CLIMATE VARIABILITY AND FOOD SECURITY
A NEW ZEALAND PERSPECTIVE

A Thesis presented for the Degree

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by

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Dedication : To Karen for her love and support throughout.

To Lena for the vitality and hope for the future that she embodies.

Abstract of a Thesis presented for the Degree of Doctor of Philosophy in Agricultural Meteorology.

CLIMATE VARIABILITY AND FOOD SECURITY A NEW ZEALAND PERSPECTIVE

The objective of this Thesis was to develop a clearer understanding of inter-relationships between climate variability and food security in New Zealand. It was considered important to both clarify crop-climate relationships and possible response options available to regional planners and individuals. This is particularly relevant in the context of a probable global climate warming.

An empirical-statistical analysis of crop-climate interactions was carried out. This was followed by a more detailed agroclimate analysis of the Canterbury region, and an evaluation of one possible response option in the face of present, and possible future, climate variability and change. This involved a field based study of shelterbelt effects. The final part of the Thesis gives a tentative assessment of the possible impacts on agriculture in New Zealand of regional greenhouse warming scenarios.

Monthly rainfall and mean temperature data were used for the crop-climate analyses. Adjustments for site changes were made where necessary and missing values estimated. Trend removal was performed on temperate grain and pipfruit yield time series. Quadratic, and in the case of pears linear, trend lines were fitted to the yield data. Analyses were performed on the residuals. No trend removal was carried out on stonefruit data.

Principal component analysis, followed by stepwise multiple regression, showed the barley crop to be the most spatially responsive to climate of the three temperate grain crops examined. Wheat was intermediate in its response and oats the least spatially responsive. Autumn sown wheat showed a negative relationship with winter rainfall and spring temperature. The dominant result with oats and barley was a negative effect on yield of late spring to early summer temperatures.

Analyses of national stonefruit data met with mixed success. Peaches and nectarines, although of the same species, gave different significant predictors. This was attributed to differences in weighting on the climate data, related to geographic distribution. The susceptibility of apricots to late frosts appeared to show through with this crop. Cherries showed a strongly negative relationship with rainfall at blossom and harvest time. The most significant predictor with plums was a positive relationship with May temperature. This was treated with scepticism. These results highlight the need for further detailed analysis of these crops at the district level.

The limited district analyses of apple yields showed a graded response to rainfall. At the extremes, the wetter Auckland district showed predominantly negative responses and the drier Central Otago district showed positive responses. A negative relationship between apple yield and July temperature was found to be a climatic response from the Hawkes Bay district. This may be related to poor fruit set and flower quality, leading to low yields, as suggested by research in England. The dominant response apparent with pears, in earlier years, was a negative relationship with January temperature. This appears to have become less limiting and may be related to increased use of irrigation over this moisture sensitive period. As with stonefruit more detailed analyses, particularly at the district level are required.

A spatial analysis of Canterbury plains climate confirmed that the climate of this region is relatively homogenous. However a general north/south division was apparent with the Rakaia river as a general dividing line. Closer analysis of rainfall data revealed that this north/south contrast is predominantly between the Christchurch area, influenced by Banks Peninsula, and South Canterbury, influenced by the narrow coastal strip and proximity to the foothills. Differences between these two areas are greater than similarities. Principal component analysis of Canterbury county wheat yields confirmed results from the weighted national and Canterbury district analyses. Waimate, in South Canterbury, proved to be anomalous in its yield response, which was consistent with the spatial analyses of rainfall and deficit day data. Drought in Canterbury was shown to become a regional phenomenon in the driest of the dry years, and to be persistent in these years. Correlation analysis between deficit day data and time series of detrended Canterbury district yield data, for temperate grains and pipfruit, showed a significant negative relationship between agricultural drought and yield.

Analysis of shelter effects revealed a hierarchical classification of sites based on the site roughness parameter, z_0. The most exposed, reference, site was well representative of open plains conditions. The least exposed, highly sheltered, orchard site showed a high degree of "decoupling" from the regional environment. Mean temperatures were significantly higher in the three, more sheltered, remote sites as compared to the reference site. Maximum temperatures were significantly higher in the most sheltered sites. In all remote sites there were significant reductions in wind speed in relation to the reference site. Evapotranspiration, based on Penman estimates, was significantly lower in the two orchard sites. Priestley-Taylor estimates proved to be more conservative, attributed to the use of a constant not calibrated for different site conditions. It is speculated that these significant differences in site microclimate could lead to yield benefits in Canterbury, through greater water use efficiency. This could contribute significantly to mitigating the effects of non-periodic, but recurrent and persistent droughts in this region.

The tentative assessment of agricultural impacts of a greenhouse warming drew from past climate analogue scenarios. The temperate grains showed slight to moderate yield reductions.

It was suggested that Southland may increase in importance as a temperate grain growing district. Assessment of fruit crops was more speculative, as shown in the results. The east coast of the South Island and Central Otago could increase in importance for the growing of temperate fruit crops. From the Canterbury regional greenhouse scenario it would appear that in the future there will be greater potential for agricultural drought in this region. The results from the agroclimate analysis and field study of shelter effects are particularly relevant in this context.

This Thesis highlights the considerable uncertainty that exists in the field of crop-climate analyses. Data bases need to be consolidated and more critical analyses made of possible response options, particularly in the face of a probable global climate warming.

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CHAPTER 1

General Introduction

1.1 Overview

On a geological time scale humans have been present on the earth for only a very small fraction of its history. Of the approximate two to six million years of human evolution, agriculture has been practised for only a small percentage of time. The beginning of agriculture marked a shift in the relationship between humans and their environment, from mobile hunter gatherer societies to settled societies growing crops in fixed localities with associated climates. It is uncertain as to how the earliest farmers coped with the natural variability of climate. However it is probable that they very quickly learned to store food to carry them through periods of adversity. Possible impacts of climate change can be deduced from proxy climatic and archaeological evidence.

More than a hundred years of instrumental record and the more recent technological revolution have vastly increased our knowledge of climate, its variability and the potential for climate to change. Concurrent with this has been a growing awareness of global environmental problems and concern about the capacity of the earth to sustain future populations. Over the last decade or so, particularly since the early 1970s food crisis, there has been a large number of expert gatherings to address issues associated with food and population. Atmospheric scientists, recognising the importance of climate to both present and future food production, have played their part.

As the result of an International Workshop held in Berlin in 1980, Bach et al (1981), recognised the importance of climate information in "designing sustainable food systems to meet world food needs within local environmental, economic, population and other social constraints".

Two aspects of food-climate interactions were examined, from the perspective of: (a) climate as a resource and (b) climate as a hazard. Schneider and Londer (1984) gave a comprehensive review of the issues and concluded that "it is not so much the weather that will permit us to get through the next ten years without major famines, for example .... rather, it is societies and the way they set up their food security systems to deal with fluctuating climate and the resulting impacts that constitute the most critical factor".

It was out of a general interest in sustainable food systems and the important role of climate in relation to food security that this thesis evolved.

1.2 Objectives

As with many projects this thesis went through an evolutionary process. The original motivation was to assess the potential of tree crops to modify the physical and biological environment in the Canterbury Plains region of New Zealand. In the very early stages a primary objective was to assess the impact of natural climate variability on crop yields in New Zealand and to evaluate the potential of well planned modification of the local and regional environment to mitigate the effects of this variability. This objective was further refined into two main aims :-

1. To gather as much information as possible about food and climate in Canterbury and carry out appropriate analyses to evaluate the agroclimate resource.

2. To conduct a field study of shelterbelt effects, comparing exposed and sheltered sites. From this information the aim was to evaluate differences in site roughness and microclimate and to assess the possible effects of shelterbelts on crop yield.

It became apparent that the agroclimate data base for Canterbury was relatively sparse and that there were limitations to what could be achieved with the field study of shelter effects. The original primary objective remained intact, but it was decided to expand the resource base. The thesis was finally organised into two major components :-

1. An evaluation of crop-climate interactions in New Zealand for a selection of grain and fruit crops. National and district yield data were collected from published sources, and climate data obtained from microfiche records. An empirical-multiple regression approach to analysis was carried out. The aim of this evaluation was to give an overview of relationships between climate variability and crop yield in New Zealand as a context setting for a Canterbury, regional analysis.

2. An evaluation of the agroclimate resource in Canterbury and an assessment of the potential of shelterbelts to modify the physical and biological environment. This fulfilled the aims identified earlier.

A logical progression from the analysis of crop-climate interactions was to give some tentative assessment of possible effects of a CO_2 warming on crop yields in New Zealand. This was very much a secondary objective.

1.3 Organisation of the thesis

The thesis is organised into four parts.

Part 1 consists of this general introduction and Chapter 2 which gives a global perspective on climate variability and food security and a brief review of approaches to evaluating crop-climate interactions. This provides an overall context setting for the thesis.

Part 2 is an evaluation of food-climate interactions in New Zealand. Chapter 3 backgrounds the New Zealand food-climate system. A brief description of New Zealand climate is given and the food system and interactions with climate are briefly reviewed. Chapter 4 describes the climate and yield data used in the analyses, and adjustments made prior to analyses. This is followed by a presentation of methods used in the empirical analyses of crop-climate interactions. Chapter 5 details the analyses of the temperate grains: wheat, oats and barley. Brief reviews of each crop in relation to climate are given, followed by a presentation and discussion of the results and a summary. Chapter 6 details the analyses of stonefruit (apricots, cherries, nectarines, peaches, plums) and pipfruit (apples, pears). A similar format to Chapter 5 is used.

Part 3 is an evaluation of the agroclimate resource in Canterbury and an assessment of the value of shelterbelts. Chapter 7 is a review and analysis of the Canterbury food-climate system. Brief reviews of climate and food production in Canterbury are given. This is followed by a review and analysis of the spatial variability of Canterbury climate. A more detailed analysis of interactions between wheat yields and climate in Canterbury is presented. This is followed by an analysis of drought and its impact on selected crops. The value of shelter is the subject of Chapter 8. A review of the physical and biological effects of shelter is given. This is followed by a description of the experimental programme for analysis of shelter effects. Chapter 9 is a presentation of the results from the field work, covering general site descriptions and evaluations of site roughness and microclimate.

Part 4 involves some further discussion, a tentative assessment of the possible impact of CO_2 warmed scenarios on crop yields, and conclusions and recommendations. Chapter 10 draws the potential for a greener Canterbury from the empirical crop-climate analyses and the analysis of shelter effects. Chapter 11 gives a review of tentative CO_2 warmed scenarios for New Zealand. This is followed by a tentative assessment of agricultural impacts, based on the empirical-statistical analyses. Chapter 12 is an evaluation of the thesis in the context of the original objectives. Conclusions are drawn and recommendations for future research are presented.

CHAPTER 2

A Global Perspective

2.1 Introduction

In the general introduction the importance of climatic information for global food security was identified. This chapter offers a brief review of some of the information that is available, discusses one general area of application of this information, and possible response options.

A brief discussion of climate and climate variability is given, with some definition of terms. This provides an important background for the remainder of the overview. As earlier identified, climate is integrally related to the activities of humans. This was clearly demonstrated by Schneider and Londer (1984). While the impact of climate variability on past societies can only be generally surmised, there is documented evidence that suggests interactions between climate and past civilizations. This is reviewed, giving a few examples. It leads into the present with an introduction to the concept of food security in the context of climate variability. The Sahelian drought of the early 1970s is used as an example.

Crop-climate models offer one means of applying climatic information to issues of food security, and a review of approaches is given. The results of such models can be useful in determining possible responses to mitigating the effects of climate variability. Some possible responses to improving food security in the face of climate variability are discussed in the final section.

2.2 Climate and climate variability

The simplest description of climate is that it is the statistics of weather (Ruttenberg, 1981). By convention climate is described by the statistics of a climatic element, such as temperature and rainfall, over a given reference period which is usually at least 30 years in length. The statistical averages of the selected elements are often referred to as the climatic "normals" for the given reference period. Schneider and Londer (1984) commented on the often erroneous use of the word "normal" in the place of "average" stating that "it is abnormal to have the statistically average weather at any one time".

The atmosphere is the medium which is most strongly associated with climate, both on an instrumental and an experiential level. However the atmosphere is only a part of a complex, dynamic and interactive system which constitutes the climate. The energy source which drives this system is the sun. While the atmosphere is the central component of the climate system, the hydrosphere and cryosphere also play important roles. The hydrosphere, particularly the oceans, acts as a heat reservoir and through the ocean currents can distribute this heat from warmer tropical latitudes to the cooler mid latitudes and polar regions. The cryosphere induces colder local climates through the high albedo and low thermal conductivity of ice (Gates, 1979). Other components of the climate system are the lithosphere, which plays a relatively passive role on human time scales, and the biosphere. Plants actively interact with climate through seasonal cycles and can also considerably modify local (micro) and regional (meso) climates. The biogeochemical cycles are a significant part of the climate system, as has been popularised with the well documented greenhouse effect. This also raises the issue of the impact of human activities on climate, which is now suspected to be occurring on a global scale with the warming effect of the greenhouse gases. More detailed descriptions of the climate system are given in Gates (1979) and Schneider and Londer (1984).

The statistical description of climate for any specified time period, for example on a monthly basis or over a 30 year reference period, is described by Gates (1979) as a climatic state. Associated with this are the boundary conditions as described by data from the oceans, cryosphere and land surfaces. Climate variability can be described by the internal variability that exists for a given climatic state, as defined by Hare (1979). There are different types of variability about the averages of the climatic elements. These are given by Hare (1979) as :-

1. periodic effects, such as diurnal and seasonal variability

2. quasi-periodic effects, such as the quasi-biennial cycle and monsoonal rainfall

3. non-periodic effects

Non periodic effects are often described as the underlying noise in a time series of climate data, however they can be important, particularly when significant anomalies occur. Examples may include heat waves, periods of drought, snow storms and floods. The increasingly documented El Niño events are another non-periodic effect which can lead to significant climatic anomalies over a wide geographic range. Generally it is the short term variability in climate that has the greatest impact on humans and their activities. Periodic effects such as seasonal variability can become integral to cultural systems, as evidenced by autumn harvest festivals, spring blossom time celebrations, which can coincide with traditional harvest and sowing times. Often it is quasi and non-periodic variability in climate that causes the most disruption to human affairs, such as failure of monsoon rains and persistent droughts.

Differences can occur between different reference periods, or climatic states. This can be attributed to the noise in the data, but may also relate to real variation, or change in climate. The most apparent contemporary example is the greenhouse effect. From the 1940s until the late 1970s there was a cooling trend in the northern hemisphere. There was considerable debate, particularly in the 1970s and early 1980s, as to whether a change in climate was occurring and if so whether it related to a cooling or warming of global temperature. Temperature trends in the 1980s suggest that a global warming is actually taking place and Schneider (1989) believes that sufficient is known to warrant implementation of policies to adapt to this apparent warming.

2.3 Climate and civilizations

A detailed chronology of past climate is given in Lamb (1974), who also gave some documentation of apparent relationships between climate and early civilizations. Bryson and Murray (1977) documented the decline of several civilizations and provided evidence that suggests some climatic connection. A brief review of the subject is also given in Pearson (1978) with an excellent overview in Schneider and Londer (1984).

Both the proxy climatic record and information drawn from early written records show parallels between changing climate and patterns of human migration, rise and fall of civilizations and changes in cultural activities. Undoubtedly climate has influenced human activities from the very beginnings of human evolution. Early hunter-gatherer societies were probably very much influenced by changes in climate. Given their mobility and relatively small numbers they probably had a far greater adaptability than later, less mobile societies. The survival of the Australian Aborigine in climatically harsh environments over a period of some 40000 years attests to the durability and adaptability of this hunter-gatherer society.

The development of agriculture gave many benefits to humans, coinciding with the beginnings of civilization. At the same time it marked a shift in the relationship between humans and their environment. Archaeological evidence shows that some early civilizations developed ingeneous means for sustaining their agriculture. However, for some, concurrent proxy climatic evidence suggests that agricultural activities were very much limited by climate. One such example is the civilization that thrived in the Indus Valley region some 5000 years ago. This region is now predominantly desert. One possible explanation for the decline of this civilization is that there was a persistent failure of the monsoon rains (Bryson and Murray, 1977). The proxy climatic evidence, as presented in Schneider and Londer (1984) suggests that this and other civilizations flourished during a period of generally warmer climate in the Holocene epoch referred to as the Altithermal or Hypsithermal.

A more recent warm period occurred approximately 1000 years ago. Schneider and Londer (1984) list a number of events that appear to be related to this warming. One of the most infamous is the settlement of Greenland by Eric the Red. This was also the time when a number of vineyards flourished in England. In the southern hemisphere this climatic optimum coincided with the arrival of the Maori in the land they called Aotearoa, as is discussed further in Chapter 3.

Following this warm period a general climatic cooling occurred leading to the Little Ice Age. Proxy climatic data from both Europe and New Zealand gives evidence of this cooling.

The availability of water is a critical factor for the survival of agriculture, as was the suggested case with the Indus valley civilization. In the 16th century a highly organised society existed in the Valley of Mexico, with an elaborate system of waterways. This was observed by the Spanish on their arrival in this valley in 1519 (Diaz, 1963). According to Redclift (1987) this system was dramatically modified over the subsequent 400 years as a result of colonization. He described the situation in 1984. The Valley of Mexico faced major environmental problems including : lack of soil nutrients, erosion, salinity, alkalinity, flooding, overgrazing and excessive deforestation.

