials. It had been noticed, before the covers were installed for the 1986/87 season, that vine A was not looking as healthy as the surrounding vines. This ill-health showed up mostly as small leaves on slender petioles. Because of the appearance

Table 3.2 Leaf Water Potential Results.

Level of Significance of Difference
Compared with Irrigated Vines

Julian Day		Vine		
		A	B	C
1986	326	5%	NS	-
	357	5%	NS	-
	363	1% *	NS	-
	364	1%	NS	-
	365	1%	NS	-
1987	5	5%	1%	-
	12	1%	1%	NS **
	19	-	5%	NS
	28	5%	1%	NS
	41	5%	1%	1%
	43	NS	1%	1%
	56	NS	1%	1%
	74	1%	1% ***	1%
	81	-	5%	-
	96	-	1%	1%

Comparisons between vines were carried out as described in Section 3.2.2. A "-" indicates that no measurements were taken, "NS" indicates that the difference was not significant, and "1%" or "5%" indicates the level of a significant difference. * - vine A was irrigated after the measurements were taken on day 363, ** - vine C was covered on day 9, *** - vine B was irrigated after the measurements on day 74.

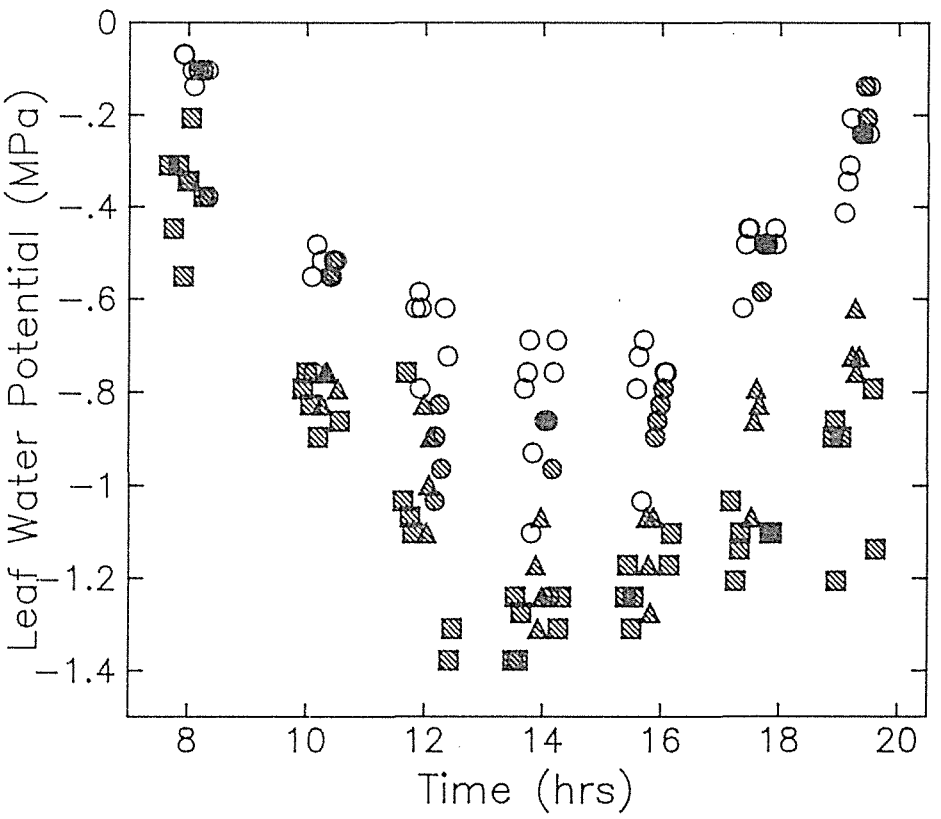

Figure 3.5 Diurnal pattern of leaf water potential for irrigated and covered vines, 14 Feb, 1987.

○ Irrigated vines

◍ Covered vine A

▨ Covered vine B

△ Covered vine C

of the vine and the low leaf water potentials, it was decided to irrigate vine A on Julian day 363, 24 days after the covers were installed and at least 17 days after the onset of stress. Even after the vine had been irrigated the leaf water potential of the vine did not rise to that of the irrigated vines until almost 2 months after irrigation had resumed. Fruit growth on vine A did not exceed that of vine B until a month after irrigation had resumed. Other authors have found that applying water to stressed vine brought about an almost immediate improvement in fruit growth (van Oostrum, 1985; K. J. M^{c}Aneney, pers. comm.). Presumably this improvement in fruit growth would also be mirrored by an attendant improvement in leaf water potential. Given this, and bearing in mind the low fruit sizes experienced by this vine in 1985/86, it seems probable that the vine is not reacting normally. Vine A is sited adjacent to a vine which, in the 1984/85 season, developed verticillium wilt. Although the fungal disease had apparently been arrested by the application of a fungicide to the soil around the affected vine, it is possible that the experimental vine was also affected. For these reasons the leaf water potential measurements from vine A will be discarded for the purpose of pin-pointing the time at which water stress first appeared.

The leaf water potential of vine B started to drop at day 5 of 1987, 31 days after the covers were installed. The volumes of water in the profile at this time will be an estimate of the lower limit of readily-available water. The first time the fruit of vine B were significantly smaller than the control vines was on day 17 of 1987. This was the first time fruit volume was measured after the time at which the leaf water potential became significantly lower. On the same day that the leaf water potentials became different, the difference in fruit size between vine B and the irrigated vines had increased a little but not enough to become significant. There may be a slight lag between the onset of water stress and the reduction in fruit growth as a result of that stress.

The cover removed from vine A was installed under another vine, C. The cover was installed on day 9 of 1987. This third vine first experienced significantly reduced leaf water potentials on day 41 of 1987, 32 days after the cover was installed.

The diurnal patter of ψ_l is such that as a vine begins to "work harder", the ψ_l of that vine during times of peak transpirational demand is lower than in a well-watered counterpart. During times of lesser transpirational demand the ψ_l's of the two vines may not be significantly different. As the availability of water to the vine decreases further, ψ_l will be lower than in the well-watered vine for a wider range of transpirational demands, until complete night-time recovery does not take place and pre-dawn ψ_l is affected. This change in pre-dawn ψ_l has been used by Prendergast et al. (1987) and Judd et al. (1987) to indicate the level of water stress at which fruit growth first becomes affected by lack of water. In this study a slightly more conservative approach has been taken. By examining ψ_l data throughout a day, mid-day decreases in ψ_l are taken into consideration. An ultra-conservative approach would be to regard any difference (between the irrigated and the non-irrigated vine) in ψ_l at any time during the day or night and of any duration as being a symptom of water stress, and therefore of the need for irrigation. As we do not know what durations and degrees of reduced ψ_l's are important for fruit growth, the method chosen to determine the need for irrigation is fairly arbitrary. In this study I have taken a middle-of-the-road approach and examined ψ_l throughout the day. This is likely to be a reasonable criterion for deciding whether or not to install an irrgation system. However once the decision to install an irrigation system has been made a more conservative approach for designing system capacity and irrigation scheduling may be desirable.

3.4 The Lower Limit of available Water.

From the comparison of the fruit size data of control vine Y and vine B, the lower limit of readily available water will be that water stored in the root zone on day 52 of 1986. A further estimate of the lower limit may be gained from the pressure bomb data from the 1986/87 season, also on vine B. If there is less water in the root zone than that remaining on day 5 of 1987, the vine will become water stressed. From both these estimates, 16.63 and 16.60 m^3 of water was stored within 2.25 m horizontally and 2.2 m vertically of the vine are not readily enough available to allow fruit growth to proceed at a rate comparable to that found in vines with higher water contents within the root zone.

When the soil is at field capacity the cylindrical soil volume described above is estimated to hold 18.6 m^3 of water. This being the case the estimate for the volume of available water is 1.25 and 1.29 m^3. Implicit in this figure is the assumption that the water stored beyond 2.25 m horizontally and 2.2 m vertically is not utilised and not available to the plant. The effect of this assumption will lead to an erroneously low value for the size of the reservoir of available water. It would appear that the volume of water extracted below 2.2 m may be between 20% and 50% of that above 2.2 m (see Section 4.3). This implies that a better estimate of the size of the reservoir may be between 2.4 and 3.0 m^3.

If drainage at water contents below field capacity is assumed to be negligible, and if the kiwifruit canopy uses the 5 mm of water m^2 day^{-1} often assumed in the design of irrigation systems (Sale, 1983), then with a canopy area of 25 m2 there is enough water stored within the root zone for 23-29 days growth, given no water is added through either irrigation or rainfall. This point will be amplified further in Chapter 5.

The size of the reservoir is set by a combination of the ability of the soil to supply water, the ability of the vine roots to extract water, and the extent of the root system. A fourth factor, which may be important, is the flow of water into the root zone as a result of the matric potential gradient set up by the extraction of water by plant roots. The importance of the latter will depend upon the hydraulic conductivity of the soil, the magnitude of the matric potential gradients, and the proportion of the soil potentially available to the plant roots which has already been explored by the kiwifruit roots. As the vines are spaced at 5 m centres, and the roots have as yet not substantially explored the soil beyond 1.3 m horizontally from the vine, the plants are effectively isolated from each other. In the absence of flow of water from the unexplored soil into the root zone, the soil outside the root zone will have a water content set by a combination of evaporation, water extraction by grasses and weeds, rainfall, irrigation, drainage, and some water extraction by the few roots growing in this soil. The soil, especially at depth, may be quite wet. In this case and also because of the cylindrical symmetry of the system, which ensures that there is a large volume of unexplored soil to supply the root zone, the flow of water into the root zone may be substantial. In this study it was found that there was a

substantial radial gradient in water content 2 m horizontally from the vine, yet the root study showed that there were few roots at this distance. It is worth discussing whether the observed change in water content at 2 m could have been as a result of lateral flow into the root zone, and this will now be done.