The message from the above example is that the activities of humans are equally important in considering connections between climate and civilizations. This was made clear by Pearson (1978) who stated that "climatic effects have to be seen as having essentially synergistic actions alongside man's decisions".

2.4 Climate variability and food security

While there is considerable evidence from the past of the inter-relationship of humans and climate change, the extent to which climate variability affected past agricultural activities can only be surmised at. It is apparent however, that as societies became increasingly organised, they also became more detached from the natural environment. In a sense this made them more vulnerable to climate perturbations, whether short or long term. No longer migratory, they often depended on food reserves to carry them through the bad years. Some devised ingeneous irrigation systems which allowed them to survive. This vulnerability to climate has continued to the present day. The advantage of 20th century humans is that they have a vast array of information at their disposal, both of the apparent effects of past variations in climate and of present food systems and related climate. To our disadvantage is that there now exist climate related environmental problems which are global in scale.

The post second world war years, up until the late 1960s were generally a period of favourable climate. This was the time of the Green Revolution which saw the development of high yielding crop varieties and a global surplus of food. Salinger (1979) described the years 1950 to 1969 as the Green Years for New Zealand agriculture. In the early post war years the Food and Agriculture Organisation of the United Nations was established. An early long term proposal of the first FAO Director-General "to stabilize world food prices through buffer stocks, to establish a world food reserve and to finance the disposal of surpluses to needy countries was rejected out of hand by member governments unwilling to make the political and economic commitments required", (Saouma, 1981).

The period of post war optimism was broken dramatically in the early 1970s. The most documented climatic event was the Sahelian drought. It was as a result of the food crisis that developed through this drought that an International Undertaking on World Food Security was approved in principal by the FAO (Saouma, 1981). One of the main calls was for governments to maintain food reserves for international emergencies.

Numerous analyses of the Sahelian drought and the human impact have been carried out. Different interpretations of events were summarised by Schneider and Londer (1984). Several scientists, such as Landsberg (1975) and Ruttenberg (1981), have shown that drought is a recurrent phenomena in this region and is a part of the natural variability of the climate. A more controversial stance was taken by Bryson (1974) who argued that the effect in the Sahel resulted from a southward shift of the subtropical high pressure belt.

One of the most detailed studies of the Sahel drought and its impact was that carried out by a team of scientists headed by Garcia (1981). They developed a theoretical framework for a systems analysis of drought and conducted a number of case studies. Systems were seen to have four main components, including :-

(a) a physical component

(b) a physico-biological component

(c) a man-generated biological component

(d) a socio-economic component

One of their main conclusions was that droughts are not directly causal in relation to famine and related human and environmental disasters. It was concluded that events were a result of a pre-existing disequilibrium in society and that "the evolution after the drought has "stricken" is much more determined by the structure of the whole socio-ecosystem than by the drought itself" (Garcia, 1981). Also included in this report was a paper on food aid, which concluded that current aid programmes are generally ineffective. Inappropriate technology and mis-application of foreign aid were identified by Glantz (1977) as being contributory factors to the Sahel disaster. While Garcia's (1981) conclusion was that structural changes in the socio-economic system were required Schneider and Londer (1984) quoted a more conservative analysis which advocated a free market approach to resolving food shortage problems. Importantly, Schneider and Londer (1984) concluded that while the actual events were undisputed, differences in ideology lead to differing emphases in analysis and interpretation.

The Sahel drought and the subsequent events is an extreme, but not isolated, case. McQuigg (1981) observed that "all of the agricultural regions of the world are subject to significant temporal and spatial climate variability. The impact of this variability on yield and production of food grain is important in each case". Concern over the prospect of climate change has accelerated interest in relationships between food crops and climate. Some developed countries in cool temperate regions have well established crop-climate research programmes such as that initiated by the Canada Committee on Agrometeorology (1977). For present and future planning it is important to understand more clearly the relationships between crops and the climates in which they are grown. The information gained can provide a valuable input into assessment of both short and long term response options.

2.5 Crop-climate modelling

The analyses of the Sahel drought showed that there is a complexity of inter-relationships between climate and food production. One approach to understanding the interactions between climate and crops more clearly is through the use of crop-climate models. The information that these may give is not a panacea for the problems of global food security, as Cusack (1981) commented, but do offer a lot of potential when used in an appropriate context. This view is also held by Steyaert et al (1981) who believed that a greater understanding of agroclimatology could be usefully applied to both improve food security and to provide input into short and long term agricultural planning.

While a crop-climate model can have deterministic and stochastic elements, three broad groupings of model are now generally accepted. These groupings were originally proposed by Baier (1979). Deterministic models are generally based on the physiological approach and are termed crop growth simulation models. Stochastic models are more statistical in nature and hence refer more to empirical-statistical models. A third type of model, one which is intermediate to the other two, is termed crop-weather analysis models.

Crop growth simulation models are mathematically based and require a detailed knowledge of crop physiology. The focus of such models is on specific plant processes such as photosynthesis, transpiration and respiration (Warwick et al, 1988). These processes are matched with real-time meteorological data, such as temperature, radiation and soil moisture. Monteith (1981) identified de Wit et al (1971) as pioneers in the field of crop growth simulation. The major advantage of this approach, stemming from the clear matching of meteorological data to plant processes, is the transportability of the models. A major disadvantage, identified by Monteith (1981), is the insatiable appetite for data of such models. In attempting to be comprehensive, they can potentially lead to greater confusion because of their complexity, Warwick et al, (1986). Other major disadvantages identified by McQuigg (1982) are the incomplete knowledge of causal and thus the resource input, is an important distinction. In this sense, empirical-statistical models are the most user-friendly. The trade-off which results from the level of input is the degree of detail obtained. Empirical-statistical models are capable of providing a general overview of relationships in the area of analysis and may identify significant features of crop-climate relationships in that area.

Simulation models can lead to a much deeper understanding of plant processes and the important role of weather and climate, and can have an application beyond the area of study. These are the significant features which are summarised by Warwick et al (1986).

There were several reasons for choosing the empirical-statistical approach in this thesis. The financial and data resource limitation under which the research was being carried out, limited the choice. Apart from this a general overview was the desired outcome of the crop-climate analyses. To achieve this overview the most appropriate scale at which to operate is at the national or regional level. This is best obtained from the empirical-statistical approach. It also allowed for an exploration of spatial differences for particular crops, as well as analyses of a wide range of grain and fruit crops.

2.6 Response options

There are two general spheres through which responses can be made to information gathered from crop-climate models and other sources. These are the socio-economic sphere, which is comprised of political and economic policy makers and instigators; and the bio-technical sphere, which requires policy direction which is generally actioned through the work of scientists and research and development programmes. These two spheres are consistent with the systems components identified by Garcia (1981), and reviewed in section 2.4.

The use of food reserves and schemes to minimize climatic risk such as crop insurance, were identified by Schneider and Londer (1984) as social policy actions. Under the bio-technical sphere Schneider and Londer (1984) identified diversification, such as multiple cropping; and weather proofing, such as through the use of irrigation and shelterbelts. Although these authors separated out biological and technical measures they are grouped together here as they are seen to be interactive. For example the use of irrigation and shelterbelts can modify the local and regional climate and provide the potential for diversification.

The remainder of this discussion is restricted to a brief elaboration of some bio-technical approaches and the possible benefits. An excellent review of microclimatology is given in Rosenberg et al (1983), who also discussed the application of microclimatology to problems of productivity in agriculture.

Microclimate modifications can be achieved through careful selection of site slope and aspect, mulching and artificial heating of soil, use of shelterbelts, frost protection and improved water use efficiency through use of antitranspirants, reflectants, changes in plant architecture and CO_2 enrichment (Rosenberg et al, 1983). Use of shelterbelts provides an attractive option because of their relatively low cost, low energy input, renewability, universal applicability and beneficial secondary effects.

Shelter effects are reviewed in more detail in Chapter 8. Rosenberg et al (1983) found the literature to be fairly consistent on the following shelter effects:

1. Shelter alters microclimate
2. Shelter reduces potential evapotranspiration
3. Shelter reduces actual evapotranspiration
4. Shelter improves internal water relations
5. Shelter provides improved opportunity for photosynthesis
6. Shelter generally increases yield

Use of shelterbelts gained favour in the Great Plains region of the U.S.A. following the Dust Bowl era in the 1930s. They were planted primarily as a means of controlling wind erosion of soil

(Rosenberg et al, 1983). The contribution of trees to food security was recognised by the FAO in the International Year of the Forest, 1985 (FAO Forestry Department, 1985). Recognised benefits from afforestation included soil and water conservation and attendant benefits; additional sources of food; fodder for livestock; additional sources of rural employment and income; fuelwood. This paper (FAO, 1985) also discussed the value of agroforestry, which was considered to contribute much needed diversification of farming systems leading to greater income stability and food security.

At the same time as shelterbelts were developed in the Great Plains widespread use of aquifer fed irrigation was adopted in this region. The main source of irrigation water is the Ogallala aquifer which Jackson (1980) and Schneider and Londer (1984) noted is being depleted at a far greater rate than it is being recharged. The latter authors commented that the very resource that may be required given a possible future warmer, drier climate may no longer be able to sustain crops in the long term. A radical solution was offered by Jackson (1980) who advocated a bio-technical fix based on a herbaceous perennial agriculture in the Great Plains region. This would involve developing previously unused genetic resources.

As a component of crop diversification Schneider and Londer (1984) identified the contribution of plant breeding. The Green Revolution highlighted the potential of plant breeding efforts, but with the associated dependence on high energy inputs met with limited success with subsistence farmers. In discussing this Roche (1985) pointed to the often quoted fact that plants used in modern agriculture represent less than 1 per cent of the earth's flora. He advocated a second front to research and development aimed at sustainable farming systems, and using neglected, traditionally valued plants. As an example Roche (1985) pointed to the shea butter tree, a plant that remains unknown and unselected by scientists and is now endangered. This was a crop of economic importance and part of a prosperous agriculture and ecologically rich and diverse landscape in Senegal and Mali in the 18^{th} century. These are now two of Africa's most ecologically impoverished and poor countries.

In summary, there are a range of responses that can be taken, given information on the agroclimate resource of a region. Crop-climate models offer one source of such information. The possible response options range from socio-economic structural changes to bio-technical measures. Some involve application and modification of conventional practices, which will be more attractive for short term planning. In some developed areas such as the Great Plains and environmentally sensitive areas such as the Sahel, more radical measures may become necessary to achieve long term sustainability. This may involve implementation of practices and tapping of resources not currently in wide use, such as those advocated by Jackson (1980) and Roche (1985).

CHAPTER 3

The New Zealand food-climate system

3.1 Introduction

Over prehistory a unique fauna and flora evolved in New Zealand. Climate played a significant role in this evolutionary process. Present native fauna and flora can give clues as to past climatic associations. The fossil record is also an invaluable tool for deducing past climate.

The arrival of the Maori people led to loss of coastal forests in some areas and extinction of some bird species. The Maori were essentially hunter-gatherers, harvesting from both sea and forest. They did practice some horticulture, but because of their very limited range of edible plants of tropical origin these activities were very much influenced by the climate of New Zealand.

By far the most dramatic changes to life in New Zealand came with the arrival of the European. They introduced a wide range of temperate crops which proved to be well suited to the climate. Land rapidly became a limited resource. Large scale clearing of forests occurred, resulting in a rapid transition to pastoral agriculture. The environmental consequences of this are still in force today.

Flat to rolling land suitable for cropping and horticulture is a valuable and limited resource in New Zealand. Past and recent history has made clear the need for careful watershed management and protection of these areas from the effects of wind and water erosion. What is also apparent is the need to understand more clearly relationships between yield and climate.

The following is a brief review of past and present associations between climate and plant life in New Zealand. It provides a foundation for analysis of food-climate interactions. First some knowledge of New Zealand climate is required.

3.2 New Zealand climate

New Zealand climate is well reviewed in a number of publications including those of Garnier (1950), Maunder (1971), Tomlinson (1976), and Steiner (1980). A brief summary is presented here.

New Zealand is located in the South West Pacific region and is spread between latitudes 34° and 47° S. The north of the country extends into the subtropical ridge. Most of the country is located in the zone of westerly flow, and this is generally the prevailing wind over the country. This westerly flow and the seasonal patterns of the subtropical high pressure belt are the predominant atmospheric features that determine present New Zealand climate. Important geographic features that further influence the climate include the oceanic locale of the country, which results in moist air streams passing over the country and has a moderating effect on temperature in most districts. The other significant geographic feature is the relief. New Zealand is a largely mountainous country, with approximately 75% of the land mass above 200 m. The dominant feature is the north-east to south-west oriented axial ranges. These are particularly dominant in the South Island, where the Southern Alps cover almost the entire length of the island, with 223 named peaks higher than 2300 m and the highest, Aorangi (Mt. Cook) peaking at 3764 m, (New Zealand Official Yearbook, 1987-1988).

A general feature of the climate of New Zealand is a succession of anticyclones and depressions. The depressions generally lie to the south of the anticyclones. Their eastward movement occurs in a roughly weekly cycle, although this pattern appears to prevail only about every one year in two. The depressions, which bring unstable weather to the country, generally have cold fronts associated with them. There is also an interannual variation in the mean latitude of the anticyclones. In winter the mean latitude is 26° S and in summer it is 36° S.

Contrasts in regional climate are generally greater between east and west than north and south. This is particularly pronounced with rainfall. The west coast of the South Island experiences the highest annual rainfall, on average, in New Zealand, due to its exposure to the westerly airflow and the orographic effect of the Southern Alps. Regions east of the axial ranges, including Hawkes Bay and Wairarapa in the North Island; Marlborough, Canterbury, North and Central Otago in the South Island, are the driest in New Zealand. In the south the contrast is marked when there are high pressures to the north and low pressures to the south of the country. This results in a strong westerly air flow onto the South Island. This tends to occur more frequently in spring time and brings heavy rainfall to the West Coast and often dry, warm Fohn winds to the Canterbury Plains.

Seasonal variations in rainfall occur in the North Island, with up to twice as much winter rainfall as summer rainfall in the north. This patterns lessens southwards. Another feature in the north of the North Island is the occasional tropical cyclone which moves down onto the country. These tend to occur with more frequency in late summer and early autumn.

New Zealand climate presently classifies as subtropical in Northland, and some pockets in the Bay of Plenty and Poverty Bay, ranging to cool temperate in Southland. Parts of Central Otago experience an almost continental type climate, with annual rainfall around 300 mm and the highest recorded temperature range in New Zealand. Canterbury, in the east of the South Island is almost semi-continental as a result of the lee effect of the Alps. The climate of Canterbury is discussed in more detail in section 7.2.

3.3 Climate and life in New Zealand: Prehistory

The New Zealand land mass originated as a part of the great southern continent known as Gondwanaland. It has been in isolation for some 100 million years. An excellent review of New Zealand's past geography is given in Stevens (1985), with a brief review of New Zealand bio-geography in the New Zealand Official Yearbook 1987-1988.

This long period of isolation led to the evolution of a unique flora and fauna, noted for their high percentages of endemic species. Geological research has shown that the New Zealand land mass has undergone many changes since its isolation from Gondwanaland. This has been influenced by the location of the land mass over the convergence of the Indian-Australian and Pacific plates. Concurrent with these large scale changes in land form have been periods of glaciation and warmer interglacials. Fossil records show periods of tropical climate with evidence of the presence of coconut palms in prehistory. There is also evidence that the Kauri tree, now confined to the north of the North Island was once distributed as far south as Canterbury. The present flora, including the Kauri, give evidence of past tropical connections, with many of these plant groups being represented in New Zealand by a single species.

According to systems of biogeographical classification the New Zealand flora and fauna is related to a number of different regional elements. These range from the tropical element, as represented by the Kauri, nikau palm and tree ferns to subantarctic and circumpolar elements, as represented by the beech forests which predominate in the south and mountainous zones of the South Island.

The most recent biogeographical element to be introduced to New Zealand is that relating to the arrival of the Maori people and more recently the European. It is estimated that prior to the arrival of the Maori people, thought to be some 800 years ago, 80% of New Zealand was forested. This was reduced to some 53%, mostly as a result of burning of coastal areas by the Maori. The introduction of the Polynesian rat posed the first threat to the unique bird life. Introduced plant material was mostly that used for food production as discussed in section 3.4. The Europeans wrought even greater changes, reducing the forest to 27% of the land area and introducing a wide diversity of exotic plants and animals, section 3.5.

3.4 Maori horticulture

Proxy climatic evidence, from the glacial record, suggests that New Zealand was in a period of warmer climate, referred to as a climatic optimum, from approximately AD 855 to AD 1620. This covers the period when it is thought that the first of the Maoris arrived in what they call Aotearoa (land of the long white cloud).