Flow within a system with cylindrical symmetry may be described by the equation;

$$\frac{\partial \theta}{\partial t} = \frac{\left(\partial \; r \; k(\theta) \; \frac{\partial \psi}{\partial r} \right)}{r \; \partial r} \qquad (3.3)$$

where r is the horizontal radial distance (m), k is the hydraulic conductivity (m s^{-1}), and ψ is the matric potential (m). A finite difference form of this equation was used to examine the flow between 1.5 and 2 m radially from the vine at a depth of 0.5 m. The depth of 0.5 m was chosen as it is at this depth that the required matric potential data were available. Water content and soil water potential data between 14/2/86 and 8/4/86 from vine A were used to calculate the hydraulic conductivity required to produce the observed change in water content. There was no tensiometer sited at 1.5 m from the vine so data from the tensiometer sited 1 m from the vine were used. As previously noted, potentials within the root zone were fairly uniform, so this should cause relatively little error.

The flow equation was rearranged to find the magnitude of the hydraulic conductivity required to produce the observed $\partial\theta/\partial t$ given the measured soil water potentials. Seven estimates of k were calculated for levels of soil water potential ranging from -28 kPa to -52 kPa. The estimates of k ranged from 1.69×10^{-12} m s^{-1} to 14.7×10^{-12} m s^{-1}, and showed no systematic relationship with matric potential. Given the relatively small range of ψ, large changes in k would not be expected, and any changes in k with ψ are likely to be obscured by variability in the θ measurements and the effects of the assumptions implied by this analysis (i.e. that $\Delta\theta$ and ψ were measured in the "same" place, which they were not; applying the finite difference formula over a distance of 0.5 m). The mean value of k was 6×10^{-12} m s^{-1}. It is reasonable to expect the hydraulic conductivity of the soil at potentials around -5 m to be at least this value. Gradwell

(1979) reported values of k, at potentials of -10 kPa, of 916×10^{-12} to 3250×10^{-12} m s^{-1} for similar soils. It is extremely unlikely that the value of k would drop by almost three orders of magnitude between a soil water potential of -10 and -40 kPa. The estimate of k is likely to be high anyway, as some of the observed reduction in water content is likely to have been due to direct uptake by the few roots that were present at 1.5 to 2.0 m.

During the period 14/2/86 to 8/4/86, 230 l of water apparently flowed into the root zone from the annulus 1.75 to 2.25 m from the vine. Also during this time the soil water potential fell from -15 to -50 kPa at 2 m. It would therefore seem likely that water was also transported from further away, in significant volumes. During the period 14/2/86 to 8/4/86, 61% of the water taken up by the vine was as a result of extraction from the annulus 1.5 m to 2.25 m horizontally from the vine. This annulus is an unexplored volume of soil and indicates the importance of lateral flow of water in supplying the vines water requirements in this orchard. As the vine matures and explores a greater proportion of the soil available to it, lateral flow will supply correspondingly less of the vine's water requirements.

Fig 3.6 shows the water contents and matric potentials measured at 0.3 and 0.5 m deep when stress was first noted for vine B in 1985/86 and in 1986/87. The water content at the 0.3 m depth is less than that at the 0.5 m depth at all radial distances from the vine. This phenomenon is characteristic of all profiles measured at this site, but is accentuated in the access tubes which were sited under the lustrelite rather than under the plastic canvas. This indicates that there has probably been some evaporation from the soil surface under the lustrelite. The effect of this evaporation on total water extraction will be small as there was little ventilation and little radiation was transmitted through the material.

The water content data shown in Fig 3.6 are interesting but are not particularly useful for irrigation scheduling. Soil water potential measurements are of more use. Unfortunately there were only a few tensiometers installed around the vines and the potentials derived from the water content and the rententivity curves did not agree well with the

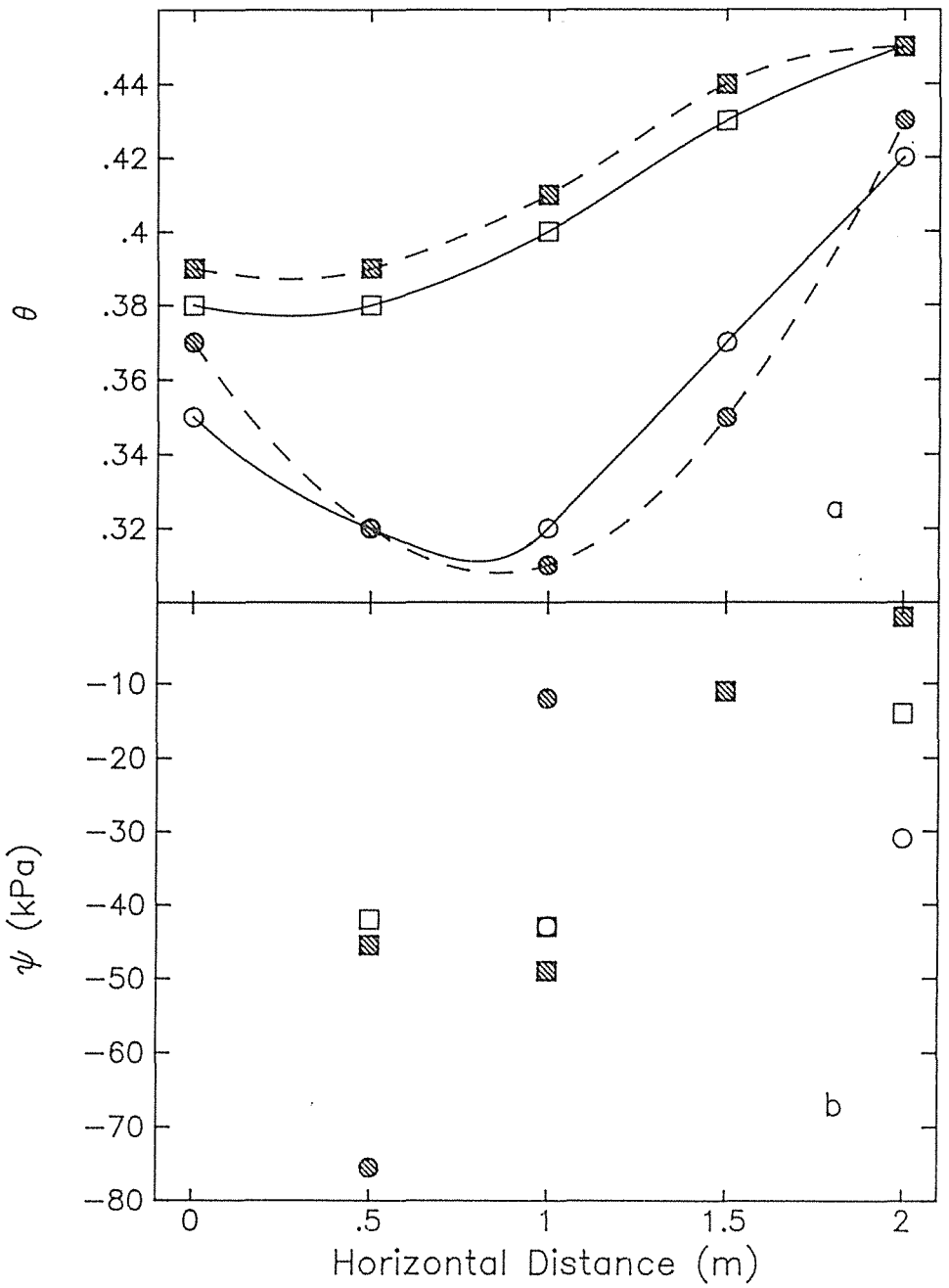

Fig 3.6 Soil water content and potential at stress point.

(a) − θ, (b) − ψ

○ 1985/86, 0.3 m deep

□ 1985/86, 0.5 m deep

⊗ 1986/87, 0.3 m deep

▨ 1986/87, 0.5 m deep

tensiometer data at the 0.3 m depth. The tensiometer readings taken at 0.3 m seem to be more variable than those taken at 0.5 m. There is reasonable agreement between the 1985/86 and the 1986/87 estimates of both soil water content and matric potential at 0.5 m depth. Based on the tensiometer data it would appear that if a tensiometer shows a potential greater than -40 kPa while placed 0.5 m deep and within the zone of occupation (within 1.3 m of the vine in this case) there should be sufficient water stored within the soil to support growth.

The change in water content between field capacity and the onset of water stress for both seasons is shown in Fig 3.7. The solid line through the data points is a cubic spline fitted using the least-squares technique. The spline has been extrapolated to estimate the point at which the water content has not changed.

In both seasons maximum water extraction takes place at 0.5-1 m from the vine, falls off slightly towards the vine, and more steeply away from the vine. In the 1986/87 season, as compared with the 1985/86 season, there is less extraction close to the vine. The overall effect has been to increase the volume of water removed slightly. The difference in water extraction between the two seasons is consistent with the growth of the root front outwards, combined with an increase in the proportion of structural roots as compared with fine absorbing roots close to the vine.

One of the factors setting the size of the reservoir, which has the ability to change with time, is the extent of the root system. Currently these 7 year-old vines have exploited just under a quarter of the soil available to them horizontally. The extent of vertical exploration, although unknown, extends below 2 m, so the potential volume of soil available may be considerably more than four times the current volume of soil explored by the roots. Although the soil beyond 1.3 m is not well-explored, substantial volumes of water have been removed from it, so the benefit of increasing the volume of soil explored, in terms of increased water availability will not be of the same magnitude.

From observations of different-aged vines in the orchard, it appears that the root front advances at approximately 0.25 m per year. This being the case the root front may have reached the 2 m point in two years time.

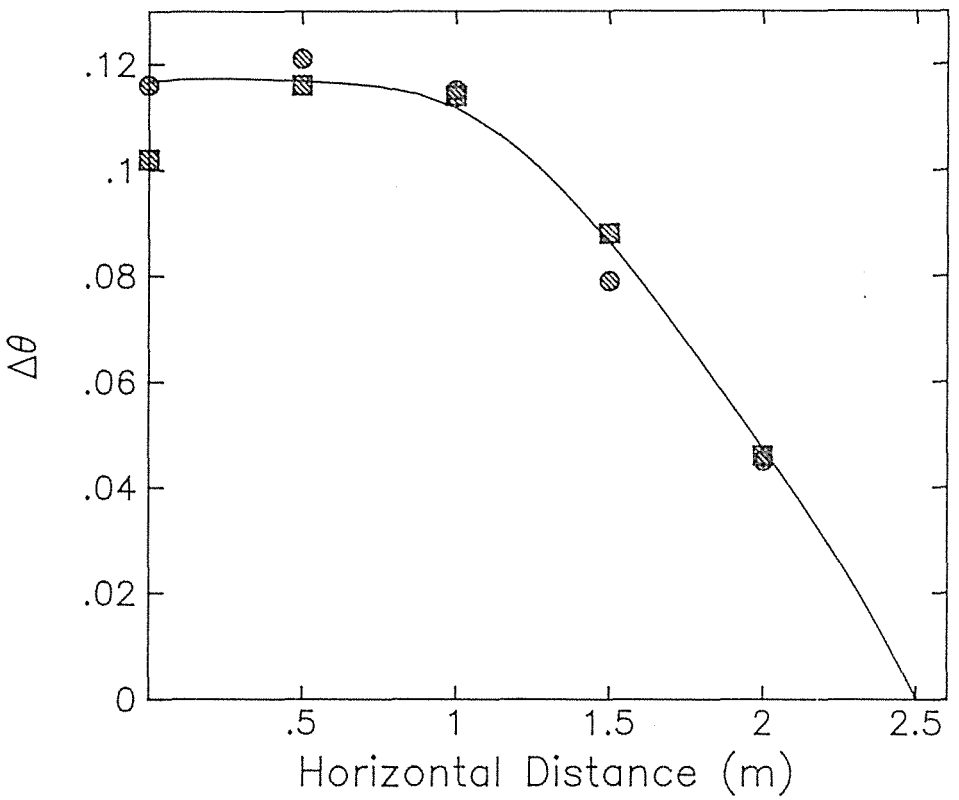

Figure 3.7 Water content difference between "field capacity" and the "stress point" in the 1985/86 season (◍) and the 1986/87 season (▧).

Once the root front has reached this point it is likely that the shape of the profile of extraction will be similar to that shown in Fig 3.7, but shifted 0.5 m to the right. If this is the case, then the reservoir of water will be approximately 2.6 m^3. This figure was derived assuming that the maximum depth of water extraction is 2.2 m but the true increase may be larger due to vertical root exploration. In the long term it seems likely that most of the soil available to the kiwifruit may yield 0.1 m^3 m^{-3} of water. Then, still assuming a maximum depth of extraction of 2.2 m, the volume of water available would be 4.3 m^3. To illustrate the effect of reservoir size on the need for irrigation, a simple, month-by-month water budget may be carried out, using long-term rainfall data from the Wanganui meteorological station and the Priestley-Taylor evapotranspiration estimated in the orchard. The assumptions used in the water budget are that the reservoir of water is as described above, the soil is at field capacity at the beginning of November, the projected canopy area for November is 12.5 m2 and from December onwards is 25 m2. It is also assumed that the vines use water at the rate indicated by the Priestley-Taylor equation. It will be shown in the following chapter that the vines under study used considerably less than the Priestley-Taylor estimate for reasons as yet unknown. The irrigation requirement for November to April is set out in Table 3.3.

Table 3.3 Monthly m^3 of irrigation water required under several combinations of reservoir size and rainfall regime.

Reservoir Size	Rainfall Percentile	Month Nov	Dec	Jan	Feb	Mar	Apr
1985/86/87	50	0.00	0.90	2.00	1.28	1.00	0.00
(2.0 m^3)	10	0.00	2.40	3.15	2.45	2.03	0.90
Projected 1988/89	50	0.00	0.00	1.93	1.28	1.00	0.00
(2.6 m^3)	10	0.00	1.84	3.15	2.45	2.03	0.90
Projected Maximum	50	0.00	0.00	0.00	0.98	1.00	0.00
(4.3 m^3)	10	0.00	0.00	2.79	2.45	2.03	0.90

If the root system develops to exploit the full volume of soil available to it, little irrigation will be required in an average year. The true situation is likely to result in an even lesser requirement for irrigation, as these calculations assume a maximum depth of water

extraction of 2.2 m. If, for example, the roots explore to 4 m (kiwifruit roots have been found to explore to deeper than 4 m, Greaves 1986) irrigation for mature vines would not be required until March even if rainfall occurs at the 10 percentile rate in each month preceeding March. The probability of this happening is of course much less than 10%.

Although this is only an approximate analysis of irrigation requirements it does highlight the importance of the reservoir size in setting irrigation requirements. It also shows that irrigation is more likely to be necessary on young plants, but may not be required on mature plants placed at wide spacings.

3.5 Recovery from Water Stress.

An examination of Table 3.2 shows that, after stressed vines have been irrigated, it takes some time for the leaf water potential values to rise to that measured in the irrigated vines. The covered vine A had not properly recovered after three weeks, while vine B had not recovered by the time leaf water potential monitoring had stopped. Stressed plants normally recover within a day or two of being rewatered, and kiwifruit have previously been observed to fit this pattern (van Oostrum, 1985). This long recovery time may be a result of the long time between the onset of stress and the application of water to relieve that stress. Alternatively it may be that not all the soil was re-wetted and the roots still in dry soil may produce a hormone which indicate to the vine that it is still short of water. A mechanism such as this has been proposed by Davies et al. (1986).

Other workers have found leaf water potential to rise to normal values in 1-3 days after irrigation in grapes (During, 1984) and kiwifruit (van Oostrum, 1985). Even though the kiwifruit in this trial were stressed for long periods (around 70 days for vine B), the long recovery period is rather odd. The minimum leaf water potentials were not markedly lower than those noted by van Oostrum (1985). One possible explanation for this behaviour is the method by which the pressure bomb measures leaf water potential, in combination with an unusual water use characteristic of these vines.

The pressure bomb "measures" the leaf water potential by applying a pressure to the leaf and petiole until sap is just expressed from the cut xylem vessels. The point at which the sap appears at the cut is known as the balancing pressure. If the balancing pressure is to measure the leaf water potential several assumptions must be made. These assumptions include that the osmotic potential is negligible and that the spatial arrangement of the water in the leaf and petiole at the balancing pressure is the same as when the leaf was attached to the vine (Boyer, 1967). That the latter assumption is not necessarily true, in rhododendron at least, was demonstrated by Boyer (1967). During (1984) found osmotic potentials of water stressed Silvaner grapes to be around -1 MPa, approximately equal to the water potential as measured by the pressure bomb. The osmotic potential in the xylem sap will be somewhat less than that in the leaves.

In irrigated vines, and the covered vines while still at high leaf water potentials, the parenchyma surrounding the central vascular bundle was observed to be moist. Upon the application of pressure, sap bubbled out of the parenchyma, often long before the end-point was reached. In the stressed vines however, the parenchyma was in a visibly drier state than in the irrigated vines. Even when the parenchyma looked to be dry, in a number of samples sap was observed to bubble out of the parenchyma. This bubbling and exudation of sap is evidence that the spatial pattern of sap distribution in the leaf and petiole has changed during the excision and pressurisation process. The effect of this redistribution will be to increase the balancing pressure, and result in erroneously low leaf water potential values (Boyer 1967, Ritchie and Hinckley 1971). The bubbling of the sap as it is expressed from the parenchyma and xylem is itself an indication that the simple explanation for the operation of the pressure bomb does not apply. The bubbling is a result of cavitation of the xylem sap. The cavitation results in increased movement of the xylem sap into the leaf, thus requiring higher pressures to force it back into the petiole again (West and Gaff, 1976).

The above points help explain why the true leaf water potentials may be higher than those measured in the pressure bomb, but not why they took so long to recover, or why fruit growth, especially on vine B, recovered almost immediately upon rewatering. The vines in the orchard block studied appeared to be healthy, produced well for their age, and their

nutritional status was good. However, under certain conditions, they used less water than one would expect given the environmental conditions to which they were exposed.

Vines of a similar age to those in Wanganui, but sited in the Massey University Research Orchard in Palmerston North, had day-time transpiration rates as measured by the heat pulse technique and estimated by the equilibrium ET equation which agreed well (S. R. Green, pers. comm). The agreement between these two measures was however poor in Wanganui. Specifically the heat pulse measurements indicated that the vines in John Carson's orchard appear to use approximately 1/3 of the Priestley-Taylor estimate of ET during the day. This phenomenon has been observed for irrigated and covered vines throughout the season (S. R. Green, pers. comm.). There appears to be something happening in the Wanganui orchard which causes the vines to use low rates of water while still enabling them to produce well and look healthy. This point will be discussed in more detail in Chapter 4. However the low transpiration rates may help explain the odd phenomena observed after irrigating the stressed plants.