The Maori people were essentially hunter-gatherers, but they practised some horticulture. The original immigrants brought with them plants from the tropics, possibly not all surviving the voyage or the more temperate latitudes of New Zealand. Crops that are known to have been grown are the kumara, taro, gourd, yam and paper mulberry. The kumara was the most successful of all and was very much a staple of the Maori, and remains important today. If, as suggested, the Maori arrived in the period of climatic optimum they would have experienced relatively little difficulty in establishing their crops, particularly in the north of the North Island. This warmer period, it appears, also allowed for cultivation in what are now climatically marginal areas for crops such as the kumara. There is archaeological evidence of early gardens at Palliser Bay at the southern extreme of the North Island (Davidson, 1984). It is also thought that horticulture was practised in the warmer coastal areas of the east and north of the South Island. Following this warmer period was the New Zealand version of the Little Ice Age, which is quite probably what led to a period of retrenchment (Davidson, 1984).

When the European first appeared en masse after the voyages of Captain Cook the Maori were concentrated in the northern half of the North Island. Kumara growing, obviously geographically more restricted by this time, had apparently been adapted to the cooler conditions that prevailed, with the practice of using storage pits to keep the tubers through the winters. The marginal nature of their horticulture and the impact of the European is well summed up by McLauclan (1981)

> The weather was the main enemy of the pre-European farmer, an enemy he fought with the rigorous canon of tapu, with an elaborate litany of hymn and incantation. The small population and subsistence farming meant he was never seriously short of suitable land. But when the Pakeha came with iron implements, potato, turnip, wheat and pastoral animals, and provided markets, the weather became at once an ally and the infertility and steepness of so much of the land became a liability.

The Maori were quick to adapt both to the Northern hemisphere crops and European methods. By 1830 they were growing potatoes and grain crops extensively in the northern half of the North Island. The wet, humid summers of this region created difficulties, particular in relation to disease, and harvesting of the grain crops. However they grew sufficient grain for mills to be built and were supplying the early Pakeha settlers with food as well as exporting potatoes and grain to Australia. They were also growing fruit trees at this time and quickly acquired propagation and grafting skills. Maize was rapidly adopted as a staple food and was grown extensively in the Poverty Bay area by the 1830s.

By the late 1850s the growing European population in the northern areas was creating an increasing pressure for land. The result was the infamous land wars that signalled the decline of the Maori and the growing dominance of the land hungry Europeans.

3.5 European cropping and horticulture

3.5.1 Grain crops

The land wars in the north coincided with the period of growing European settlement in the South Island. Large tracts of tussock land, in the foothills and high country were taken up for extensive sheep farming. The potential of the Canterbury Plains for grain growing was quickly realised. This probably filled the void that resulted from the conflict in the north. There are several publications that chronicle the history of grain growing in New Zealand. These include a history of wheat growing in New Zealand by Hilgendorf (1939), a historical review of the Barley industry by Malcolm (1983) and brief reviews for each of the principal grain crops by Claridge (1972).

The climate of Canterbury, with its lower humidity and, on average, cooler weather, was found to be ideally suited to the growing of grain. The relatively dry summers, are in a lot of years favourable to the ripening and harvesting of crops, although years of prolonged moisture deficit conditions can lead to yield reductions. The one grain crop found not suited to the south was the warm temperate maize crop. This was found to be more suited to the warmer conditions of the northern half of the North Island. It was mentioned earlier that the Maoris in the East Cape area quickly adopted maize as a major crop. This district remains one of the principal growing areas of this crop.

3.5.2 Fruit crops

It is probable that fruit growing was widely practised by the early settlers, who would have had small farm orchards to supply their immediate needs, and certainly was by the Maori. Although fruit growing wasn't formalised into an industry until 1916, with the establishment of the N.Z. Fruit Growers Federation, it was operating on an informal basis prior to this time.

Partly through a process of trial and error, and partly through the endeavours of a few entrepreneurial characters, climatic zones were identified that were suited to the growing of particular crops. Often it was the knowledge and persistence of a relatively small group of enthusiasts. This is partly true of the citrus industry, and is certainly true of the kiwifruit industry, which has displaced apples as the dominant fruit crop in terms of percentage area grown. Proximity to the market would also have influenced development of the fruit industry, and this is particularly true of Auckland.

A summary of growing districts, the principal crops in each in terms of percentage of national area and general climate classification, after Robertson (1958), is given in Table 3.5.1. Fig. 3.5.1 shows a map of New Zealand showing the 1974 statistical divisions, representative of the principal growing districts given in Table 3.5.1. Annual rainfall and mean temperature data is also given. Spatial variations in rainfall and temperature do have an obvious effect on patterns of distribution.

Table 3.5.1

General distribution of crops in relation to climate in New Zealand

Growing district	Principal crops	General climate	Mean temp.	Mean rainfall
Northland	Citrus, sub-tropicals	Warm, humid summers, mild winters	15.1	1682
Auckland	Peaches, plums, grapes, pipfruit	Warm, humid summers, mild winters	15.3	1185
South Auckland	Maize, berry-fruit	Warm, humid summers, mild winters	13.3	1201
Bay of Plenty	Maize, citrus, kiwifruit, sub-tropicals	Very warm summers, mild winters	14.0	1349
East Cape	Maize, citrus, grapes	Very warm summers, moderate winters	13.8	1010
Hawkes Bay	Pipfruit, stonefruit, grapes	Very warm summers, moderate winters	14.1	824
Wellington	Wheat, barley, peas	Warm summers, mild winters	12.9	995
Nelson	Pipfruit, berryfruit	Very warm summers, mild winters	12.5	955
Marlborough	Peas, cherries, pipfruit, grapes	Very warm summers, moderate winters	12.7	642
Canterbury & North Otago	Wheat, oats, barley, peas, berryfruit, pip-fruit	Warm summers, cool winters	11.6	666
Central Otago	Stonefruit, pipfruit	Very warm, dry summers, cold winters	10.6	343
Southland	Wheat, oats, blackcurrants	Warm summers, cool winters	9.7	1037

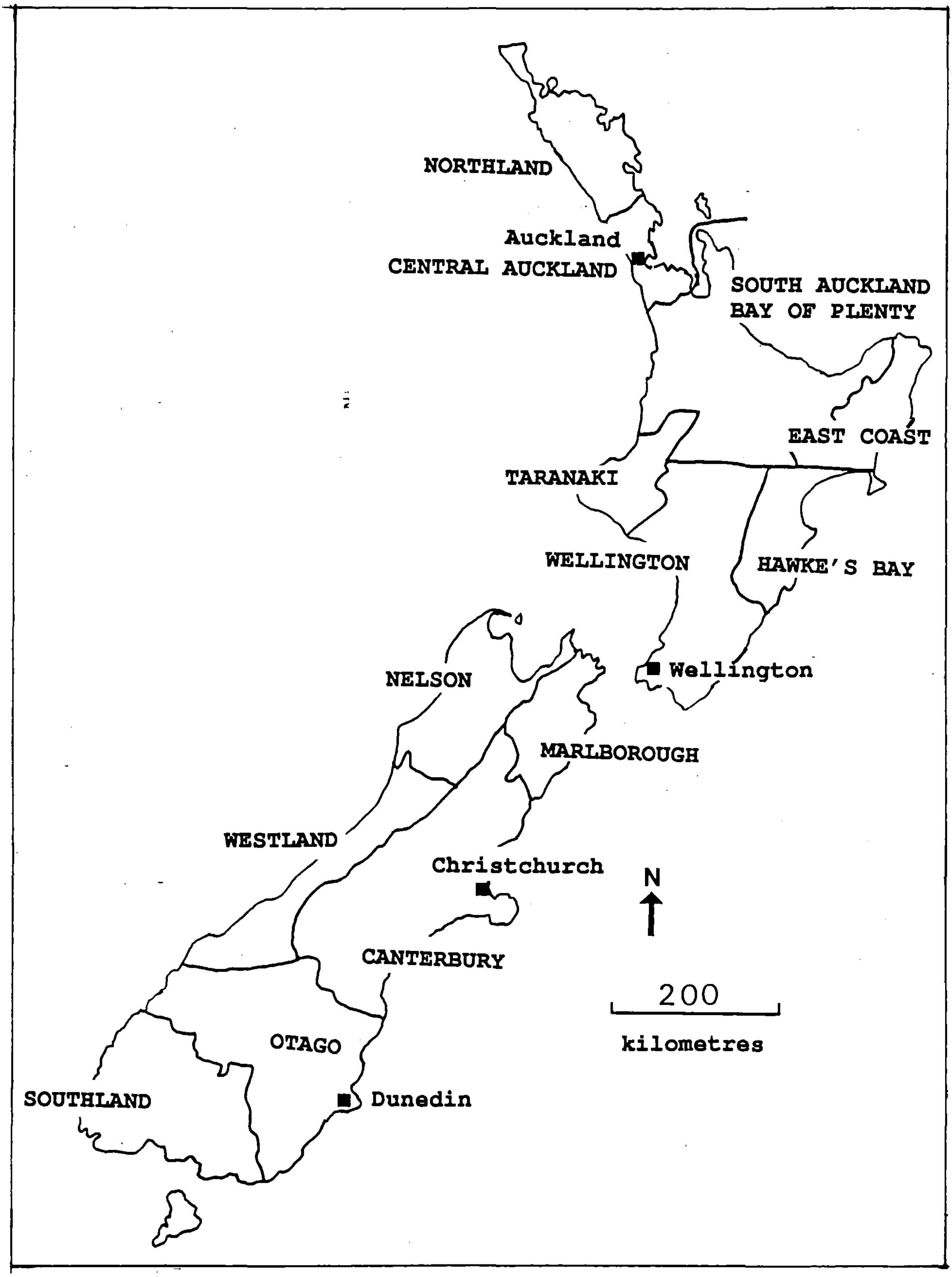


Fig. 3.5.1 New Zealand statistical divisions (1974)

Presence of local microclimates are particularly important for some fruit crops and don't reflect in mean statistics from often exposed climate stations. Maize and subtropical fruit production predominates in the north of the North Island. Some pip and stonefruit are grown to satisfy the Auckland market, but generally the less humid districts of Hawkes Bay, Nelson, Marlborough, Canterbury and Central Otago are more suited to these crops. The Wellington district, in particular the Rangitikei and Manawatu, is the predominant temperate grain growing area in the North Island, and has become more significant on a national scale. However the temperate grains predominate in Canterbury and to lesser degrees in Otago and Southland, where the cooler temperate conditions are more suited to the these crops.

3.6 Crop-climate interactions

Although New Zealand was originally largely forested, its climate proved well suited to pastoral farming, cropping and horticulture, as highlighted in section 3.5. Particularly dominant in the country's export industry over the last hundred years have been the products based on the growing of grass. This was achieved by clearing large tracts of relatively flat to hilly land of their natural forest cover. In areas such as the Canterbury Plains the forest was long gone when the Europeans arrived, but substantial modification of the environment still occurred. What was not appreciated over this pioneering period was the intricate balance between the land and the atmosphere.

Soil erosion both by wind and water are major environmental problems in New Zealand. Under periods of extreme climatic conditions the vulnerability of the deforested and modified land are made very apparent. There are numerous historical examples of this. However it serves to relate to very recent history, and the present, to heighten the awareness that these aren't just events of the distant past.

In March 1988 a tropical cyclone, named Bola, was diverted to the west of the North Island by an eastward moving anticyclone. The warm, moist, easterly airstream associated with this was uplifted by the higher terrain of the North Island axial ranges. The result in the East Cape and Hawkes Bay region was 24 hour rainfalls of up to 100 mm or more (McGavin, 1988). This occurred on three consecutive days. The largely deforested hills of this region, particularly around the East Cape, could not absorb rainfall of such intensity. The high levels of surface runoff led to widespread flooding in the coastal plains. Around Gisborne and neighbouring areas this had a devastating impact on cropping and horticultural land. Losses were estimated in hundreds of millions of dollars.

In the same year the east coast of the South Island was experiencing its driest year on record. This record dry period persisted into 1989. A more detailed review of drought in Canterbury is given in section 7.7. The impact of this drought was far more insidious than that of Cyclone Bola. After a dry ten month spell, beginning in November 1987, Canterbury farmers were hoping for sufficient rainfall in spring to bring soil moisture out of deficit. Instead a persistent strong westerly flow onto the South Island led to a well above average frequency of dry, warm Nor'westers in Canterbury. With relatively sparse shelter in many areas and many soils cultivated and sown in hope of spring rainfall the situation was ripe for wind erosion. This occurred with particular severity on several days in October, 1988. Many cropping farmers were left with the prospect of recultivating, to a finer tilth to extract every last bit of moisture, and re-sowing in the hope of rain. The nor'westers abated into the summer months, but the drought persisted.

Both Cyclone Bola and the Canterbury drought have had direct measurable effects on yield of crops in affected districts. Although events of the intensity and severity of Cyclone Bola are relatively rare in New Zealand, agricultural drought is a common occurrence in many parts of New Zealand (Finkelstein, 1971), although not often with the severity of the present one. However it occurs with sufficient frequency to be an important determinant of year to year variability in yield in a number of districts. The timing of agricultural drought in relation to the developmental stage of a crop is of particular importance, as this can result in yield depressions, as will become apparent later.

Periods of above average rainfall can also impact on yield and again timing is important. Warm temperatures, if associated with drought conditions can place greater physiological stress on developing plants. Warm, humid weather can lead to problems with disease. As was made apparent in section 3.5, New Zealand climate is well suited to the production of many temperate and some subtropical crops.

However it is also important to realise, as many farmers and horticulturists do, that yield and climate both vary from year to year. Both rainfall and temperature can have measurable effects on yield and there is sufficient evidence to suggest that these effects may be related empirically.

With concern growing over the potential effects of the CO_2 related warming on New Zealand, it is appropriate and timely to explore both spatial and temporal variations in yield and climate and their interactions. Spatial and temporal analysis of New Zealand climate was carried out in a significant study by Salinger (1981). Some of the methods used are employed here, as described in Chapter 4. An earlier study by Maunder (1965) examined empirical relations between yield and climate in New Zealand for a range of crops and primary products, and an assessment was made of the economic significance of these relationships. Computer technology, length of the data record and availability of data imposed some limitations on this work. More powerful computers and developments in computer software have enhanced the potential for exploring empirical relationships. Length of record remains a problem with some crops as does availability of data.

Examination of empirical crop-climate relationships using national and district yield data forms the basis of this part of the thesis. The importance of trees for slope stabilisation, watershed management and shelter was touched on briefly. This is elaborated on, particularly in the context of shelter, in the next part of the thesis.

CHAPTER 4

Data and Methods for crop-climate analyses

4.1 Introduction

The climate of New Zealand is well documented through a network of climate stations. A relatively small number have been in operation since the middle of the nineteenth century. The network has since expanded to give an extensive coverage of the country. This historical record formed the basis of Salinger's (1981) research. He highlighted the importance of rigorous checking of station records, to eliminate as much as possible potential sources of error and hopefully improve the signal of the data. The data used in this current analysis, of crop-climate interactions were similarly carefully checked, following the procedures used by Salinger (1981).

Yield data were gathered from various published sources at the national, district and in the case of wheat, county level. Unlike the climatic record there is not the same possibility of making adjustments to the data. Some simple adjustment for trend is possible, but it is generally impossible to both identify and quantify all contributing factors to trend in yield.

Methods of assessing spatial patterns of variation in yield and climate are outlined. These are the multivariate analysis techniques of principal component and cluster analysis. Principal component analysis was used as a preliminary to multiple regression analysis. Not all of the yield data were conducive to a spatial analysis, particularly when it was only available on a national scale. Some spatial analyses gave poor results. To cover both of these eventualities alternative approaches to multiple regression analysis were used. In all cases maximum use was made of the data to both detect and verify important interactions between yield and climate. This involved trying different methods and comparing results and, where possible, retaining data for verification.

4.2 Climate data

4.2.1 Selection of climate stations

Seasonal and monthly rainfall and mean temperature data were used in the analysis. The selection of climate stations from which data was used was influenced by the spatial and temporal spread of available yield data and the quality of the climatic record. Selected stations and related districts or counties are presented in Appendix A. For national and district grain data, analysis was for the years 1933-1983, for wheat in Canterbury 1945-1981, for pipfruit 1941-1981 and stonefruit 1963-1981. Fewer stations were operational in the earlier period and in some cases the record was unreliable. This restricted the selection of stations, particularly for the principal component analysis. A more detailed spatial analysis of Canterbury climate, in Chapter 7, used all available data for three selected periods, so that consistency of patterns over time and space could be examined in more detail.

Very useful selected site summaries are given in Salinger (1981), and these were used as a baseline for the selection or rejection of sites. Adjustments to the record were made where possible. It was the quality and length of the climate record that influenced the period of analysis of the grain crops. Yield data for these crops was available earlier than 1933, but there weren't stations operational in all growing districts prior to that time.

Few of the selected climate stations were directly representative of field conditions, with most being located in towns, cities or forests. Providing the climatic record is as free from error as possible, this isn't too much of a problem. Generally multiple regression yield analyses deal with yield data averaged over fairly large areas. In New Zealand the smallest unit is a county. Significant relationships are generally related to regional geography and the interaction with synoptic scale weather phenomena. The important consideration therefore is that the climate data be representative of a climatic response area, as defined and identified for New Zealand by Salinger (1981). This was the criterion for station selection in the analyses that involved district yield data. It could not always be satisfied as some districts cover more than one rainfall or temperature response area, or may be transition zones. This was more the limiting factor than whether or not the climate data was fully representative of field conditions.