If, after a vine is irrigated, the water absorbed is preferentially directed towards the leaves and fruit, rather than towards a general rehydration of the tissues, for example the parenchyma in the petiole, this would help explain why the fruit started to grow at an increased rate once water had been applied to the stressed vines. If the water potential of the fruit and growing points had also been monitored then the additional information may have been useful for supporting or refuting this explanation.

3.6 Conclusions.

The size of the reservoir available to 7 year-old kiwifruit vines on the Westmere silt loam is estimated to be 2.1 m^3. Under conditions of 50 percentile rainfall, a reservoir of this size will mean that irrigation will be required from mid-January to March. Given the wide spacing of these plants, the maximum reservoir is projected to be 4.3 m^3 (assuming a maximum depth of extraction of 2.2 m). A reservoir of this size would mean little need for irrigation during average years, but that in

extremely low rainfall years irrigation may be required from January to April.

As the depth of rooting is known to exceed 2.2 m, and so it was not possible in this study to determine fully the absolute size of the reservoir of available water. It is however possible to estimate the length of time the vines can adequately grow without running short of water. In this chapter the length of time that irrigation is not required has been calculated using the Preistly-Taylor ET equation to estimate transpiration. In the following chapter however the pattern of water use will be characterised, allowing more definite conclusions to be made about the need for irrigation on this soil type.

The leaf water potential measurements taken in this orchard agree with the findings of Judd and M^{c}Aneney (1986) and van Oostrum (1985) that the leaf water potential of stressed vine does not rise above -0.1 MPa.

Fruit growth appears to be relatively sensitive to water stress. In the 1986/87 season, decreased fruit growth lagged behind decreased leaf water potentials by approximately 1 week. However, the fruit growth pattern does not conform to the grow/no-grow hypothesis of Judd and M^{c}Aneney (1986). Rather, during the time water was withheld from the vines, fruit growth exhibited the same growth pattern as the irrigated vines, but at a slower rate. There was some indication of compensatory growth after water had been applied to previously stressed vines.

One unexpected feature was the length of time taken for the leaf water potentials to recover in stressed vines after the application of water to relieve that stress. Normally recovery takes 1-3 days. However in this study recovery took three weeks or longer.

CHAPTER FOUR

TEMPORAL PATTERNS OF WATER EXTRACTION

4.1 Introduction.

The concept of potential evapotranspiration arose in the 1940's and 50's as a result of field scale experiments relating water use to environmental factors. The attraction of potential evapotranspiration, which states that under certain conditions the rate of water use is essentially independent of plant and soil factors, is undeniable. And this attraction has no doubt contributed to the vast amount of effort directed towards finding a "better" and "simpler" formulae for determining the potential evapotranspiration (see for example Tanner, 1967). An equally large effort went into deriving crop factors for those situations where actual evapotranspiration did not equal potential evapotranspiration (see for example Doorenboos and Pruit 1974 or Garnier et al. 1986). Apart from the obvious utility of the potential evapotranspiration concept, another the reason for the continuing effort is that many agricultural crops appear to use water at a rate which is reasonably well described by such formulae (e.g. M^{c}Aneney and Judd, 1983; Green et al., 1984; Clothier et al., 1982).

Considering the apparent success the potential evapotranspiration formulae have had elsewhere, their use in orchards is then not surprising as potential evapotranspiration was considered to be independent of plant cover. However, in his original paper, Thornthwaite (1944) placed certain limits on the type of plant cover to which potential evapotranspiration could be applied. These restrictions included that the plant cover should be an extensive surface of short, green, well-watered crop of uniform height, which completely shades the ground (Anon, 1956).

Given these conditions, the rate of water use by the crop is supposed to be "climatologically determined" (Stanhill, 1973). It is difficult to see how a sheltered kiwifruit orchard can fit these criteria. Far from being

extensive, a typical orchard block will normally be less than 100 m long by 40 m wide. These dimensions are very small compared to the many kilometres that it may take for an overhead air mass to adjust to the vegetation beneath (Burman et al., 1975). The environment may also change within the orchard block as a result of windbreak effects. The crop is not short, nor is it of uniform height. Shelter trees may be 10 m tall, the vines 2 m and the sward beneath the vines perhaps 100 mm. Only the strips of grass beneath the vines may be uniform and short. Most orchardists would aim to ensure that the vines were well watered at all times. This treatment is sometimes, but not always, extended to the shelter trees. The areas of the soil which are not within the area wetted by the irrigation water emitter, and the grass strips, are likely to be short of water for significant lengths of time during the summer months.

Thus kiwifruit orchards do not appear to fit any of the criteria particularly well, if at all, yet the potentail evapotranspiration principle is being applied to orchards (Garnier et al. 1986, Tan and Layne 1981, Hoffman et al. 1982, Rogers et al. 1983). To consider whether potential evapotranspiration can be applied within the orchard it is necessary to consider the response of the vines to changes in environmental conditions, as they are considered to be the principle transpiring agent within the orchard.

A kiwifruit orchard can often be a small, isolated area within a totally different land use pattern. The orchard in Westmere, for example, is surrounded by mixed arable and pastoral farming and is only 10 km from the Tasman Sea. During the summer the surrounding pasture and crops may be quite short of water, so that the irrigated orchard is a green, readily transpiring oasis in an otherwise dry area. An air mass travelling over the pasture on a hot, sunny day would become warmer and drier as it passes over the surrounding vegetation. This hot, dry air mass then moves over the irrigated orchard. The rate of water loss by the kiwifruit vines is determined by the energy receipt (both intercepted radiant energy and advected energy, Trought 1985) and the plant resistance to water loss. Due to the surrounding dry vegetation, the contribution of advected energy to the demand for water from the plant can be high. However the shelter trees influence the sensitivity of the air immediately surrounding the kiwifruit vines to the air blowing into the orchard. If the shelter trees

were very efficient at reducing wind speed and turbulence in the orchard block, the saturation deficit in the orchard would be unaffected by the condition of the advected air mass. In this case the saturation deficit would approach an equilibrium value set by canopy resistance and (R_n-G) ($R_m$mmn is net radiation in W m^{-2} and G is the energy directed towards heating the soil, also in W m^{-2}). The other extreme is when turbulence is increased to such an extent that vertical gradients in temperature or humidity have become very small. In this case the saturation deficit at the leaf surface is set by the advected air mass, thus causing the transpiration rate to be largely determined by the saturation deficit of the advected air.

The true condition must lie somewhere between the two extremes presented above. Close to the shelter the air will be less turbulent than further away, and gradients of temperature and humidity will be large. This case was described by Jarvis and M^{c}Naughton (1986) and M^{c}Naughton (1986) as being decoupled. The term "decoupled" refers to the lack of dependence of transpiration rate on the condition of the overhead air mass. The extent of decoupling found in an orchard will depend upon the efficiency with which the shelter lowers windspeeds and prevents turbulence within the orchard. This efficiency is likely to vary from day-to-day (depending on the strength and direction of the wind) and also within the orchard block (depending on whether the position of concern is within the quiet or the wake zone, M^{c}Naughton 1986).

To further complicate matters, the presence of both the live shelter and grass strips have the capacity to alter the environment experienced by the kiwifruit vines. Both the shelter trees and the grass transpire, and will therefore decrease the saturation deficit of the air, and so tend to reduce the transpiration rate of the kiwifruit vines. Generally the grass strips do not receive irrigation water and, as the kiwifruit canopy develops, receive decreasing amounts of radiant energy. Often the shelter trees are also non-irrigated, so as the season progresses the grasses and shelter are likely to make a decreasing contribution to the total orchard water use. The presence of shelter is also likely to reduce vine water use by decreasing the amount of solar radiation the vines receive. In a narrow block with tall shelter the vines may be shaded from mid-afternoon to mid-morning. If during this time the leaves are dew-covered or the

saturation deficit is low, transpiration is likely to be lower than would otherwise be expected from meteorological measurements taken at any place other than in the orchard block itself.

4.1.2 Measurement and Estimation of Evapotranspiration in Orchards.

Let us now contrast the difference in the reaction of the vines in the orchard to changing environmental conditions with differences in pan evaporation and the Priestley-Taylor estimate of potential evapotranspiration. The primary difference between the pan and the vine in terms of water loss, is that water loss from the pan is reduced by aerodynamic resistance only, whereas the vine can also control water loss by altering the stomatal resistance. The vine also experiences an aerodymanic resistance but it is in series with the stomatal resistance, so that water loss is not as sensitive to changes in the aerodynamic resistance. As a result the pan may be more sensitive to local turbulence than a plant. At high saturation deficits some plants may close their stomata, so that water is conserved. Pans have no such mechanism to do this and will be more sensitive to saturation deficit than the plants. Also, of course, the geometries of the evaporating surfaces are different.

The Priestley-Taylor equation is based on equilibrium evapotranspiration with an empirical term to account for a moderate (26%) advective enhancement. The formula has been shown to work reasonably well in the absence of strongly advective conditions for agricultural crops (Priestley and Taylor, 1965). Over a range of conditions it gives values of evapotranspiration roughly equivalent to Penman's equation (M^{c}Naughton, 1976), and the use of more complex equations which require additional monitoring of environmental conditions may not be justified in terms of increased accuracy for crops or pastures (Clothier et al., 1982). There is no way however that the Priestley-Taylor equation can exhibit the changes in evapotranspiration rate between and within days as may be expected due to variation in coupling between the environment near the vine and the overhead air mass. Nor can the equation predict the quite high rates of non-radiation related water usage during the night as sometimes observed by S. R. Green (pers. comm.).