4.2.2 Site change adjustments and missing value estimation

The methods of Salinger (1981) were employed in making adjustments for site changes, and estimating missing values. It wasn't possible to directly employ his results as some analyses were to be carried out using seasonal climatic data. Comparisons between sites before and after site changes using seasonal values showed different responses in different seasons. Data was adjusted accordingly. Methods are briefly summarised, with more detail and examples in Appendix A.

For the preliminary analysis of Canterbury wheat site comparisons were made over the 1945-1981 period. To gain familiarity with the methods rigorous checking of the data was done. This initially involved making graphical comparisons to detect differences between sites. Neighbour stations were selected for comparison using the rainfall and temperature response areas delineated by Salinger (1981). On the basis of this graphical comparison, some stations were removed from further consideration. This was supported by Salinger's (1981) site descriptions. For analyses that involved New Zealand wide data these site descriptions sufficed as a means of selecting sites suitable for analysis and determining which ones required adjustment. Climate data for these New Zealand analyses were adjusted back to 1928, where the record went back that far.

Site change adjustments

For stations retained for the analysis monthly rainfall and temperature data were combined into seasonal data sets defined as March-May, autumn; June-August, winter; September-November, spring; December-February, summer. The mean difference between the station in question and nearest neighbour stations was taken and comparisons made between them before and after site changes using a t-test as a test of significance. Where the difference was significant, adjustment was made to the data before or after the site change. The data were adjusted to the most consistently exposed site in all cases. Rainfall ratios were taken for comparison and adjustment of the Canterbury climate data. For the New Zealand analyses rainfall data from the published homogenous rainfall series was used (Thompson, 1984). Data from districts not represented in this series were used without adjustment. Generally the record was clean for these sites, or the data used was for more recent years and was more reliable.

Adjustments were made to the relevant months based on the seasonal analysis. Once these adjustments were made it was possible to estimate missing values.

Missing value estimation

The same criteria as Salinger (1981) were used for missing value estimation. He discarded records with more than twelve months of missing data in thirty years or twenty months for longer time series. None of the records used in this work were discarded on the basis of these criteria. The mean temperature anomaly, or rainfall ratio, for the month in question was calculated from nearest neighbour stations. Adjustment was then made to the monthly mean of the station in question, either by addition of the average temperature anomaly or multiplication by the average rainfall ratio.

4.3 Yield data

Sources of yield data were the N.Z. Wheat Review, N.Z. Agricultural Statistics publications, M.A.F. Horticultural Statistics bulletins, N.Z. Apple and Pear Marketing Board Annual Reports. The earliest formal collection of yield data began in 1869 for the principal grain crops of wheat, oats and barley. Potato yields were also collected at this time. Data were collected on the basis of administrative districts. In 1915 the N.Z. Statistics Department began detailed recording of fruit crop statistics, collecting tree number and yield data. This was continued up until 1930. Over this period data were collected by visiting properties. After the 1930-31 season a postal data collection system was introduced, which resulted in a reduction in the quantity and detail of statistics collected including a reduction of collection of data for fruit crops. Data for the main grain crops has continued to be collected through to the present on a district basis. However there are gaps in the record, when for various reasons data wasn't published on a district basis in Statistics Department publications. Yield per area data for the grain crops were not published at the county level on a consistent basis until 1971. Latterly these publications have only incorporated data from the principal growing areas. The N.Z Wheat Review proved the most reliable source of county wheat yields back to 1945, particularly for the main growing districts in the South Island. Further wheat yield data has been sourced in one of the several appendices of Tauheed's (1948) thesis, but was not used in the analyses presented here.

Apple and pear yield and tree number data were sourced from N.Z. Apple and Pear Board Annual reports, from 1941-1965. This was originally collected by the then named Department of Agriculture. More recently M.A.F. collected horticultural statistics for the period 1963-1981. This was aggregated to give national yields, areas and tree number for each crop. The district data were not published. Some is on file in raw form with John Wilton, M.A.F.

In general the yield data has been collected in a relatively uncoordinated manner. One of the purposes of this work has been to identify as many sources of yield data as possible. It is important that this is done so that maximum value can be obtained from the data, particularly in the important field of crop- climate relationships.

It is uncertain what further detail is on file with the Statistics Department. It would certainly be invaluable if the county record could be extended as far back as possible for as many crops as possible. This is most possible with the grain crops. These problems are not new, being a source of comment in several theses, most recently that of Maunder (1965). Perhaps with the greater imperatives associated with concern over the CO_2 warming effective moves will be taken to rectify the situation.

Despite problems in obtaining data, in the end sufficient were obtained to give some excellent results. A spatial analysis of wheat, oats and barley was made possible with the district data. A more detailed analysis of Canterbury wheat yield was possible with county data, which is presented in Chapter 7. Weighted analyses of national yields was carried out for both grain and fruit crops.

The nature of the yield data used in the analyses is shown in Table 4.3.1. Earlier yields were given in Bushels per acre. Kilogram equivalents for each crop are given as well as conversion factors for bushels to kilograms.

Table 4.3.1

Yield data used in empirical-statistical crop-climate models

Crop	Administrative level	Period	Unit	Weight of bushel (kg)
Wheat	National	1933-1983	T/ha	27
	District	1933-1983	T/ha	
	County	1945-1983	T/ha	
Oats & barley	National district	1933-1983	T/ha	18 & 23
Stonefruit	National	1963-1981	T/ha	19
Pipfruit	National	1941-1965	Bu/tree	Apples, 18
		1963-1981	T/tree & T/ha	Pears, 17
	District	1941-1965	Bu/tree	

Trend removal

In all cases a time series of yield per ha (or yield per tree in the case of apples and pears) was plotted. With all grain crops there was an obvious trend. Up until the 1940s there weren't too many major technological changes with these crops, in terms of relative impact on yield. Mechanisation of farm operations was probably the main technological advance in these earlier years. Since then major advances in plant breeding, further advances in mechanisation, use of pesticides and improved farm management have all contributed to significant advances in yield per hectare. The level to which each of these has contributed to higher yields is very difficult to quantify. Examples of trend removal for each of the crops examined are given in the relevant sections in Chapters 5, 6 and 7.

The 1963-1981 time series of yield for fruit crops didn't always show clear trends, and in fact apples and pears were the only fruit crops where trend removal was carried out. For the rest, raw yield data were used in the analysis.

A range of methods can be used to remove trend, from moving averages to simple linear regression lines. In most cases quadratic lines consistently gave the best fits to the data, and so these were generally used. The one exception was the pear data where a linear regression was an adequate fit. Such methods are by necessity simplifications of reality as it would be impossible to quantify and identify all contributory factors to trend. Often it can be relatively crude, but generally it separates out significant positive and negative anomalies, which are the principal source of interest. Detail can be lost with less significant anomalies, particularly over longer time series. Residuals about fitted lines were retained for further analyses.

4.4 Principal Components Analysis (P.C.A.)

An excellent introduction to principal components analysis is given in Manly (1986) and a more detailed review in Daultry (1976).

The basic aim of P.C.A. is to recombine a set of correlated variables into a set of uncorrelated indices. The original variables are transformed in such a way as to describe the same amount of variability with the same number of variables. The transformation process involves identification of different axes of variability, that are orthogonally separated and therefore uncorrelated. The first axis is selected to account for as much of the total variance as possible. The second, while uncorrelated with the first, is chosen to account for as high a proportion of the remaining variance as possible. This procedure of axis selection continues until there are the same number of axes, or uncorrelated indices, as original variables and the total variance is the same.

Where there is a high degree of correlation between the original variables it is not uncommon that most of the variance is accounted for by the first few indices, or Z variables as Manly (1986) calls them. The obvious advantage is that these few indices can be used to describe most of the underlying patterns of variation, which may not be immediately obvious from the original data set. Higher order indices can be discarded as they progressively account for less and less of the total variance. This is a very useful property for further analysis, particularly where an original set of ten to twenty variables can be recombined into a much more manageable set of three to five indices, that may collectively account for 90% or more of the variance in the original data set.

It is a common practice to code the variables in the original set to zero means and unit variance, i.e. standardising, prior to P.C.A. The purpose of this is to avoid any one variable having a biasing effect on the resultant principal components. When this is done the correlation matrix is effectively used in the analysis, from which eigenvalues and eigenvectors are calculated. The eigenvalues are described as being the variances of the principal components (P.C.s) of the covariance matrix (Manly, 1986), which becomes the correlation matrix after standardising. The vector of constants associated with each eigenvalue is known as an eigenvector.

The eigenvalues therefore describe the amount of variance accounted for by each of the indices, or principal components. The elements of the eigenvector are the constants $a_{i1}, a_{i2}, \ldots\ldots \ldots a_{ip}$, and are effectively weighting factors that are used to recombine the original data to derive the principal components. Thus each principal component can be defined as :-

$$Z_i = a_{i1}X_1 + a_{i2}X_2 + \ldots\ldots + a_{ip}X_p$$

where a_{i1} to a_{ip} are the weighting factors and X_1 to X_p are the original variables.

Application

P.C.A. can be a useful tool for exploring underlying patterns in a data set. For example with climate data it may be used to describe spatial variations in response characteristics. If the first few eigenvalues account for most of the variance then study of the eigenvectors associated with these may reveal underlying patterns of variation. This can be taken further by deriving the principal components and interrelating these with other variables or indices. This was done by Salinger (1981) in his analysis of New Zealand climate, in which he derived temperature and rainfall P.C.s and correlated these with a selection of circulation indices. A more local study of rainfall patterns and associated synoptic characteristics was carried out by Trewinnard and Tomlinson (1986) for mid-Canterbury. A further use for the P.C.s is in multiple regression analysis. The obvious advantage is the reduction of variables used as input to the regression. This can overcome the problem of too many variables and uncertainty about which ones to exclude. An example of its application is in the analysis of wheat yields in relation to climate in Western Australia by Wigley and Tu Qipu (1983). They successfully applied P.C.A. multiple regression analysis to describe spatial variability in yield in relation to spatial variability in climate in this region.

In the work reported here P.C.A. was used both in a descriptive sense, to explore spatial variations in climate (Chapter 7) and define response areas in a region, and as a preliminary to multiple regression analysis (Chapters 5 and 7) between yield for a selection of crops and climate. An example output of eigenvectors, for barley and associated climate data, is given in Appendix B.

For all analyses P.C.A. was carried out using the PRINCOM procedure on the SAS package, on the VAX computer network at Lincoln.

4.5 Cluster analysis

Although generally only used in this thesis as an exploratory tool, and as a check on P.C.A. results, a brief description of cluster analysis is given here. As with P.C.A, an excellent introduction to cluster analysis is given by Manly (1986). Cluster analysis basically involves numerical methods for classifying data. Objects are placed in classes so that similar groups are placed in the same class. As with P.C.A. it can expose patterns in the data not immediately apparent to the eye. The clustering may not always be distinct, and it can be confusing when several of the numerous clustering techniques are used and give differing results. So some preconceptions of how objects may cluster can help, although as Manly (1986) stated, the clustering may not conform to preconceptions.

There are many different algorithms used, the main ones falling into two general groups. These are :-

1. **Hierarchic techniques**

   These produce a dendrogram or hierarchical 'tree'. There are both agglomerative and divisive methods, although the former are the more common. The agglomerative method begins with all objects being alone. These are progressively grouped together, by various numerical methods, until eventually a single grouping, or cluster is achieved. The divisive method starts with all objects being together. These are progressively divided until all groups contain a single object.

2. **Partitioning techniques**

   These generally involve an iterative process whereby objects are moved into and out of groups throughout the analysis. The process continues until the groups stabilise, the number of groupings being predetermined. Because the optimum number of groups is not known the process is repeated to obtain the best number of groupings.

   The process begins with centres being established for groups to cluster around. Through the iterative process new centres are calculated and objects may be moved to new groupings.

Manly (1986) made it clear that there is a degree of subjectivity involved in cluster analysis, with no universally accepted best method.

A wide range of options are available on the SAS statistics package. Both agglomerative and divisive hierarchical clustering methods were used, as well as a disjoint method using the VARCLUS procedure on SAS.

Prior to cluster analysis variables were standardised to means of zero and variances of one, as recommended by Manly (1986), although this can have the negative effect of minimising group differences. Cluster analysis can also be used as a tool for reducing the number of variables prior to P.C.A., as done by Wigley and Tu Qipu (1983) in their spatial analysis of wheat. The reverse, i.e. P.C.A. prior to clustering is also used in some cases (Manly, 1986), where the first few P.C.s account for most of the variance in the data. Neither was considered necessary as a result of exploratory analyses.

4.6 Multiple regression analysis

Multiple regression analysis is often used as an exploratory tool, sometimes unkindly referred to as a "fishing expedition" (Wesolowsky, 1976), although it is further pointed out that fishing expeditions can often be successful. This is particularly true if there is some local knowledge as to where the best fishing spots might be. This approach has become increasingly popular over the last few decades as a tool for exploring crop-climate interactions. Generally this relies on historical yield and climate data as described in sections 4.2 and 4.3.

The early approaches involved gathering yield data from a particular area, performing a trend removal if necessary, and relating yield to climate data from a single representative station. The most commonly used climatic variables are temperature and rainfall because of their generally superior record. This was the general approach of Maunder (1965) in his analysis of food production in relation to climate over 27 counties in New Zealand. As well as rainfall and temperature data, he included sunshine hours in his analysis. In other early studies spatially averaged yield and climate data over large areas were used in a multiple regression analysis (Thompson, 1969a, 1969b, 1970). In such cases it is normal procedure to weight the climate data according to the percentage area of the crop in each growing district or county, as demonstrated by McQuigg (1982).

There has been a proliferation in multiple regression analyses of crop-climate interactions over the last two decades. This has been made particularly easy by the development of powerful, user friendly software packages such as SAS. Some of the work has been relatively shoddy, other studies giving valuable insights, particular when used in conjunction with other sources of information on possible crop-climate interactions. Some researchers remain sceptical about the value of such analyses, such as Monteith (1981). Others, such as Katz (1977) have sought more critical use of multiple regression analysis. Some more recent applications have taken heed of these words of caution, and have given more credibility to empirical studies of crop-climate interactions.

One relatively novel approach has been the application of P.C.A. as a means of reducing variables prior to multiple regression analysis. A critical analysis of wheat yield in Western Australia was made using such an approach (Wigley and Tu Qipu, 1983). This enabled them to evaluate spatial patterns of yield and climate and their interactions. The results of the P.C.A. facilitated the latter by accounting for a large degree of the spatial variation in yield and climate in the first few P.C.s. This allowed substantial reduction in the numbers of both predictands and predictors used in the analysis.

It is appropriate to look at some of the limitations of multiple regression analysis in more detail.

4.6.1 The coefficient of determination

The coefficient of determination (R^2) is defined as the ratio of the sum of squares due to regression to the sum of squares about the mean of Y. It is a 'black box' statistic according to Katz (1977), being a measure of the explanatory power of the regression (Wesolowsky, 1976). This latter author demonstrated through examples that both the number of variables and observations can influence the value of R^2 and that a high or low value does not directly imply a good or bad result. The problem was discussed in detail by Wigley and Tu Qipu (1983), whose conclusion was that there should be some form of independent testing of the result. This is discussed further, later in this discussion.

4.6.2 Nonlinearity

As pointed out by Katz (1977) relationships between yield and any given climate variable are not necessarily linear, as plant physiological research shows. This is not easily resolved, as simply squaring to give a quadratic function may not necessarily reflect reality either. Some form of transformation of the data may be justified where a spatial analysis of yield is carried out over a large region where there is wide spatial variation in climate, particularly with rainfall. This was done by Wigley and Tu Qipu (1983). It is also important to remember that climate data is generally given as monthly means or totals, and therefore short term extremes, particularly with temperature, that may impact on yield are averaged out. This latter situation can be resolved by complementary studies such as that carried out by Mearns et al (1984), which explored the possible impact of short term temperature extremes on yield of corn in the U.S.A.

4.6.3 Multicollinearity

Multicollinearity is cited by Wesolowsky (1976) as being one of the chief causes of misinterpretation and misuse of regression analysis. Correlation between independent variables can lead to three main problems (Wesolowsky, 1976) :-

1. The standard errors of the regression coefficients are increased.

2. In extreme cases computational difficulties can arise.

3. A priori selection of variables can lead to omission of variables that may be correlated with those retained. This can lead to biasing of estimators for those regression parameters retained.

While a correlation matrix can highlight significant pairwise relationships, there still exists the problem of correlation between a variable and a linear combination of other independent variables.

The advice given by both Katz (1977) and Wesolowsky (1976) is to make as much use as possible of a priori analysis. This should be based as much as possible on a theoretical knowledge of probable interactions, including whether the response to any particular variable is likely to be positive or negative. Often there needs to be some trade off between a priori selection and exploratory analysis as relationships can be revealed that are not supported by the literature, but do have some apparent connection with reality. The situation can be compounded by the fact that crops can respond differently under different climatic conditions and that principal limiting factors can change both spatially and temporally.

In the present work no climate data were excluded from exploratory multiple regression analysis. Correlation analysis showed some significant relationships between predictors, but these did not predominate. The literature base generally provided clues for reducing the number of variables for further analyses, although often variables were retained that had no support from the literature. It cannot be discounted that some potentially significant predictors were excluded, or their effects masked. However the methods used are generally supported by the strength of the results. The weaknesses are also apparent.

4.6.4 Model verification

One means of assessing the relative importance of the result is to carry out a test on independent data as suggested by Wesolowsky (1976) and done by Wigley and Tu Qipu (1983). In the latter case this involved using part of the data for developing a calibration model and then carrying out a verification procedure on the remainder of the data. This simply involved using the calibration model to estimate yield over the verification period and to correlate these values with actual yield for the same period. The length of the time series for which yield data is available is the main limiting factor to carrying out such an analysis.

Verification was not always possible in this study, particularly for the fruit crop data for which there was generally only a 19 year record available. Other time series were conducive to verification. In all cases every two years out of three were used for calibration and every third year retained for verification.

4.6.5 Summary and SAS procedures

This brief review has highlighted some of the main problems associated with multiple regression analysis. It is apparent that such an approach should be treated with a degree of caution. Used in an appropriate context it can give valuable insights into crop-climate relationships, and can offer a basis for the more detailed studies as advocated by Monteith (1981). It is essentially an empirical approach that can highlight dominant relationships, that can be connected to biological reality. But as a 'black box' approach it can also lead to spurious results. Discussion of results in this thesis is based on the assumption that there is some connection to reality, even where not supported by the literature. In some cases no logical explanation is possible and the predictors are assigned 'black box' statistic status. There is therefore a degree of speculation in some of the discussion of results. If at least some of these are confirmed as important by further study then the effort is not wasted.

For all analyses stepwise multiple regression was used. This is a very useful tool for exploratory analysis, particularly where there are a large number of independent variables. There are a range of selection methods, based on different selection criteria, for stepwise model development. The three methods used were forward selection, backward elimination and maximum R^2 improvement. Forward selection begins with no variables in the model. A minimum F value is set for entry. At each stage the method selects the variable with the largest F value. The process continues until no more variables satisfy the entry requirement. Backward elimination begins with all variables in the model, and in a stepwise manner eliminates those that are least significant, until all remaining variables satisfy the required level of significance. The third method starts with no variables. It selects that with the highest R^2. The next variable that gives the most improvement in R^2 is included. Variables can be replaced at each step until the best improvement in R^2 for that number of variables is obtained. Experience showed that the R^2 method generally gave the same results as forward selection, and that the models with the highest R^2 generally had predictors with the highest F values. An F=4 cut-off was generally used, although in some cases F=2 models are included in the results for the purpose of discussion.

All analyses were carried out using PROC STEPWISE from the SAS package on the Lincoln VAX.

4.7 Application of methods

4.7.1 Grain crops

The east coast region of the South Island is New Zealand's principal grain growing region. Any analysis of national yields must take this into account. National, and in some cases district, yield data for wheat, oats and barley is available back to the 19th century. The unreliability of the climatic record from some stations, or the lack of it from some growing districts restricted the period of analysis to the 1933-1983 period. Quadratic trend lines were fitted to all yield time series and analysis carried out on the residuals.

P.C.A. multiple regression

A spatial analysis of district yields and climate was carried out for the three crops mentioned using the P.C.A. multiple regression procedure. Both climate and yield data were standardised for this analysis. The growing seasons selected for the P.C.A. analysis were autumn (March-May), winter (June-August), spring (September-November) and summer (December-January). If the record for a particular district had too many missing values it was excluded from the analysis. In all cases these were districts that contributed little to national yield. In all analyses a MAXR stepwise multiple regression procedure was used as this generally proved superior to the backward elimination procedure. The purpose was to explore spatial patterns of yield and climate over the country and to see whether they could be interrelated in terms of an empirical model of national yield.

For the P.C.A. models adjusted climate data for as many stations as possible were used in the analysis. This was important for growing districts that are relatively heterogeneous in their rainfall and temperature responses. A total of 15 rainfall and 13 temperature stations were used in this analysis.

Verification was carried out for each of the yield principal components on which multiple regression was carried out. In all cases this involved the first three P.C.s. Verification of each of these was carried out by correlating predicted versus actual yield P.C.s over both the calibration and verification periods. Verification on a district basis was done following the rationale of Wigley and Tu Qipu (1983). They assumed that the yield estimate for each district was the sum of the products of the loadings, from the P.C.A., for each district and the estimated P.C.'s. This is given by :-

$$\hat{x} \approx a_{i1}\hat{z}_1 + a_{i2}\hat{z}_2 + \ldots\ldots a_{ip}\hat{z}_p$$

where a_{ip} are the loadings and $\hat{z}_p$ are the P.C. estimates. This assumption was tested by estimating yield using the actual P.C.s as input, using the first three P.C.s. Correlations between estimated and actual yield for each district were highly significant in all cases. The procedure was then repeated using estimated P.C.s for both the calibration and verification periods, to give the verification result. The final step was the development of models from all years, where verification was significant.

Weighted and district multiple regression

As a check on the value of this approach further analysis was carried out relating national yields to climate data weighted according to the proportion of the crop threshed in each district. A single representative climate station was selected from rainfall and temperature response areas as delineated by Salinger (1981). Not all growing districts fell within the same climatic response area and so the station corresponding to that part of the district where most of the crop was grown was chosen.

For both analyses an almost unbroken period spanning 51 years allowed retaining of data for verification. Every two years out of three were chosen for calibration with every third year retained for verification. There were missing values for some years for the district data, but the national record was unbroken. District data were analysed separately for the principal growing districts as a further evaluation of spatial relationships with climate. As with the national models, data were retained for verification.

An initial run on the data was carried out using monthly climate and yield data for all years. From the results of this seasonal data sets were derived in an attempt to identify critical periods. Calibration and verification was then carried out using the monthly and seasonal climate data. Experience showed that the seasonal models verified best so that in some cases verification was only carried out with the latter. As with the P.C.A. analysis the final step was the development of seasonal models from all years.

The presentation of results in each case is preceded by a brief review of the general crop-climate relationships. Where possible a brief summary of possible physiological responses is included. This is followed by a brief review of each crop's relationship with climate under New Zealand conditions, including results of previous empirical analyses. The results are discussed within the context of this reviewed material.

4.7.2 Fruit crops

Stonefruit

There was generally less flexibility in the analysis of the fruit yields. For stonefruit there were only 19 years worth of observations, so it was not possible to retain data for verification. Data were readily available only on a national basis. For all of the stonefruit no trend in the yield per hectare data was apparent, so raw data were used in the analysis.

A representative climate station was selected for each of the main growing districts and a set of weighted monthly climate data derived for each crop. Weighting factors were based on the five yearly surveys carried out by M.A.F., with district area data averaged for the years 1968, 1973 and 1978.

Review of the literature suggested periods of climatic sensitivity, but initially data for all months were included. For each crop the climate data had to be lagged to give the growing year, based on normal harvest completion times. For apricots, plums, nectarines and peaches the growing year chosen was March to February. The bulk of these crops are usually harvested by this time. For cherries the growing year was the calendar year. While rainfall data was transformed in the P.C.A. of grain crops this was relaxed in the analysis of fruit crops as it was not considered to give significant improvement in the results.

Preliminary analysis showed high sensitivity to monthly climate data and low sensitivity to seasonally averaged data. Both forward selection and maximum R^2 improvement methods were used in exploratory analysis. In some cases backward elimination was also carried out on reduced data sets.

As with the grain crops the analysis was supported as much as possible by the literature. The generally poorer literature base, and shorter time series gave greater potential for inclusion of black box statistics. Some of the discussion of results must therefore be treated as speculation.

Pipfruit

Initial analysis of apples and pears was for the same 19 year period, 1963-1981. Application of methods was the same as for the stonefruit, although analysis of yield per tree was also carried out over this period. The growing year for both crops was chosen as June to May. Trends were fitted to yield per hectare data for apples and pears and to yield per tree data for pears. No trend in yield per tree for apples was apparent over this period.

Further data was sourced, on a per tree and district basis for the years 1941-1965. A linear trend was fitted to both the apple and pear data. Separate analyses on yield per tree, by district and nationally, were carried out for this period. Weighting factors for the national analysis were different from the 1963-1981 period.

As a final step national yield per tree data were combined for the two periods as were the two separately weighted climate data sets. For this combined period a linear trend was fitted to the pear data and a quadratic to the apple data. This longer time series allowed for model verification. As with grains two years out of every three were used for calibration and every third year for verification.

A much stronger literature base was available for pipfruit than for stonefruit, and results tend to be less speculative. There are still possible black box statistics.

CHAPTER 5

Analysis of grain crop-climate interactions

5.1 Wheat

5.1.1 Wheat-climate relationships

According to Lamb (1967) there are few places in the world that are too hot for the growing of wheat. However it does not do well under hot, humid conditions as experienced in most parts of the tropics. The best conditions for growth and development of wheat grain are said to be "a cool, moist growing season followed by a bright, dry and warm ripening period of 6-8 weeks, with a mean temperature of 18-19 °C " (Kirkham and Kanemasu, 1983). While wheat is grown globally under a wide range of temperature conditions it appears that availability of moisture sets the limits and has the most direct effect on yield. Claridge (1972) delineated two major zones in the world, according to moisture availability. These are the low rainfall areas of North America and Australia, which are associated with low yields, and higher rainfall areas (500-1000 mm per annum) where mixed farming is generally practiced allowing the maintenance of soil fertility. Europe and New Zealand fall into this latter category.

Moisture and water use

Soil moisture at seeding is considered to be very important to a successful wheat crop (Schlehuber and Tucker, 1967). It is also observed that when seasonal precipitation and soil moisture are combined they account for a large percentage of the variation in yield. Lamb (1967) noted that wheat yields were positively correlated with available moisture in the dry northwest of the U.S.A. In the east there tended to be a negative correlation with winter and early spring rainfall. An excess of rainfall can waterlog the soil, which can slow warming of the soil in spring and interfere with aeration and nitrification (Lamb, 1967). Humid conditions arising from a lot of rain, combined with warm temperatures can lead to disease problems. Wet conditions at maturity can interfere with harvesting of the crop.

Wheat has low total water requirements compared with other crops (Schlehuber and Tucker, 1967). However there are critical moisture sensitive growth stages. Table 5.1.1 shows water use by winter wheat at different developmental stages, under optimum moisture conditions (Schlehuber and Tucker, 1967).

Table 5.1.1

Water use by wheat

Period	Water use (mm/day)
Autumn	1.8
Winter	0.8
Beginning of spring growth to the jointing stage	2.3
Jointing-to-boot stage	4.1
Boot-to-flower stage	6.4
Flower-to-milk stage	8.9
Milk-to-dough stage	7.6
Dough stage to maturity	3.8

The boot to flower stage is generally considered to be the most critical stage for moisture stress as it affects the number of grains set (D. Martin, pers. comm.). Wheat is a relatively drought resistant plant. This resistance to dry conditions is greatest at the seedling stage and decreases as the plant develops (Lamb, 1967).

Temperature

Temperature, in most areas where wheat is grown, is not directly limiting to the growth and development of wheat, however it does regulate the rate of development. Higher temperatures lead to faster development, which results in a shorter duration of growth and generally lower yields. Its wide geographic distribution attests to the fact that it is able to withstand temperature extremes, although very high and very low temperatures reduce the rate of photosynthesis. A general observation was that both spring and summer wheat grow best at relatively low soil temperatures (Schlehuber and Tucker, 1967). It appears that it is under conditions of drought that temperature can become most limiting. Lamb (1967) stated that "drought is frequently accompanied by high temperatures and drought injury may be intensified because of the heat". Conditions are not usually hot enough in Canterbury to cause drought injury except under conditions of very strong advection (Martin, pers. comm.). The peak water use period, at the fruiting stage, would appear to be the time when warmer temperatures would have their greatest potential to be limiting. A period of drought, combined with warmer temperatures could be physiologically very stressful at this stage of development, as a result of stomatal closure under conditions with a high potential for evapotranspiration.

5.1.2 Wheat in New Zealand

Claridge (1972) generally reiterated what has already been discussed in relation to climate. Observations under New Zealand conditions show that in general yield is favoured by a reliable spring rainfall and ample sunshine and dry conditions at harvest time. Soil moisture is considered to be the factor most directly affecting yields from year to year, particularly during October and November which relate to the jointing to flowering stage of development. Excessive rain in autumn and winter is considered to have a negative effect on yield of autumn sown wheat. This is possibly related to leaching of nitrates from the soil, and perhaps the factors mentioned by Lamb (1967). Above average rain in the spring may cause rank growth and subsequent lodging.

Several empirical crop-climate studies have been carried out in New Zealand. Those based on Canterbury data are reviewed in section 7.6. The most recent work is that of Maunder (1965) who carried out a multiple regression analysis of yield and selected climate variables. He explored relationships for a range of selected counties, which were representative of most growing districts in New Zealand. The most important climatic factors that he identified from his multiple regression analysis were :-

1. A dry, warm October
2. A cool November
3. A dry December
4. A cloudy January
5. A wet, sunny February

These need to be put into the context of the different districts in which wheat is grown in New Zealand. The county by county correlations carried out by Maunder (1965) suggest that in the higher rainfall areas of New Zealand drier springs are preferred. In the lower rainfall areas wetter springs seem to be preferred. In the North Island wheat is generally spring sown. The principal growing areas of the North Island are centred in the Rangitikei and Manawatu, to the south-west. Mean annual rainfall in Bulls and Palmerston North is 874mm and 995mm respectively, which is approaching the upper limit of the optimum range for wheat. Claridge (1972) notes that rain at harvest time can be a problem in these areas. In Nelson and Marlborough districts in the South Island it is observed that summer drought can be a problem, particularly in Marlborough. The relatively warm summer conditions in this district could compound effects of moisture stress in drought years. In Canterbury and North Otago the wheat was predominantly autumn sown, until the last two to three years which have seen a move to spring sown wheat. Waterlogging of the soil can be a problem after wetter than average winters in these districts and spring and summer droughts can be limiting to yield. In the remainder of Otago and Southland the crop is spring sown and generally high yielding. This was attributed to the higher soil fertility and higher rainfall over the growing season (Logan, 1983). A corrected rainfall series for Invercargill gives a mean annual rainfall of 1090 mm. This is at the upper limit of the optimum range. Temperatures are on average cooler here than in the growing districts of the North Island, and more favourable for wheat yield. Harvest is later in Southland than in Canterbury and North Otago which can be delayed further by adverse conditions and lead to problems with ripening (Claridge, 1972).

Although this synopsis of districts explains some of Maunder's (1965) results there are two that appear anomalous. A dry, warm October appears contrary to the literature which suggests that cool, moist conditions are preferred at this time. A wet, sunny February would generally be unfavourable, rather than favourable at or near harvest. The preference appears to be for warm, dry conditions for ripening of the crop.

5.1.3 Wheat-climate analyses: results

National wheat yields from 1928-1983 and fitted quadratic trend are shown in Fig. 5.1.1.

P.C.A. multiple regression analysis

The proportion of variance accounted for by the first three principal components in the P.C.A. of yield and seasonal climate are presented in Table 5.1.2a. The results suggest that spatial variations of yield and rainfall across the country are much greater than that of temperature.

The first yield eigenvector gave positive loadings to all districts. Loadings were highest on Wellington and Nelson districts and the east coast of the South Island. Taranaki was an anomaly, with an almost zero loading. The second yield eigenvector contrasted the North Island and Marlborough with Canterbury, Otago and Southland. The former had positive loadings. The dominant feature of the third eigenvector was a strong positive loading on Taranaki.

The first eigenvector for rainfall, for the three seasons examined, tended to positively load the east coast of the South Island and the west of the North Island. Napier and Invercargill appeared as anomalies. The second eigenvector had positive loadings for the west of the North Island and Southland. The other two seasons for the second eigenvector had their highest positive loadings on the east of the North Island as did the third. The third eigenvectors for spring and summer rainfall had high positive loadings on the east of New Zealand, from Napier south. Lower pressures to the north of New Zealand and higher pressures to the south generally lead to positive rainfall anomalies in the west and south of New Zealand. Districts to the east of the axial ranges are rain shadow areas under such conditions. Spatial patterns of climate in relation to circulation phenomena are examined in detail in Salinger (1981). The data used for this analysis were chosen to be representative of growing districts and did not cover the country as a whole. Spatial variation in rainfall is complex, influenced by the axial ranges and predominant circulation patterns. Further discussion is restricted to those rainfall P.Cs that appear as significant yield predictors.