The Penman-Monteith equation is more theoretically based than the estimation methods discussed above, but also requires much more plant and meteorological information. The equation has been shown to estimate the water use of vines or trees in orchards reasonably well (Edwards and Warwick 1984; Judd et al. 1986; S. R. Green pers. comm.). Other methods for obtaining the rate of water use of individual vines include the water balance technique and the heat pulse technique. The use of the water balance technique has been discussed in Chapter 2. The heat pulse technique measures sap flow within the stem by introducing a pulse of heat to trace the ascent of sap. The method was first used by Huber (1932), Huber and Schmidt (1937) and was developed by Swanson and Whitfield (1983). The technique has been further developed for use in kiwifruit (Green and Nicholson, 1987; Green and Clothier, 1987).

4.2 Methods.

The method of measuring the change in the storage term in the water balance and controlling the remaining variables has been discussed in Chapter 2. The integration of the individual $\Delta\theta$ measurements to obtain the volume of water extracted was discussed in Chapter 3. In this chapter we are primarily concerned with water use before the onset of water stress.

4.2.1 Micrometeorological Measurements.

In order to make sense of the observed water use rates, it is necessary to compare the rates with concurrently-measured environmental variables. For this study it was decided to use the Priestley-Taylor (Priestley and Taylor, 1972) equation. This particular equation was chosen as it is commonly used, and it is relatively simple to take the required measurements. The Penman-Monteith equation would have provided a more accurate estimate of vine water use, but the required plant-based measurements could not be automated, making the method unsuitable for prolonged use.

If the Priestley-Taylor equation is to be used on a daily basis then the energy directed towards heating the soil may be ignored, thus reducing the equation to;

$$\lambda E = 1.26 \frac{s}{s + \gamma} R_n \qquad (4.1)$$

where λ is the latent heat of vapourisation of water (MJ kg^{-1}), E is the rate of evapotranspiration (kg m^{-2} day^{-1}), s is the slope of the saturation vapour curve at the mean temperature (mPa $°C^{-1}$), g is the psychrometric constant (mPa C^{-1}) and R_n is the net radiation (MJ m^{-2} day^{-1}). The relevant measurements, temperature and radiation, were taken with an Algin evapotranspiration meter which senses and logs air temperature and solar radiation (Algin Scientific, 1985). The daily cumulative solar radiation is converted to net radiation using a standard linear regression equation (Clothier, 1977). The evapotranspiration meter also calculates evapotranspiration using the Priestley-Taylor equation. The Algin evapotranspiration meter was sited at the height of the upper canopy at one end of the experimental block (see Fig. 1.2).

4.3 Results and Discussion.

Cumulative water use, as estimated by the water balance technique and the Priestley-Taylor equation, is shown for the pre-stress period in the 1985/86 and the 1986/87 seasons in Figs 4.1 and 4.2 respectively. In both seasons the water use estimated by the water balance technique is substantially less than that estimated by the Priestley-Taylor equation. Full canopy cover of 25 m^2 has been assumed in converting E from kg m^{-2} day^{-1} to litres.

Part of the discrepancy between the two measurements may be explained by failure to measure soil water content to the maximum depth of extraction. This is however unlikely to be the sole reason, as water would have had to be extracted to a depth of 8 to 10 m to completely make up the difference. The maximum rooting depth in august, 1983 was approximately 1 m (Hughes et al., 1986) and it is very unlikely that root exploration has occurred at the rate of 2 m per year required for water extraction to occur at 9 m (allowing for some upward flow of water to the roots).

The comparison of the heat pulse estimates of vine water use (S. R. Green, pers. comm.) and water balance estimates of vine water use suggests that water extraction below 2.2 m may be 20-50% of the extraction above 2.2 m. assuming an intermediate value of 35%, the maximum depth of

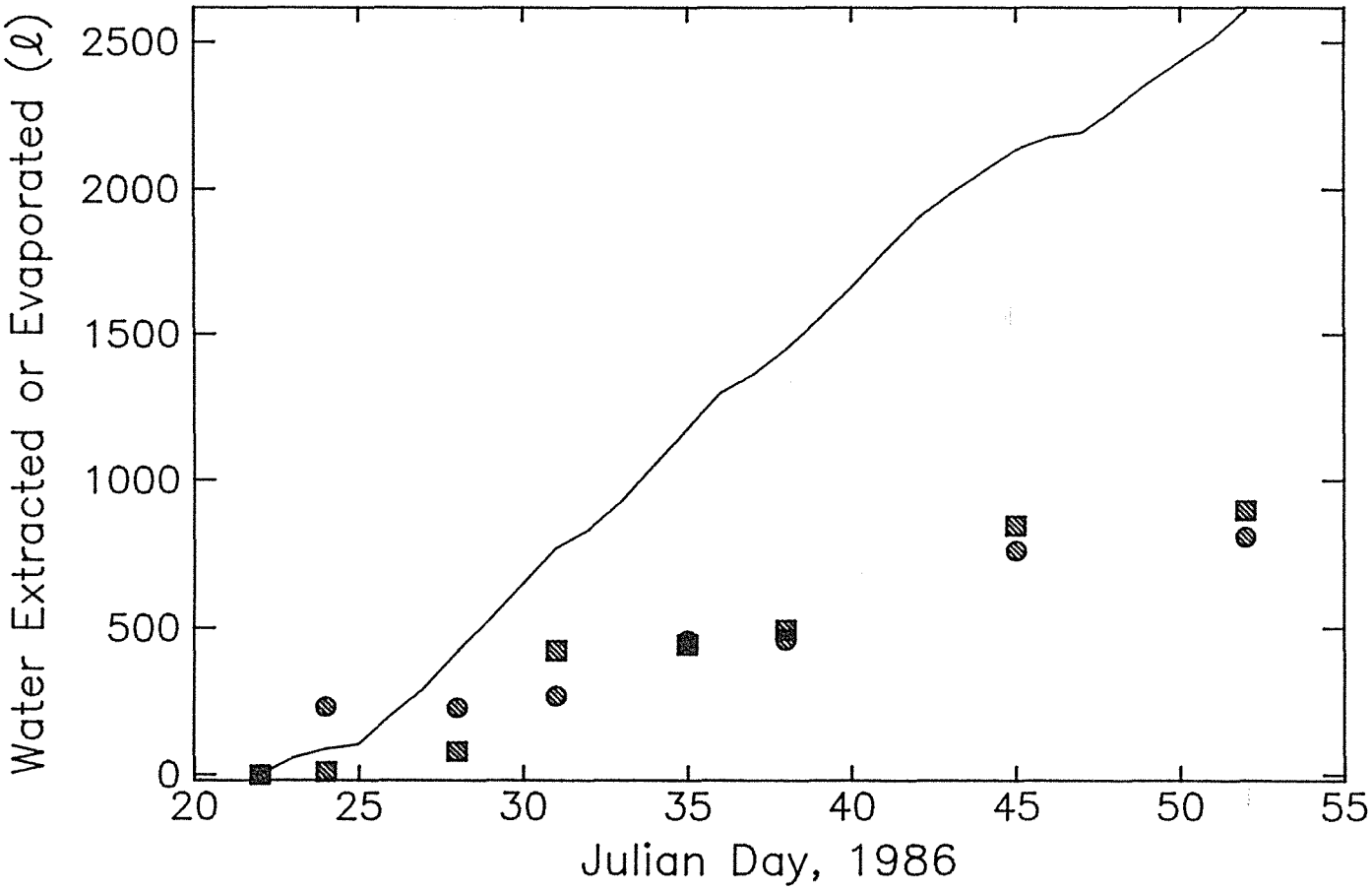

Figure 4.1 Comparison of cumulative evapotranspiration estimated by the water balance technique on vine A (◍) and vine B (▨) and the equilibrium rate (——) in the 1985/86 season.

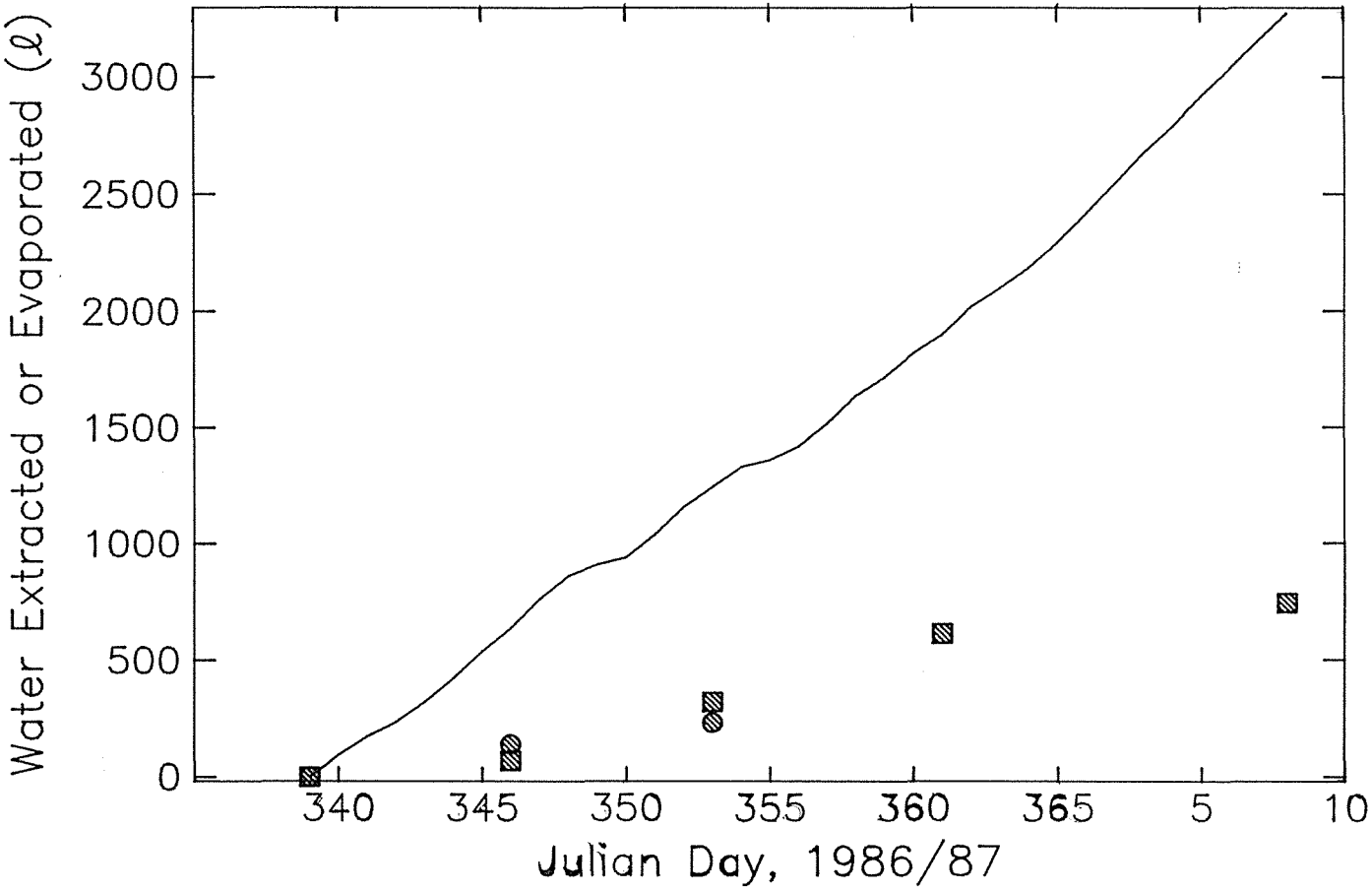

Figure 4.2 Comparison of cumulative evapotranspiration estimated by the water balance technique on vine A (◍) and vine B (▨) and the equilibrium rate (——) in the 1986/87 season.

extraction may be 3 m. In that case actual water use would be 38% of the equilibrium value.

For the purposes of discussion, let us now assume that the vines in the Carson's orchard are using water at 38% of the equilibrium rate. Possible explanations for this discrepancy between the acutal water use rate and the equilibrium value are; (i) that the vines are using water at the Penman-Monteith rate but that in a sheltered orchard this rate is considerably less than the equilibrium rate, (ii) that kiwifruit vines, for physiological reasons, use less water than predicted by the equilibrium rate, and (iii) that the vines in the Carson's orchard are deviants and are somehow abnormal or different from most kiwifruit vines.

Taking the first option, there are several studies relating vine water use as measured by the heat pulse technique (Edwards and Warwick 1984, S. R. Green pers. comm.) or excision techniques (Judd et al. 1986, S. R. Green pers. comm.) to the Penman-Monteith rate which have reported reasonable agreement between the two estimates. The second part of the argument is that the Penman-Monteith rate is significantly lower than the equilibrium rate. Obviously the relationship between the two will vary depending on the environmental conditions. Judd et al. (1986) found that the Penman-Monteith rate was 21-49% higher than the equilibrium rate under extremely advective conditions. S. R. Green (pers. comm.), working under less extreme conditions, also found the Penman-Monteith rate to be higher than the equilibrium rate. This then would not help explain the findings of the current study.

The second option is that the kiwifruit vines use less water than generally predicted using equilibrium methods. One other study has been published comparing a water balance estimate of evapotranspiration to equilibrium evapotranspiration. This was van Oostrum (1985). In this study the soil water extraction data were unfortunately sparse (only two distances from the vine were monitored in both cases) and the data were originally analysed without respect to an obvious horizontal radial variation in water extraction. Van Oostrum (1985) compared cumulative mm of equilibrium evapotranspiration with cumulative mm of water extracted from the soil at a given distance from the vine. The method of analysis would have been appropriate for a one-dimensional system, such as pasture,

but not, for reasons discussed in Sections 3.2.1 and 3.2, for immature kiwifruit vines. In the study by van Oostrum (1985), there may have been water extraction below the maximum depth of water content measurement.

Ideally these data would be analysed again to take account of radial variation, but not enough data are available to do this. A less satisfactory, but the only, alternative is to re-analyse the data from the current trial the same way as carried out by van Oostrum (1985). Fig. 4.3 shows a plot of cumulative equilibrium evapotranspiration against cumulative soil water deficit at 0.5 and 1 m from the vine. Calculated without regard for an obvious radial variation in water uptake with distance from the vine, there is a good correspondence between equilibrium evapotranspiration and the cumulative water deficit, similar to that noted in the other study. Bearing in mind the variation in water extraction, and the water which must have been extracted below the depth of measurement, it would then appear that any correspondence between soil water deficit calculated without respect to horizontal variation in water extraction and equilibrium evapotranspiration is coincidental. This analysis does not prove that the properly calculated water balance estimate for the study of van Oostrum (1985) would have been of the order calculated in the current study but it does present the probability that the water balance estimate may have been less than the equilibrium value.

As mentioned previously, heat pulse estimates of sapflow were taken in both the irrigated and non-irrigated vines. From these measurements it appeared that vine transpiration as measured by the heat pulse technique was considerably lower than that estimated by either the Penman-Monteith or Penman equations. The heat pulse estimate of water use was of the order of 30% of the Penman value (S. R. Green, pers. comm.), rather than the 20-25% resulting from the water balance technique. Some discrepancy would be expected and the 5-10% probably represents extraction from the volume of soil below the neutron probe measurements.

The discrepancy between the heat pulse and Penman-Monteith estimates is disturbing, as similar studies in other similar kiwifruit orchards, though trained on a T-bar rather than a pergola, have produced good agreement between the two estimates (S. R. Green, pers. comm.). The low rate of water use could have many explanations, including perhaps that the root

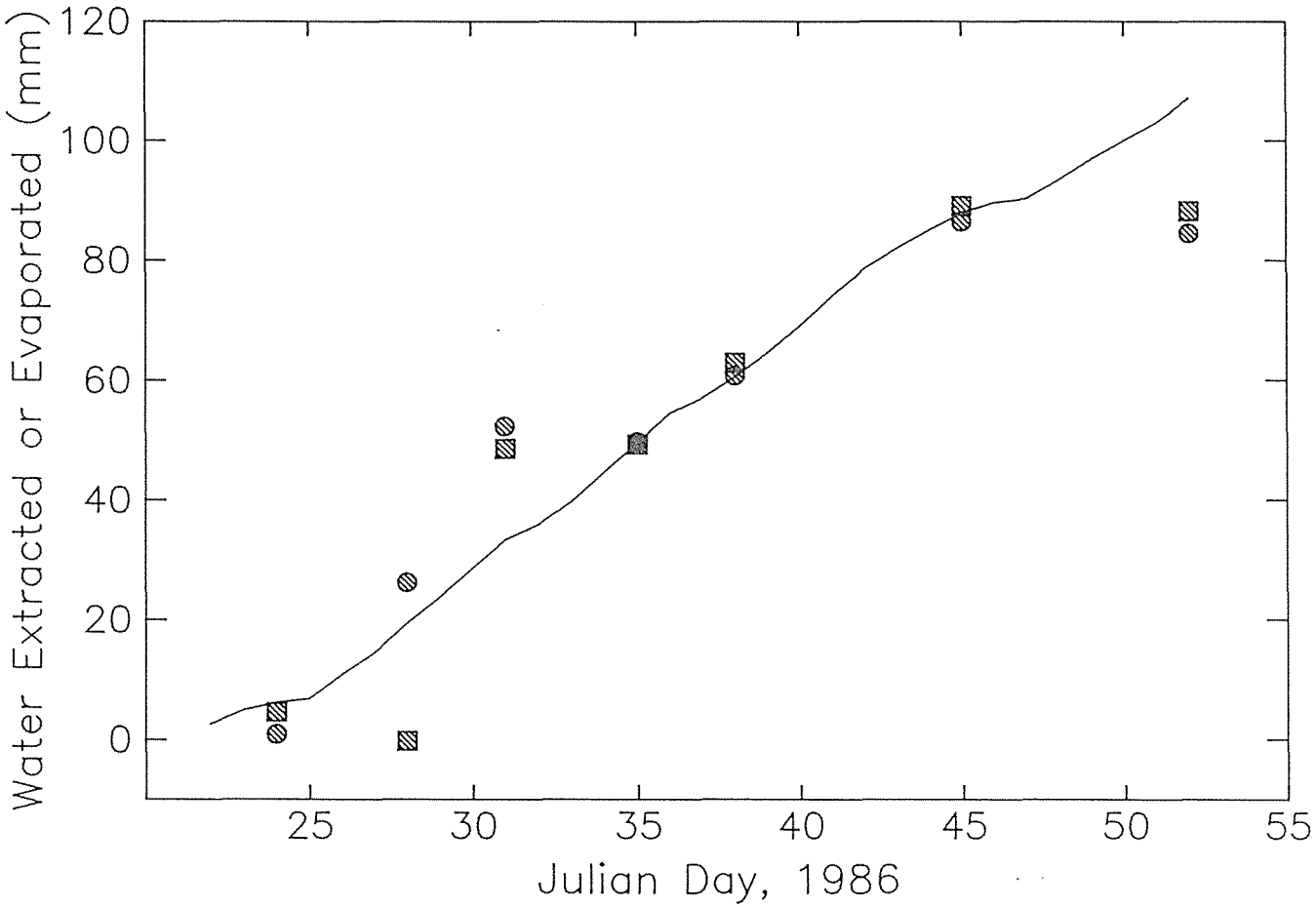

Figure 4.3 Comparison of evapotranspiration estimated by the equilibrium rate (——) or the water balance technique when radial variation is ignored. Extraction at 0.5 (◍) or 1 m (▨) from vine B, 1985/86 season.

system developed to a certain stage which allowed the vine to use water at the lower rate demanded of a vine trained on a T-bar (because of the lower projected area) and the root system has not yet developed to cope with the larger canopy area of the pergola trellised vine (S. Green, pers. comm.). However, if this were the case, why were leaf water potentials comparable to other "normal" orchards, why did the stomata not at least partially close, and why was fruit and replacement cane production comparable to other orchards? at this stage these questions remain unanswered.