Fig. 5.1.1 New Zealand wheat yield and quadratic trend 1928–1985

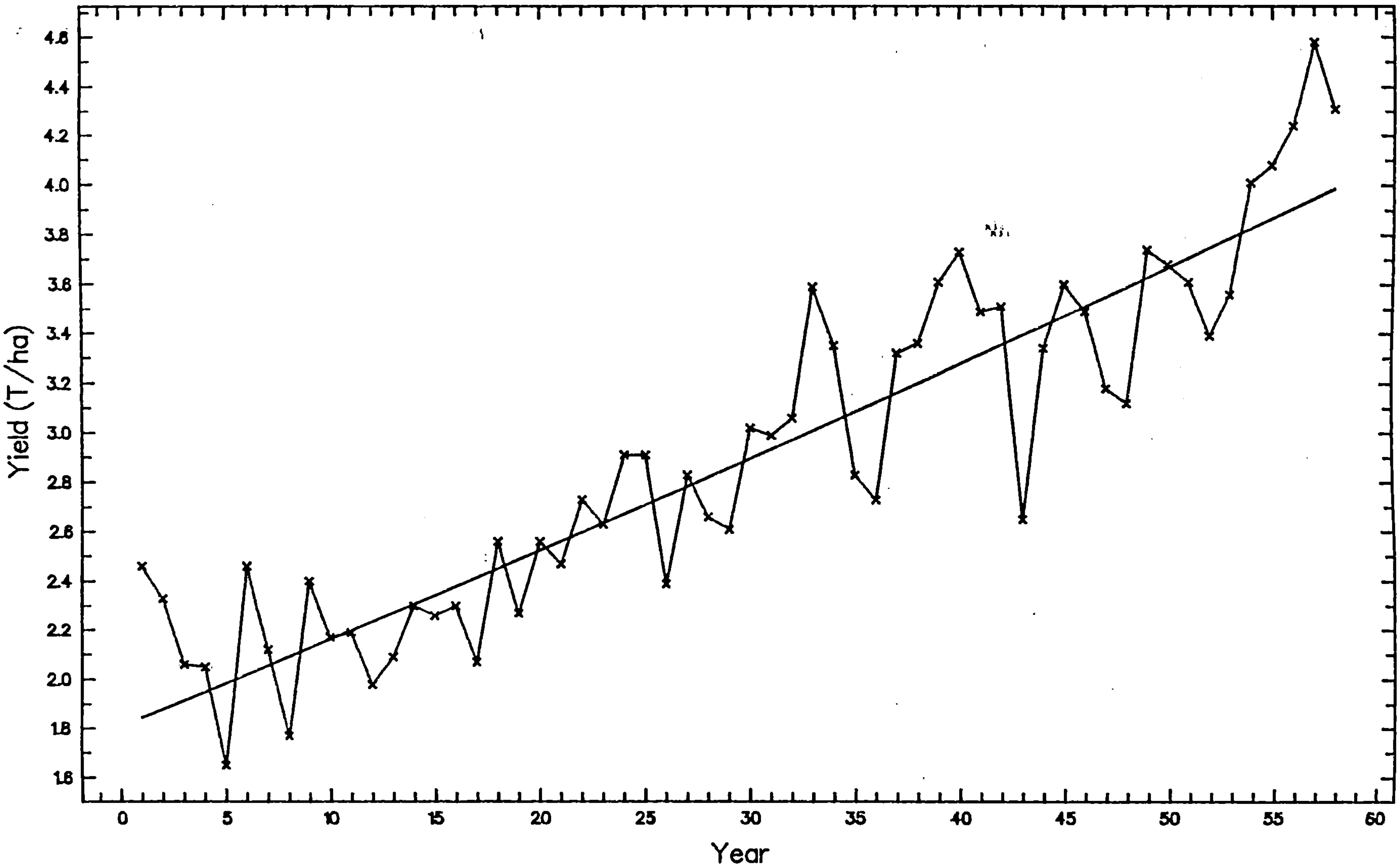


Table 5.1.2

(a) Principal component analysis: proportion of variance accounted for by the first three P.C.'s

Variable	P.C.1	P.C.2	P.C.3
Wheat yield	0.38	0.51	0.64
WRAIN	0.46	0.57	0.67
SPRAIN	0.37	0.51	0.63
SURAIN	0.33	0.51	0.62
WTEMP	0.75	0.87	0.91
SPTEMP	0.75	0.84	0.90
SUTEMP	0.88	0.92	0.95

(b) Correlation coefficients from wheat model verification

District	Calibration	Verification
South Auckland	0.29	0.30
Hawkes Bay	0.56	0.36
Taranaki	0.79	-0.48
Wellington	0.64	0.34
Marlborough	0.63	0.25
Nelson	0.49	0.42
Canterbury	0.49	-0.08
Otago	0.36	0.28
Southland	0.58	0.21
YIELD1	0.67	0.44
YIELD2	0.74	0.03
YIELD3	0.54	-0.35

(c) YIELD1, F=4, multiple regression model
Model R^2=0.47; F=8.74; P>F=0.0001

Variable	B value	F	P>F
Intercept	-0.00008047		
SPRAIN1	-0.21559179	4.87	0.0333
WTEMP3	-0.64331176	4.34	0.0438
SPTEMP1	-0.28367221	12.19	0.0012
SUTEMP1	-0.20559363	7.85	0.0079

The pattern with temperature is similar in all seasons. The first eigenvector in all cases gave similar loadings to all districts, suggesting that seasonal responses to temperature are similar over the whole country. This is attested to by the high proportion of the variance accounted for by the first principal component. The second eigenvectors for winter and spring temperature and the third for summer temperature showed a general north to south gradation. The former two had positive loadings on the east and south of the South Island. The latter had positive loadings on Te Aroha (South Auckland) and Napier (Hawkes Bay) and to a lesser degree other North Island stations. The third eigenvector for winter temperature gave positive loadings to South Auckland, the north of the South Island and Central Otago. Eastern districts showed negative anomalies.

The results of the verification procedure for the P.C.A. multiple regression, using the F=4 model developed from the calibration data are presented in Table 5.1.2b. The model based on the first yield P.C. was the only one to verify satisfactorily. It was an encouraging result given the spatial variability, particularly with yield and rainfall. Verification of individual districts showed Taranaki to be a strong anomaly, as shown up in the P.C.A. Canterbury, also, verified poorly. This is important as Canterbury is by far the dominant wheat growing district in New Zealand. Any model that fails to satisfactorily account for crop-climate relationships in this district is of questionable value in examining national yield variations. This result could be reflecting different climatic responses to autumn sown wheat, which was grown in Canterbury and North Otago over the period of analysis, and spring sown wheat which is grown in all other districts.

A model for all years was developed for YIELD1 and the F=4 result is shown in Table 5.1.2c. The interesting feature is the predominant influence of temperature on yield. The assumption is made, based on the verification results that the model is more a reflection of climatic relations with spring sown wheat. All but one of the predictors are first order P.Cs. The strongest loading of WTEMP3 was on Nelson district. There was also a higher loading on Nelson in YIELD1. Further, Nelson verified the best of all districts. There is therefore some bias towards this particular district, which is a minor wheat growing area. The other three predictors tend to reflect patterns in all districts. It is recalled that SPRAIN1 was biased towards the west of the North Island and the east of the South Island. There was no strong bias in SPTEMP1 or SUTEMP1. On the basis of this it might have been expected that the model would verify relatively well for Canterbury.

A negative relationship with spring rainfall suggests that most districts are likely to have surplus rainfall to needs at this time. This is more likely in higher rainfall areas in the west and south. Wet springs would delay soil preparation and sowing of spring sown wheat and thus delay the crop. Negative relations with spring and summer temperatures suggest that temperature conditions are above the optimum over this period in most districts of New Zealand. Cool, moist conditions are generally favoured at this time. In most parts of New Zealand there is the potential for spring and summer drought, particularly in the latter period. Warmer temperatures could have an indirect negative effect on yield under such conditions, as previously discussed.

Weighted and district analyses

The proportion of wheat grown in each district is shown in Table 5.1.3a. A noticeable transition occurred around 1945, with a significant increase in the proportion of wheat grown in Southland, and to a lesser degree in the Wellington district. There was a corresponding decrease in Canterbury. The climate data were weighted for these two periods for an analysis of national yield.

Table 5.1.3

(a) Proportion of wheat grown by district (weighting factors)

District	Period 1928-1945	1946-1985	1928-1985
Hawkes Bay	0.000	0.010	0.01
Wellington	0.020	0.060	0.04
Nelson	0.010	0.000	0.00
Marlborough	0.025	0.020	0.02
Canterbury	0.810	0.645	0.70
Otago	0.110	0.130	0.13
Southland	0.025	0.135	0.10

(b) N.Z. wheat yields versus weighted climate data; correlation coefficients from seasonal verification

Calibration	Verification
0.55	0.64
p=0.0007	p=0.0060

(c) New Zealand versus weighted seasonal climate data; multiple-regression model

R^2=0.32; F=10.88; p=0.0001

Variable	B value	F	P>F
Intercept	2.745		
WRAIN (Jun-Sep)	-0.002	12.65	0.0009
SPTEMP (Sep-Dec)	-0.197	13.62	0.0006

An initial analysis of yield versus all monthly values of rainfall and temperature revealed quite persistent seasonal effects. A calibration model using the monthly data was derived and verified poorly. The seasonal climate data, derived from the patterns apparent in the preliminary analysis, gave a good result. Correlations for the verification and calibration periods are given in Table 5.1.3 as is the F=4 model using all of the data. The result was highly significant with a high correlation coefficient for the verification period. The two predictors, winter rainfall and spring temperature are also highly significant. Both show a negative relationship with yield. With a high proportion of the crop being threshed in Canterbury it would be expected that this result would be strongly biased towards Canterbury conditions. Analysis of the Canterbury data confirms this.

Climate data were taken from Christchurch and Lincoln climate stations for an analysis of Canterbury yield. Rainfall data for Christchurch were taken from the homogeneous rainfall series (Thompson, 1984). Lincoln temperature was used as it was adjusted to a more exposed site, being more representative of field conditions. The result, given in Table 5.1.4, is the same as for New Zealand yield.

Table 5.1.4

(a) District wheat yields versus seasonal climate data; Correlation coefficients from model verification

District	Calibration	Verification	
Canterbury	0.67 p=0.0001	0.54 p=0.0305	
Otago	0.46 p=0.0081	0.39 p=0.1355	
Southland	0.55 p=0.0011	0.08 p=0.7811	
Variable	**B Value**	**F**	**P>F**
(b) Canterbury wheat yield-seasonal climate (F=4) model R^2=0.39; F=14.65; p=0.0001			
Intercept	3.848		
WRAIN (Jun-Sep)	-0.002	22.96	0.0001
SPTEMP (Sep-Dec)	-0.264	14.84	0.0004
(c) Otago wheat yield-seasonal climate (F=4) model R^2=0.20			
Intercept	2.752		
SUTEMP (Nov-Jan)	-0.189	11.21	0.0016
(d) Southland wheat yield-monthly climate (F=4) model R^2=0.09			
Intercept	1.455		
SPTEMP	-0.114	4.68	0.0357

The calibration model, using seasonal climate data verified well with a significant correlation between actual and predicted values. The predictors were exactly the same as for the New Zealand weighted model and were highly significant. Both the N.Z. weighted yield model and the Canterbury result therefore reflect relationships with autumn sown wheat. Claridges (1972) review of climatic influences on yield in New Zealand highlights the same climatic phenomena as deduced from this analysis. Winter rainfall appears to be a major limiting factor to autumn sown wheat and is possibly related to leaching of nitrates as earlier mentioned. Wheat tends to be grown on the heavier soils in Canterbury and so waterlogging in winter could reduce soil aeration and delay warming of the soil in spring and thus check or delay earlier spring growth. Canterbury soils can dry out relatively quickly in spring without regular rainfall and drought conditions can develop fairly rapidly. This can be a particular problem in springs with a high frequency of drying northwest winds. Once the soil is showing a moisture deficit the rising average temperatures of spring and early summer could make the developing plants particularly vulnerable in prolonged dry spells. This is reflected in the relationship with spring temperature. A more detailed analysis of Canterbury wheat-climate interactions is given in section 7.6.

Other districts analysed were Otago and Southland. Together with Canterbury they account for around 90% of the wheat grown in New Zealand. Seasonal data sets were derived for both on the basis of a preliminary analysis of all months. Results are presented in Table 5.1.4.

Otago district is a transitional climatic zone between Canterbury and Southland. This reflected in the rainfall and temperature response areas delineated by Salinger (1981). North Otago tends to be more similar to Canterbury, whereas South Otago tends towards Southland. This is also reflected in the division between Canterbury and North Otago where wheat is autumn sown and South Otago and Southland where the crop is spring sown. Most of the wheat in Otago is grown in Waitaki in the north, although in latter years South Otago has also become an important growing area in this district. The homogenous rainfall series for Oamaru was used, with temperature data from Waimate. This was the closest station with a good temperature record and was considered to be more representative than Naseby, the next closest station, which is inland and away from the main wheat growing area of North Otago. The lack of representative climate data for South Otago was a problem. Ideally separate analyses of North and South Otago should have been made but data were not available in sufficient detail over the period of analysis to allow this.

The result with Otago reflects these problems. A verification carried out using the monthly climate data gave a poor result. The seasonal model gave a very good result considering the differences within the district, both with climate and sowing time. The only significant predictor was summer temperature. North Otago is particularly prone to summer drought so that above average temperature conditions over this period could be quite limiting to yield.

Invercargill and Gore were the representative climate stations for rainfall and temperature in Southland. The monthly model verified poorly and the seasonal calibration model failed to produce any significant predictors, so no verification was attempted. This suggests that climatic conditions are generally not as limiting to yield of wheat in Southland. A model for all years using the seasonal data showed spring temperature to be the only significant predictor, showing a negative relationship with yield. Temperatures can be limiting in some years, but obviously with not as much frequency as drier and warmer districts.

5.1.4 Summary

A dominant feature with all analyses was the negative relationship with spring and summer temperatures. This appeared to be a characteristic with both autumn and spring sown wheat. The two national yield models are to a degree complimentary. The first appeared to characterise dominant crop-climate relationships with all districts except Canterbury and Taranaki. This provides a useful gauge of climatic relationships with spring sown wheat. However the result with Southland suggests that temperatures tend to be more limiting in the warmer districts, and where there is greater potential for drought in spring and summer. The result with Otago also highlighted the difficulty in dealing with districts that are spatially variable in climate and sowing time. Applying the P.C.A. approach allowed for better representation of spatial variations in climate but lack of reliable records in key areas was a problem. There was a further advantage in applying P.C.A. The margin of error in the yield data from lesser growing districts will be relatively greater than in larger districts, given the same method of data collection. Exploring spatial patterns with P.C.A. may facilitate the separation of the signal from the noise of the data, which appears to have at least partially occurred with the P.C.1 model.

The weighted model reflected the bias towards Canterbury as the principal wheat growing district. With the result being repeated in the Canterbury model, the latter provides a good indicator of national crop-climate relationships. It also reflects relationships with autumn sown wheat in this district.

The failure of the monthly calibration models to verify well in all cases and the general success of the seasonal models is worth noting. This suggests a strong seasonal interaction with yield. Persistence of above average winter rainfall in Canterbury or warm dry spring and summer conditions in all districts seems to have a more significant impact than for example a wetter than average July in a period of average winter rainfall.

5.2 Oats

5.2.1 Oat-climate relationships

Oats are a widely grown crop, often being grown in areas that are marginal in terms of climate according to Claridge (1972). This was attributed to the historical tendency to consume the crop on the farm where it was grown, particularly as feed for horses up until the early 20th century. Generally they are less climatically adaptable than wheat or barley, with highest yields being obtained in regions where the climate is cool and moist.

Moisture

The moisture demand of oats, to produce a given unit of dry matter, is higher than that of any other cereal except rice (Coffman, 1961). Best results, with irrigation, are achieved over the period from the 5-leaf stage to flowering (Coffman, 1961). High soil water contents before emergence can reduce yield. The same can occur after the blossom stage. An early study by Van der Paauw (1949) highlighted the importance of moisture in the growth and development of oats. Lack of moisture at the time of panicle production was found to reduce grain yield. Drought conditions at later developmental stages also had detrimental effects on yield through reduced weight of individual grains. If a period of moisture deficit was associated with warmer temperatures then it appeared that the drought stress was greater.

Temperature

Coffman and Frey (1961) state that there are repeated references in the literature to the preference for a cool climate for the best production. Cold soils are preferred for spring sown oats and cool to cold soils for an autumn sown crop. The periods when cool temperatures are most desirable are germination and the period of greatest growth which covers the shooting, booting and heading stages (Coffman and Frey, 1961).

This brief review highlights both the temperature and moisture sensitivity of oats. The most sensitive developmental stages, to both rainfall and temperature, appear to be the same. Cool, dry conditions are preferred for germination and in the period of greatest growth, from shooting to heading, cool and moist conditions are required. This period corresponds to late spring and early summer, when the potential for agricultural drought is high.

5.2.2 Oats in New Zealand

The best milling oats in New Zealand are grown in Southland which provides the ideal conditions of fairly fertile soils, ample moisture and a cool climate (Claridge, 1972). Parts of Otago and Canterbury also provide similar conditions, generally on the heavier soils and nearer the foothills where rainfall is higher.

Varieties for milling tend to be spring sown in Southland, where there is sufficient moisture for the crop. In Canterbury oats for milling tend to be autumn sown so that plants can benefit from the early spring growth flush when soil moisture is less likely to be in deficit.

Maunder's (1965) analysis of oats suggested that the following climatic factors were critical for above average yields :-

1. A wet, cloudy November
2. A dry, cool December
3. A warm January

Wet, cool conditions in late spring and early summer are important, as suggested by both the literature and Maunder's (1965) analysis. Closer to harvest warm and quite probably dry conditions seem to be preferred. Maunder (1965) noted that these are desirable conditions in warm temperate areas such as New Zealand, but also observed that in cooler climates warmer than average conditions appear to be beneficial.

As with wheat the principal growing districts in New Zealand are Canterbury, Otago and Southland. The spatial divisions for autumn and spring sown oats appear to similar to those for wheat.

5.2.3 Oats-climate analyses : results

A graph of national oat yields for 1928-1983 and fitted quadratic trend is given as Fig. 5.2.1.