4.4 Conclusions.

Due to the rather odd apparent water use behaviour of the vines in this orchard, it is not possible at this stage to reach definite conclusions as to the rate of water use by kiwifruit vines in relation to commonly measured meteorological variables. However one powerful cautionary note is evident concerning the effect of a wrong assumption about symmetry on water balance estimates of water use. Van Oostrum (1985) implicitly assumed uniform water extraction with horizontal distance from the vine, even though water extraction at the two distances measured was markedly different. In doing this both studies indicated that actual vine water use was comparable to the equilibrium rate. When the data from the current study are analysed in the same inappropriate fashion (that is disregarding variation in water extraction) the same conclusion could be reached. However when the data are analysed taking due regard of the radial variation in water extraction, the volume of water extracted from the soil volume, as measured by the neutron probe, accounts for only 25-30% of equilibrium evapotranspiration. Heat pulse measurement of sap flux on vines in the orchard indicate that transpiration may proceed at 40% of the equilibrium rate, whereas similar measurements at other sites have indicated that evapotranspiration may proceed at a rate well-described by the equilibrium rate (S. R. Green, pers. comm.). The difference between the heat pulse estimate and the water balance estimate is probably a result of not measuring water content deeply enough.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

5.1 The Spatial Pattern of Water Extraction.

Water extraction with time was monitored to a depth of 2.2 m. It was found that there was little variation in water extraction with depth. This lack of variation is in contrast to extraction patterns measured under pasture (M^{c}Aneney and Judd, 1983) or peaches (Garnier et al., 1986). The kiwifruit vascular system, particularly the roots, has an extremely high conductivity (M^{c}Aneney and Judd, 1983). The uniform extraction is probably in part a result of the high root conductivity.

There was significant extraction of water at the maximum depth of measurement, indicating that the 2.2 m long access tubes were not deep enough to allow full characterisation of water extraction with depth. A study undertaken 3 years earlier in same orchard block (M^{c}Auliffe, 1985) revealed little extraction below 1 m. Therefore the root system has grown enough in the three years between the two studies to allow the maximum depth of extraction to increase by more than 1 m. This growth will have substantially increased the volume of soil water available to the vine.s

A concurrent study of vine root distribution showed that at 2 m deep, the root density was substantially lower than values found near the surface. However, in the majority of samples taken roots were found to be present (P. W. Gandar, pers. comm.). As samples were taken to a maximum depth of 2 m the lower limit of root exploration was not determined. Wherever the root front had reached, that depth, plus an allowance for upward movement of water, will set the maximum depth of water extraction.

The pattern was replicated in two directions, along and across the row. Water extraction along and across the row was found not to be significantly different. Root distribution studies indicated that beyond 1.3 m from the vine root length density fell markedly, although some roots

were still found 2.75 m from the vine. The soil available to the vine roots may then be divided into two zones. The first is the zone of occupation, defined as the volume of soil well-explored by roots. In this soil, for 7 year-old vines, the zone of occupation extends to 1.3 m horizontally and greater then 2 m vertically. Water extraction within the zone of occupation showed a more-or-less constant degree of water extraction by the time water stress set in. Before this time, water closest to the vine may have been preferentially taken up. It is not possible be more conclusive about this because there are limited data available for the early stages of extraction.

The second zone is the zone of exploration. In this volume of soil there are some roots, but most of the soil is not occupied by roots. This zone starts where the zone of occupation ends and extends half-way to the next vine. In the zone of exploration, less water was extracted from the soil than in the zone of occupation. Also in this zone, the time at which water stress was first experienced, water extraction decreased linearly with horizontal distance from the vine. Extrapolation of the profile of water extraction with horizontal distance from the vine indicated that at 2.5 m from the vine there was no extraction of water.

Thus it would appear that the horizontal pattern of water extraction could be modelled as a constant level of extraction to the periphery of the zone of occupation, followed by a linear decline in water extraction to reach zero at 2.5 m. The constant extraction within the zone of occupation is determined largely by root factors, so this pattern would be expected occur in all soils. Extraction from the zone of exploration, assumed to be predominantly lateral flow into the zone of occupation, is dependent largely on the matric potential gradient and on soil hydraulic properties. These, especially the latter, may vary between soils, so that the importance of extraction from the zone of exploration may vary between soils.

Radial variation in water extraction has also been noted by van Oostrum (1985). In this study, however, only 2 distances were monitored, one of which was likely to be in the zone of occupation and the other in the zone of exploration, so the detailed pattern of extraction could not be determined.

5.2 The Size of the Reservoir of available Water.

Fruit growth (in both seasons) and leaf water potential (in the 1986/87 season only) were monitored on irrigated and non-irrigated vines to indicate the onset of water stress. In this way it was possible to determine the reservoir of water readily-available to the vines. This reservoir is the amount of water which may be extracted from the soil before the onset of stress. In the 1985/86 season there was considerable variation within and between the irrigated and non-irrigated vines in crop loading and initial fruit size. This made comparison of fruit size between vines difficult. However one irrigated vine (Y) and the non-irrigated vine (B) had similar crop loads and initial fruit sizes, so that the fruit size on these two vines could be compared. During this season, the other covered vine (A) suffered considerably more than vine B in terms of reduction in fruit size, even though vine A was irrigated from early April onwards whereas vine B was not.

In the 1986/87 season, fruit were selected for uniform flowering characteristics and type of cane. The subsequent good agreement in the fruit size of the irrigated vines was probably a reflection of this careful selection. Despite the application of water early in the season (some time before vine B showed symptoms of water stress), vine A still exhibited lower leaf water potentials and stunted fruit growth. Neither leaf water potential or fruit growth improved for almost a month after the application of water. Due to the rather unusual behaviour of this vine, the data collected from vine a were not used to determine the size of the reservoir.

Fruit growth and leaf water potential measurements agreed to within 5 days as to when vine B had become stressed. The estimate of the size of the reservoir was 1.26 m^3 in the 1985/86 season and 1.29 m^3 in the 1986/87 season. After correction for the amount of water extracted from between 2.25 and 2.5 m horizontally from the vine and below 2.2 m, the reservoir was estimated to be 3.1 m^3. Approximately 60% of the readily available water came from the zone of exploration, thus suggesting the importance of lateral flow in supplying water to immature kiwifruit on the Westmere silt loam. As the vine roots occupy more of the soil available to them, the importance of lateral flow of water into the root zone will decrease.

The root front, that is the futhermost extent of the zone of occupation, was observed to grow at approximately 0.25 m per year in the orchard under study (Clothier et al., 1986). If root growth continues at this rate, the reservoir in 1988/89 is projected to be 3.3 m^3, and at full maturity (probably 1993/94) 4.3 m^3. The above figures are based on a maximum depth of extraction of 2.2 m. By comparing heat pulse and water balance estimates of vine water use, it was estimated that extraction below 2.2 m was between 20% and 50% of that above 2.2 m. Taking an intermediate value of 35%, it may be estimated that the total reservoir is currently 3.1 m^3. With no increase in water extraction below 2.2 m as the vine matures the reservoir for 10 year-old vines and at maturity is estimated to be 4.7 and 6.7 m^3 respectively. These reservoirs represent very large volumes of water, and as the vine approaches maturity, irrigation may not be required.

The matric potential at 0.5 m deep at the onset of stress was just below -40 kPa. Pre-dawn leaf water potential (i.e. at no sap flow) is often assumed to indicate the water potential of the soil. Van Oostrum (1985) suggested that vines with pre-dawn leaf water potentials of less than -140 kPa were water stressed. M. J. Judd (pers. comm.) suggests that vines should be considered to be water stressed if the pre-dawn leaf water potential is less than -100 kPa. Results from the current study would tend to confirm these findings. Using either estimate, it appears that the pre-dawn leaf water potential at the onset of stress is considerably lower than the soil water potential. This may, partially at least, be explained by the possibility of night-time transpiration, to which kiwifruit appear to be prone (S. R. Green, pers. comm.). Then tensiometers in the soil measure the matric potential at some distance away from the root surface which will be higher than the soil water potential experienced by the plant, due to the potential loss produced during flow to the root.

5.3 Vine Water Requirements.

When the prevailing conditions are fairly calm, trees in sheltered orchards have been found to use water at the equilibrium rate (Judd and M^{c}Aneney, 1983; S. R. Green, pers. comm.). Under dry windy conditions vines have been found to use water at a rate well-predicted by the

Penman-Monteith equation but at a rate considerably higher than the equilibrium rate (Judd et al., 1986). The vines in the current study were however found to use water at approximately 40% of the equilibrium rate. Two other water balance studies undertaken in kiwifruit orchards have been published. Both of these studies were analysed with an incorrect assumption about the symmetry of water extraction, so that their conclusions that water was extracted at the equilibrium rate may not necessarily be true. The water extracted may, in fact, represent considerably less than the equilibrium rate.

5.4 Implications for Irrigation System Design and Operation.

Factors important for the hydrological design and the operation of irrigation systems are the size of the reservoir of readily-available water and the rate at which the plant requires water. Also important are the proportion of the root system which should be irrigated to ensure adequate uptake of water, and the volume of available water which may be stored in the soil wetted by the irrigation emitter.

First consider the reservoir of readily available water. This is the volume of water which may be extracted from the soil around the kiwifruit vine without incurring penalty to fruit growth. The upper limit is set by the "field capacity" of the soil, and the lower limit by a combination of the minimum potential which can be exerted by the plant roots without causing leaf water potential to fall so low that plant growth processes are adversely affected, and the hydraulic conductivity and retentivity of the soil.

Although soil water potential is the property which influences the ability of the plant to extract water from the soil, irrigation recommendations are often made based on soil water content rather then on soil water potential. Available water is usually defined as the water between field capacity and the permanent wilting point (-1500 kPa) and the crop is then allowed to extract some arbitrary proportion of the available water (see for example Jamieson et al., 1984; Anon, 1983) before irrigation is recommended. The water which may be extracted is then multiplied by the area which the roots are presumed to extend and an "effective" rooting depth to produce a volume of extractable water. The effective rooting

depth is often fairly arbitrarily defined. Anon (1983) for example, suggests 0.5 m as an effective rooting depth for kiwifruit. Although this method for determining the volume of extractable water is simple to understand, the estimate produced may be considerably different from the true value, depending on the veracity of the assumed rooting depth. Using the recommendations of Anon (1983) for a silt loam, the reservoir of water may be calculated to be 1.0 m^3 for fully mature vines. Contrast this figure to that estimated in Chapter 3 of 6.7 m^3 as a minimum estimate of the reservoir of available water. In this instance the true reservoir at maturity will be more than 6 times that calculated by the method outlined. A discrepancy of this order may lead to the conclusion that irrigation will be required by mature vines when it will not actually be necessary.

The method outlined by Anon (1983) does not take into account the variation in supply of water to the plant as the vine matures. When grown in an orchard, the relative growth of the canopy and root system are out of phase. While the canopy may take only three years to completely cover the area allotted to it, the roots may take 10 years or longer to completely explore the soil available (Gandar and Hughes, 1987). This imbalance results in peak irrigation requirements occurring in the first few years of the vines life. Irrigation systems are however usually designed for mature vines. For example a three year old vine, assuming the roots extend outwards at 250 mm $year^{-1}$ (Clothier et al., 1986), may be able to obtain little more than 0.2 m^3 of water, compared with over 6.7 m^3 at 10 years. The water requirements of the vine will however be constant as in both cases the vine has full canopy cover.

The growth of the root system, and associated increase in the size of the reservoir, is important for the choice and siting of the irrigation emitter, and for the orchard manager when scheduling irrigation. If the type of irrigation emitter chosen is a mini-sprinkler or micro-jet, a typical wetted radius may be 1 m. To avoid droplets being intercepted by the stem the emitter is likely to be sited about 1 m away from the vine stem. An emitter sited in such a manner would result in less than half the applied water landing within the zone of occupation when the vine is less than 4 years old. Although some of the water which has been applied outside of the root zone would flow inwards towards the roots, much of the water would be wasted. The vine would be approximately eight years old

before all the applied water landed on the soil which was occupied by the roots. For vines younger than 8 years, as some of the applied water would not reach the roots, the irrigation interval would need to be shorter to allow for the wastage. Indeed, if the irrigation system were designed to adequately water young vines, it may then become considerably over-designed for mature vines. A more usual condition would however be that the system would be designed for mature vines and the young vines would be inadequately watered. Under-watering of young vines, although not causing an immediate decrease in income, as exportable fruit yields are low at this time, may lead to stunted cane, and perhaps root, growth so increasing the length of time taken for the vine to come into full production. In times of high land values and interest rates this delay may be economically important enough to encourage the design of irrigation systems which cater for young vines as well as mature vines.

The growth in the size of the reservoir also has implications for the orchard manager when deciding when to commence irrigation and for scheduling irrigation. Because the size of the reservoir grows with vine age, and the amount of useful water applied by the irrigation system grows, experience gained in irrigation scheduling while the vine was young will not be directly applicable to older vines. This stresses the importance of objective scheduling tools. If the scheduling tool used is a water balance, proper account will need to be made of the growth in size and geometry of the root system. Alternatively, if a tensiometer is used, the manager need only know the critical ψ and the horizontal extent of root growth, to ensure that the tensiometer is placed within the zone of occupation. The horizontal growth of the root system can easily be determined by digging a shallow trench radially from the vine. Considerably more work would be needed to determine the vertical extent of the root zone needed if the water balance technique is to be used.

This study appeared to give a very low rate of water use in kiwifruit vines, approximately 40% of the equilibrium rate. Other studies have indicated that vine water use is well described by the equilibrium rate (Edwards and Warrick, 1984; S. R. Green, pers. comm.), except under windy conditions where it may be considerably higher (Judd et al., 1986). At this stage it may be best to take a conservative approach and use the equilibrium rate for the design of irrigation systems. The rate of water

use is needed when deciding if irrigation is needed at all (in conjunction with the size of the reservoir of available water), the design of any irrigation system, and for irrigation scheduling if the water balance method is to be used. Lower water use rates will mean that irrigation is less likely to be required and that return intervals will be longer than if the water use rate were high. The rate of water use is likely to be lower in the first 2-3 seasons, when the canopy is developing than in older vines. Canopy cover is also incomplete for approximately the first month of each season.

In summary, the implications of this study for irrigation system design and operation result from the findings that, within the zone of occupation water is relatively evenly extracted, and that there is a potentially large reservoir of available water. The zone of occupation is the volume of soil completely explored by roots. This zone grows radially in a horizontal direction at approximately 250 mm $year^{-1}$. The vertical growth rate is not known, but there is some evidence that vertical growth may exceed horizontal growth. Within this volume of soil, water is uniformly extracted and the matric potential will fall below -40 kPa in this zone before stress sets in. It is therefore recommended that irrigation takes place when soil water potential falls to -40 kPa. This will allow for a margin of saftey. Substantial amounts of water may flow into the root zone, but the importance of this flow to the water supply of plant may vary between soil types and vine ages.

The size of the reservoir of readily available water grows with vine maturity and is likely to reach a maximum at 10 years. A conservative estimate is to assume that the zone of occupation grows outward, hemi-spherically, at 250 mm $year^{-1}$, and that within this volume, the water held in the soil between field capacity and -40 kPa is readily available. In fact, the reservoir will be considerably larger than this estimate, as the roots appear to grow faster than 250 mm $year^{-1}$ vertically, and flow into the root zone from the surrounding soil can contribute large volumes to the reservoir.

5.5 Further Research Needs.

This study has highlighted the potentially large reservoir of water available to kiwifruit planted in the Westmere silt loam. Although van Oostrum (1985) did not quantify the size of the reservoir available to the 4 year old kiwifruit in his study on the Ohinepanea loamy sand, the fact that vines receiving only rainfall over an extremely dry season did not show reduced fruit growth as compared with irrigated vines, indicates that his vines also had access to large volumes of water. In contrast to these studies, standard estimates of the volume of water available to mature kiwifruit planted at 5 m centres ranges from 1.25 to 2.5 m^3 (Anon, 1983). This study has shown that for the Westmere silt loam, at vine maturity, the reservoir will be greater than 6.7 m^3. In order to assess accurately the size of the reservoir, attention should be paid to the size of the root system. Further work, similar to that described in Hughes et al. (1986), needs to be carried out to establish the rate of growth of root systems in response to soil, plant and environmental factors. An understanding of root system size, and the hydraulic properties of the soil, will allow an estimation of the size of the reservoir of available water at any given vine age.

The rate of water use by kiwifruit vines is important for irrigation system design and operation. This study has appeared to show very low rates of water use in one orchard. Further, more detailed, work should be carried out in Carson's orchard to either refute or confirm the findings of the current study to calculate a more complete water balance. Heat pulse and excision experiments carried out in other orchards have shown much higher rates of water use. additional studies of undisturbed vine water use should be carried out in an effort to resolve this discrepancy.

In order for orchard managers to make informed decisions about the need for irrigation, studies on the impact of irrigation on fruit size and quality are required. Several trials purporting to study the effect of non-irrigation on fruit size have been carried out (see for example Barber, 1987; New Zealand Kiwifruit authority, 1986; Lupton, 1986). Many of these trials have been carried out without adequately monitoring environmental and plant variables and so are of little use for examining irrigation benefit in any season or site other than the one in which the

trial was carried out. Properly replicated and controlled trials studying the effect of various degrees of water stress on fruit growth at different stages of the season, with adequate monitoring of soil, plant, and atmospheric conditions are the only type of trial useful for furthering knowledge of irrigation benefit for kiwifruit.

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