P.C.A. multiple regression analysis

Table 5.2.1a shows the variance accounted for by the first three P.Cs. from the P.C.A. of standardised oat yield residuals, temperature and rainfall. As with wheat the result suggests a greater spatial variability across the country with yield and rainfall, than with temperature.

The first yield eigenvector had positive loadings on all districts, with South Auckland and to a lesser degree Hawkes Bay appearing slightly anomalous. No clear geographic pattern was apparent from the other two yield eigenvectors.

The climate stations used for the analysis were the same as for wheat, although New Plymouth was excluded because of a broken yield record for the Taranaki district. Results of P.C.A. of climate data were essentially the same and reference can be made to section 5.1.3.

P.C.A. multiple regression analysis of oats was done initially with a backward stepwise routine. A second run with the maximum R^2 routine gave the same result as the backward procedure for YIELD1 and YIELD3 and a very similar result for YIELD2. Verification results from the backward stepwise regression are presented in Table 5.2.1b. The best of the yield models was YIELD3, although the correlation coefficient was not highly significant. Some individual districts calibrated relatively well, but overall the result was poor. Significant anomalies were Otago and Southland which are two principal oat growing districts. Because of the uncertain value of the result, and generally low significance no further analysis was carried out.

Fig. 5.2.1 New Zealand oat yield and quadratic trend 1928–1985

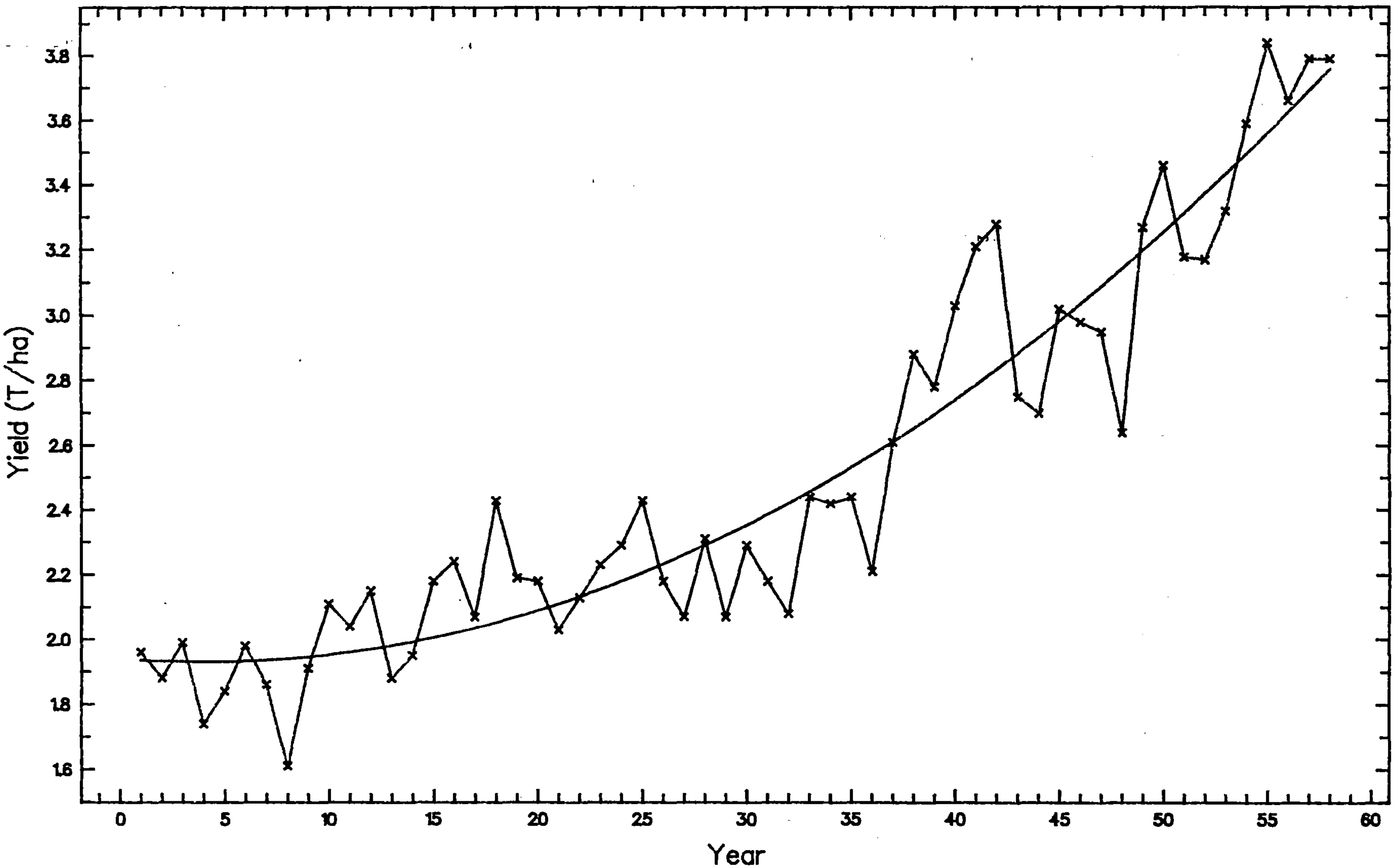


Table 5.2.1

(a) Principal component analysis; proportion of variance accounted for by the first three P.C.'s

Variable	P.C.1	P.C.2	P.C.3
Oat yield	0.41	0.61	0.73
WRAIN	0.47	0.58	0.69
SPRAIN	0.37	0.50	0.60
SURAIN	0.34	0.53	0.64
WTEMP	0.72	0.85	0.90
SPTEMP	0.75	0.84	0.90
SUTEMP	0.88	0.92	0.95

(b) Correlation coefficients from oat yield model verification

District	Calibration	Verification
South Auckland	0.56	-0.16
Hawkes Bay	0.67	0.25
Wellington	0.54	0.30
Marlborough	0.49	0.26
Nelson	0.52	-0.07
Canterbury	0.67	0.35
Otago	0.50	-0.26
Southland	0.56	-0.49
YIELD1	0.60	0.06
YIELD2	0.83	-0.33
YIELD3	0.44	0.26
Overall	0.56	-0.06

Weighted and district regression

The proportion of oats grown in each district was relatively stable over the period of analysis, so that weighting factors averaged over the entire period could be used. These are given in Table 5.2.2a. As mentioned earlier Canterbury, Otago and Southland dominate as the principal oat growing districts. Separate analyses were carried out for these districts. Canterbury is relatively less dominant for this crop than for wheat and Southland is relatively more so. This reflects the greater suitability of the climate of this latter district for the growing of oats, particularly for milling.

Weighted rainfall and temperature data sets for New Zealand were derived using these average factors. Preliminary analysis using monthly data for all years suggested a yield response to seasonal conditions, although not as pronounced as with wheat. Most noticeable was a significant negative relationship with November and December temperatures. A calibration model was developed using derived seasonal climate data. Correlation coefficients for both the calibration and verification data are shown in Table 5.2.2b. The seasonal model verified strongly. A model using seasonal climate data for all years is shown in Table 5.2.2c and indicates a highly significant negative influence on yield from the mean of November and December temperatures. The result was almost exactly the same as that achieved with the monthly data.

This result reflects the sensitivity of oats to warmer than average temperatures in late spring and early summer. Quite probably this is associated with conditions of moisture deficit, as can be commonly experienced at this time in many parts of New Zealand, particularly in the drier east coast districts.

Table 5.2.2

(a) Proportion of oats grown by district: weighting factors

District	Period=1928-1984
Hawkes Bay	0.01
Wellington	0.02
Marlborough	0.01
Canterbury	0.52
Otago	0.17
Southland	0.27

(b) N.Z. oat yields versus weighted seasonal climate data; correlation coefficients from model verification

Calibration	Verification
0.54 p=0.001	0.63 p=0.0062

(c) N.Z. oat yield-seasonal climate model
Model R^2=0.34

Variable	B value	F	P>F
Intercept	1.791		
SPSUTEMP (Nov-Dec)	-0.126	24.76	0.0001

The lesser dominance of Canterbury as an oat growing district is reflected in the results for this district as shown in Table 5.2.3b. Verification was not as good as for the national weighted model, but still satisfactory. Models using monthly and seasonal data for all years gave similar results. Interesting are the significant negative relationships with winter and early spring rainfall. This is contrary to the observation of Claridge (1972) that winter rain is desirable for autumn sown oats, which predominate in Canterbury. If it is a true relationship then the explanation may be similar to that for autumn sown wheat in Canterbury given in section 5.1.3. It was suggested earlier that there is an apparent association between late spring and early summer rainfall and temperatures over the same period. November shows up as a critical moisture sensitive month as is December for temperature. This period would generally correspond to the most moisture sensitive developmental stages of the plant and the period when the crop is most sensitive to drought, particularly if associated with above average temperatures. The result suggests that oats are more sensitive to shorter term moisture deficits and periods of above average temperature conditions than wheat.

The Otago seasonal model verified poorly. Results from an analysis of yield versus seasonal climate for all years are presented in Table 5.2.3c.

Table 5.2.3

(a) District oat yields versus seasonal climate; correlation coefficients from model verification

District	Calibration	Verification
Canterbury	0.69 p=0.0001	0.45 p=0.0787
Otago	0.55 p=0.0013	0.14 p=0.61
Southland	0.57 p=0.0007	0.28 p=0.3008

Variable	B value	F	P>F
(b) Canterbury oat yield versus seasonal climate, F=4, model Model R^2=0.58; F=11.57; P>F=0.0001			
Intercept	2.479		
WRAIN (Jun-Aug)	-0.001	6.51	0.0144
SPRAIN (Sep-Oct)	-0.002	11.59	0.0015
NOV RAIN	0.004	18.70	0.0001
SPTEMP (Sep-Oct)	-0.114	6.72	0.0130
DEC TEMP	-0.070	10.81	0.0021
(c) Otago oat yield versus seasonal climate, F=4, model Model R^2=0.16			
Intercept	1.673		
SPSUTEMP (Nov-Dec)	-0.120	9.06	0.0042
(d) Southland oat yield versus seasonal climate, F=4, model Model R^2=0.13			
Intercept	1.020		
SUTEMP (Dec-Jan)	-0.070	7.05	0.0109

The only significant predictor was the mean temperature for November and December. Although of interest this relationship is not strong enough to be considered as an important relationship over the district as a whole. In Otago a greater proportion of oats are grown in the south. The climate data used was the same as for wheat, being representative of North Otago. Different climatic responses of yield over the district may be the explanation for the poor result, combined with the lack of fully representative climate data.

Southland verified better than Otago, but the result was still not a highly significant one as seen in Table 5.2.3d. Spring sowing in Southland is up to a month later than in Canterbury. Some lag in development of the Southland crop could be expected. This is reflected in the result which shows December and January to be critical temperature sensitive months. This is associated with a weaker positive relationship between yield and November to January rainfall. Some years are obviously limiting in terms of available moisture over the summer period, but this relationship is less pronounced than in the drier districts of Canterbury and North Otago. Interestingly there was a negative association with winter and October rainfall In the F=2 model, not presented here. Both could be associated with delays in spring sowing time because of either waterlogged soils or wet weather delaying cultivation and sowing of the crop.

5.2.4 Summary

From the literature it was apparent that oats, although grown widely, generally prefer cooler and moister conditions than wheat. This greater climatic sensitivity would make it more difficult to quantify relationships over the country as a whole and perhaps explains the lack of success with the P.C.A. multiple regression analysis.

The strong result with the weighted analysis highlights the temperature sensitivity of the crop in late spring and early summer, most probably associated with moisture deficit conditions. Analysis of the three principal growing districts suggests that this temperature response is graded from north to south, at least in the South Island. Canterbury and North Otago are both warmer and drier than South Otago and Southland in summer. Although temperature can also be limiting in late spring and early summer in Southland, this apparently occurs with less frequency than Canterbury.

Of interest also is the stronger negative relationship with winter and early spring rainfall in Canterbury than Southland. Canterbury is more anomalous in the context of Claridges (1972) observation that cooler, moister conditions are preferred over this period. The weaker negative association in Southland tends to reinforce this observation, although there may be very wet years that lead to delayed sowing and result in lower yields.

5.3 Barley

5.3.1 Barley-climate relationships

Barley has the widest ecological adaptation of all cereals, with only wheat approaching it in its breadth of adaptation (Poehlman, 1985). It thrives in cool, relatively dry temperate regions. Because the barley plant evolved in marginal winter rainfall areas it completes its life cycle rapidly. It is this that gives it such a wide adaptability and enables it to tolerate both hot, dry and cool, humid climates. As with wheat and oats, barley is intolerant of hot, humid tropical areas.

Barley has a lower water requirement and transpiration rate than other cereals (Poehlman, 1985) and for this reason is often regarded as being a drought resistant crop. Research has shown a positive yield response to additional rainfall or to irrigation, suggesting that it is drought escaping rather than drought resistant (Poehlman, 1985).

A comprehensive review of environmental influences on the development, growth and yield of barley was given by Gallagher et al (1983). General climatic influences on various growth and developmental stages were summarised. The simplified relationships with temperature and drought are presented in Table 5.3.1. There is a positive relationship with temperature until the end of spike development. At this stage temperature can be limiting, particularly if associated with drought conditions. According to Claridge (1972) "warmth and moisture during tillering and adequate soil moisture at flowering (usually in December) are the important factors to induce a high yield from spring sown barley". Warm temperatures appear to be positively associated with early growth, but can reduce production of tillers, ears and grains per ear because of more rapid development under such conditions. Drought can apparently be limiting to growth throughout the growing season. Higher temperatures can be tolerated nearer to harvest, following spike emergence, and can stimulate grain growth (Claridge, 1972). In general higher temperatures have two effects in relation to grain growth (Martin, pers. comm.). Higher temperatures increase photosynthesis and hence the rate of grain growth, and increase the process of maturation and hence reduce the duration of grain growth. Usually the latter outweighs the former, leading to reduced yield.

5.3.2 Barley in New Zealand

Barley is normally spring sown in New Zealand, with September and October being the main months for sowing. Gallagher et al (1983) believed that the timing of spring sowing can have a significant effect on final yield. A wet winter in 1974 delayed spring sowing. This was followed by a dry November to January period which resulted in below average yields (Logan, 1983). It is obviously desirable to have the crop well established before the onset of summer drought conditions, weather permitting.

Table 5.3.1

Environmental influences on the development, growth and yield of barley. From Gallagher et al (1983)

(a) Climatic influences on development

Stage	Phase	Temperature	Drought
Sowing			
	Germination	+++	
Emergence			
	Leaf initiation	+++	
Collar initiation			
	Ear initiation	+++	
Terminal spikelet		-	-
	Ear growth	+++	
Anthesis			
	Grain growth	+++	+
End of grain growth			

(b) Climatic influences on growth

Stage		Temperature (warm)	Drought
PHS		-	--
Respiration		+	
D.M. growth rate			--
Leaf appearance rate		+++	
Leaf expansion rate		+++	--
	area/leaf	++	--
Leaf death rate		++	+
Root growth rate		++	+
Tillering rate		++	--
	max tiller no/plant	--	---
Tiller death rate		++	+++
	ear no/plant	--	--
Ear growth rate		++	-
	grains/ear	--	--
Grain growth rate		++	
	kernel mass	--	?

The work of Malcolm (1947) showed the months of November and December to be critical moisture sensitive months for barley in New Zealand. These results came from a correlation analysis of county yields with monthly rainfall and temperature for the years 1924-25 to 1944-45. He considered December in particular to be a critical moisture sensitive period with high temperatures at this time accentuating the yield depression in years of moisture deficit. This result was achieved largely using Canterbury data, and obviously is influenced by the average sowing time of the crop. In some areas and years November, rather than December was a more significant month in terms of the potential for yield depression. No definite relationships were found for any of the North Island districts.

Maunder's (1965) analysis generally supported the results of Malcolm (1947). Positive climatic influences on yield were summarised as follows :-

1. A warm October
2. A cloudy November
3. A wet, cool, cloudy December
4. A cool January
5. A warm February

The results of both of these empirical analyses are mostly consistent with the simplified summary given by Gallagher et al (1983). The conclusion of Malcolm (1947) was that mean temperatures in New Zealand were slightly too high for optimum yields in relation to the prevailing moisture conditions. It is presumed that this is a reference to the impact of summer drought at the flowering stage.

5.3.3 Barley-climate analysis: results

As with wheat and oats, a quadratic trend was fitted to the national and district barley data. National yield per hectare and trend for the years 1928-1983 are shown in Fig. 5.3.1

P.C.A. multiple regression analysis

The P.C.A. yielded a similar result to wheat and oats in terms of the relative proportions of variance accounted for by each of the variables as seen in Table 5.3.2a. Eigenvectors for barley and associated climate data are given in Appendix B as an example output.

The loadings were positive for all districts for the first yield eigenvector. Hawkes Bay, Wellington, Marlborough, Nelson and Canterbury had the highest loadings and North Auckland and Otago the lowest. This represents a degree of bias towards eastern districts of both islands. The second yield eigenvector gave positive loadings to South Auckland, Taranaki, Wellington and Southland.

Fig. 5.3.1 New Zealand barley yield and quadratic trend 1928–1985

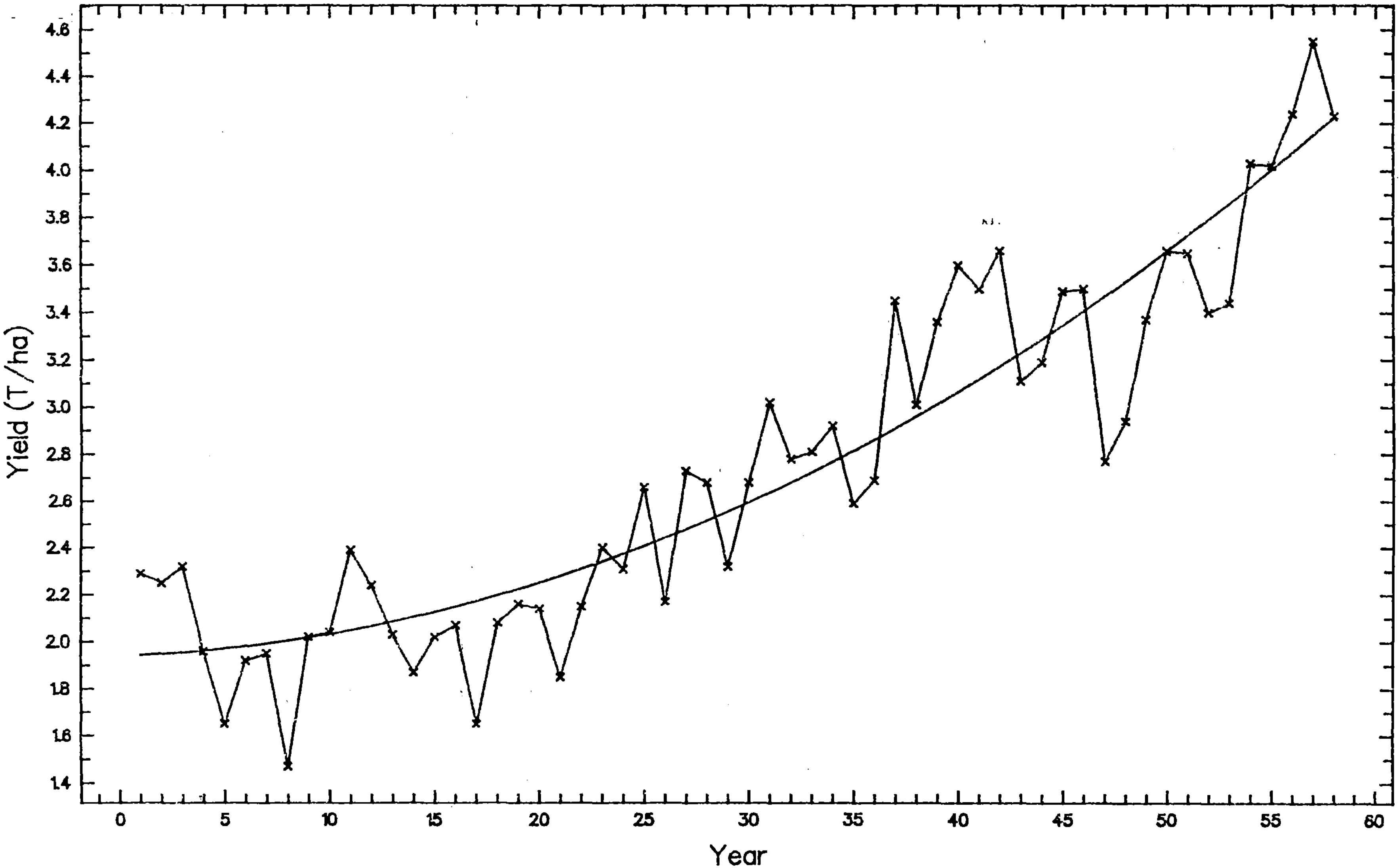


Table 5.3.2

(a) Principal component analysis; proportion of variance accounted by the first three P.C.'s

Variable	P.C.1	P.C.2	P.C.3
Yield	0.38	0.55	0.67
WRAIN	0.44	0.55	0.65
SPRAIN	0.35	0.49	0.59
SURAIN	0.33	0.50	0.62
WTEMP	0.73	0.86	0.89
SPTEMP	0.74	0.83	0.88
SUTEMP	0.88	0.92	0.95

(b) Correlation coefficients from barley yield model verification

District	Calibration	Verification
North Auckland	0.32	0.21
South Auckland	0.51	0.33
Gisborne	0.38	0.42
Hawkes Bay	0.64	0.36
Taranaki	0.57	0.36
Wellington	0.60	0.35
Marlborough	0.63	0.30
Nelson	0.71	0.28
Canterbury	0.73	0.37
Otago	0.44	0.40
Southland	0.61	0.25
YIELD1	0.76	0.39
YIELD2	0.72	0.61
YIELD3	0.36	0.05
Overall	0.56	0.33 (p=0.0001)

(c) YIELD1, F=4, model
Model R^2=0.45; F=6.02; p=0.0004

Variable	B value	F	P>F
Intercept	-0.00003		
SPRAIN1	-0.280	6.10	0.0182
SPRAIN2	-0.425	5.81	0.0210
SURAIN2	-0.538	10.50	0.0025
SPTEMP1	-0.177	4.07	0.0510
SUTEMP1	-0.202	5.62	0.0231

(d) YIELD2, F=4, model
R^2=0.48; F=8.78; p=0.0001

Variable	B value	F	P>F
Intercept	0.00006411		
SPRAIN1	-0.215	8.46	0.0060
SPTEMP1	0.188	11.69	0.0015
SUTEMP2	-0.562	5.44	0.0251
SUTEMP3	-0.735	6.78	0.0131

In South Auckland barley has predominantly been grown in the Waikato, with smaller amounts in the Bay of Plenty. In Wellington district the Rangitikei and Manawatu are the main barley growing areas. The second yield eigenvector therefore predominantly accounts for barley growing districts to the west of the axial ranges in the North Island and in the south of the South Island. North Auckland stands out as a strong positive anomaly in the third eigenvector.

The results with the P.C.A. of rainfall and temperature follow similar patterns to those from previous analyses. Slight variations occur according to which districts are covered in the analysis. Discussion will be restricted to significant predictors from the multiple regression analysis.

Calibration models for YIELD1 and YIELD2 verified very well, particularly for the latter, as Table 5.3.2b shows. All districts had satisfactory positive correlations, although none statistically significant. The overall correlation for the verification period was significant however (p=0.0001). This is an excellent result considering the wide geographic variation that exists, particular as it manifests in terms of yield and rainfall. The important question is, can the spatial variation in yield be explained in terms of spatial variation in climate. With wheat there was some success and with oats none. With barley it appears that a good degree of explanation is possible.

Models for YIELD1 and YIELD2 , for all years, are presented in Table 5.3.2c and Table 5.3.2d. An immediately apparent inconsistency is the negative response to SPTEMP1 with YIELD1 and the positive response of the same predictor to YIELD2. This provides a key to the interpretation of the results.

As mentioned P.C.A. of yield gave positive loadings to all districts, with some bias towards districts east of the axial ranges. YIELD2 was strongly biased to the west of the North Island and Southland. Intuitively it appears that the different yield responses to temperature may be related to geographic differences in rainfall. Rainfall totals, for winter, spring and the year as a whole for all stations used in the analysis, are given in Table 5.3.3. Mangonui, in North Auckland, is ignored as the yield response in this district was anomalous. Highest rainfall areas are in western districts and the south of the South Island. Nelson is transitional between these and the rain shadow areas that lie east of the axial ranges. The hypothesis that the different response may be related to spatial variations in rainfall and therefore moisture availability is at least partly reinforced by an examination of yield relationships with other predictors.

YIELD1 is negatively related to both spring rainfall and temperature. Rainfall, in the sowing months of September and October could delay sowing and lead to lower yields. This would be more of a problem in higher rainfall areas, particularly where there is also a relatively high winter rainfall. Wet winters and springs obviously occur with sufficient frequency in both wetter western and southern districts and drier eastern districts to show through in YIELD1. While eastern districts may experience wetter than average years that delay sowing they can also experience relatively severe spring and summer moisture deficits. Years when rainfall is limiting to yield may be the reason for the negative relationship with temperature in the YIELD1 model.

Temperature is also limiting in summer, across the country. It is assumed that the negative relationship between yield and summer rainfall relates to the months of January and February, when the moisture demand is tailing off and dry conditions are preferred for ripening and harvesting of the crop. The way in which the seasons were divided for the analysis of grain yields (spring, Sep-Nov; summer, Dec-Feb) probably masks out any possible positive response to November and December rainfall. These are the moisture sensitive months as identified by Malcolm (1947) and relate to the critical moisture sensitive flowering stage of barley.

YIELD1 verified less well than YIELD2, partly because it only had a relatively small bias towards the drier eastern districts and tended to aggregate relationships over all districts. The spring temperature relationship, however, appears to be more related to conditions in the east.

The relationships in the YIELD2 model are clearer and explain the better verification result. This can be related to a definite bias towards higher rainfall districts. As with YIELD1, spring rainfall is negatively related to yield. Rainfall is more likely to be in excess to requirements in the west and south and would probably have a direct impact on sowing time. A positive association with spring temperatures suggests that warmer years may be related to lower spring rainfall and thus earlier sowing or lead to more rapid warming of the soil and thus allow the crop to take full advantage of available soil moisture. It may be a combination of both phenomena, but not necessarily in the same growing season. As the growing season progresses and temperatures become warmer the potential for drought increases.

A negative relationship with summer temperature suggests that lack of moisture may be limiting at this time, even in the higher rainfall areas. SUTEMP2 is loaded more towards eastern districts and SUTEMP3 is loaded towards the North Island, with highest loadings on Hawkes Bay, South Auckland and North Auckland. Neither of these patterns directly relates to the YIELD2 loadings. It may reflect an association in years with warmer and possibly drier conditions in the east and higher rainfall in the west. This was a dominant pattern in 1988 which generally gave lower pressures in the north and higher pressures in the south. This led to wetter, and warmer conditions in the north and west of the North Island. A southward shift in the mean latitude of anticyclones gave wetter conditions on the west coast of the South Island as well. The net effect on eastern districts from Hawkes Bay to North Otago was for warmer and drier conditions.

Table 5.3.3

Seasonal and annual rainfall at selected New Zealand climate stations

Station (district)	Winter	Spring	Annual
Mangonui (Northland)	471	310	1397
Ruakura (South Auckland)	361	297	1201
Te Aroha (South Auckland)	451	347	1459
New Plymouth (Taranaki)	477	381	1573
Palmerston North (Wellington)	275	241	995
Napier (Hawkes Bay)	250	158	824
Masterton (Wellington)	301	228	982
Nelson (Nelson)	265	240	979
Appleby (Nelson)	276	224	955
Blenheim (Marlborough)	183	150	642
Christchurch (Canterbury)	191	138	659
Waimate (South Canterbury)	139	160	645
Oamaru (North Otago)	127	127	549
Alexandra (Central Otago)	56	84	343
Dunedin (Otago)	234	218	930
Invercargill (Southland)	250	261	1090

Weighted and district regression

There have been some noticeable fluctuations in the proportion of barley threshed by district. The proportion threshed in Canterbury has fluctuated from 38% in 1935 to 79% in 1958. Even within this district variations have occurred. In earlier years, until the 1940s, barley was almost exclusively grown in Ellesmere county. Since then Ashburton has become the dominant growing area in Canterbury. Until 1948 only 3%, on average, of the crop was grown in Wellington district, but since 1964 has ranged from 12-19%. Otago averaged 25% of the crop from 1928-1937, steadily dropped to reach an average of 6% from 1958-1969 then rose to average 10% in the

1980s. There is no distinctive transition as with wheat, so average weightings were derived for all years and are given in Table 5.3.4a. Analysis was carried out on national yield versus weighted climate data and for Hawkes Bay, Wellington, Marlborough, Canterbury and Otago districts. Methods were the same as for wheat and oats.

Table 5.3.4

(a) Proportion of barley grown by district; weighting factors period: 1928-1985

District	Proportion
South Auckland	0.01
Hawkes Bay	0.05
Wellington	0.09
Nelson	0.03
Marlborough	0.08
Canterbury	0.60
Otago	0.12
Southland	0.02

(b) N.Z. barley versus weighted seasonal climate model correlation coefficients from model verification

Calibration	Verification
0.72 p=0.0001	0.45 p=0.0675

(c) N.Z. barley yield; weighted seasonal model
Model R^2=0.51; F=11.94; p=0.0001

Variable	B value	F	P>F
Intercept	1.753		
SPRAIN (Aug-Oct)	-0.003	27.19	0.0001
SPSURAIN (Nov-Dec)	0.003	12.76	0.0008
SURAIN (Jan-Feb)	-0.002	5.20	0.0272
SPTEMP (Sep-Oct)	-0.128	7.17	0.0102

The New Zealand yield versus weighted seasonal climate model verified well as seen in Table 5.3.4b. The significant predictors, using all years in the regression, are very similar to those selected in the YIELD1, P.C.A. model as seen in Table 5.3.4c. The notable difference was the inclusion of rainfall for the critical moisture sensitive months of November and December. This confirms the earlier suspicion that the effect of these months was masked out in the P.C.A. model. The model presented here is weighted heavily to the east coast of the South Island. It shows a strong negative effect of August to October rainfall on yield. This confirms that the spring rainfall relationship in the YIELD1 model reflected both eastern and western district effects. The negative association with early spring temperatures affirms that this relationship in the YIELD1 model was reflecting east coast conditions. It seems that the ideal combination, at least in eastern districts, is for cool, dry conditions over the sowing and early developmental period. As before drier conditions seem to be preferred nearer to harvest.

Correlation coefficients from district model verification are presented in Table 5.3.5 and district regression models in Table 5.3.6.

Table 5.3.5
District barley yields versus seasonal climate data
Correlation coefficients from model verification

District	Calibration	Verification
Hawkes Bay	0.55	0.35
	p=0.0018	p=0.2041
Wellington	0.75	0.06
	p=0.0001	p=0.8220
Marlborough	0.59	0.32
	p=0.0004	p=0.2278
Canterbury	0.66	0.62
	p=0.0001	p=0.0104
Otago	0.60	0.48
	p=0.0003	p=0.0597

The Hawkes Bay calibration model verified satisfactorily considering the relatively lower proportion of the crop grown in this district and hence the greater potential for error in the data. Being in the rain shadow of the axial ranges in the North Island this district is relatively prone to summer drought. The negative relationship with November to December temperature may be a secondary effect, related to years of fairly persistent moisture deficit. There is a weaker negative relationship with January rainfall, which came through in the F=2 model, this being consistent with the result from the N.Z. analysis.

Wellington district verified poorly. This may be partly due to the relatively wide geographic variation within this district, particularly in relation to climatic response areas. It covers both the southwest and southeast of the North Island. Obviously there are limitations in choosing a single climate station to be representative of the whole district. As before with Wellington, Palmerston North in the west was chosen, this being the region where most of the barley is grown. However the significant contribution from the Wairarapa, ideally should not be ignored. For interest a model using seasonal climate data is included. Relationships are consistent with previous results and reflect yield responses that appear to be relatively universal over all districts.

Table 5.3.6 Barley: district crop-climate models

Variable	B value	F	P>F
	(a) Hawkes Bay barley vs seasonal climate (F=4) model Model R^2=0.19; F=4.79; p=0.0134		
Intercept	4.178		
JAN RAIN	-0.003	3.95	0.0535
SPSUTEMP (Nov-Dec)	-0.240	7.46	0.0092
	(b) Wellington barley vs seasonal climate (F=4) model Model R^2=0.31; F=6.28; P>F=0.0013		
Intercept	2.321		
SPRAIN (Sep-Nov)	-0.002	11.04	0.0019
DEC RAIN	0.002	6.06	0.0180
NOV TEMP	-0.140	6.52	0.0144
	(c)Marlborough barley vs seasonal climate (F=4) model Model R^2=0.29; F=9.00; P>F=0.0005		
Intercept	2.693		
NOV RAIN	0.004	6.27	0.0159
SPSUTEMP (Oct-Dec)	-0.199	9.08	0.0042
	(d) Canterbury barley vs seasonal climate (F=4) model Model R^2=0.49; F=10.52; p=0.0001		
Intercept	1.352		
WSPRAIN (Aug-Sep)	-0.003	21.31	0.0001
SPSURAIN (Nov-Dec)	0.003	14.13	0.0005
SURAIN (Jan-Feb)	-0.002	6.04	0.0181
SEP TEMP	-0.125	7.28	0.0099
	(e) Otago barley vs seasonal climate (F=4) model Model R^2=0.49; F=10.47; p=0.0001		
Intercept	0.676		
MAY RAIN	0.003	5.93	0.0191
DEC RAIN	0.002	6.27	0.0161
AWTEMP (May-Jun)	0.160	9.50	0.0036
JAN TEMP	-0.137	16.57	0.0002

Marlborough verified similarly to Hawkes Bay. In this district November is the critical moisture sensitive month and temperatures over this period generally appear to be above optimum for the prevailing moisture conditions.

The Canterbury model verified very well. The result closely matches that obtained with the New Zealand weighted model. The combination of months is slightly different but both relate to the same periods. The relationship with spring rainfall and temperature is strongest in September. The result with the monthly data demonstrates this. It confirms the earlier suggestion that relatively cool, dry conditions are preferred for spring sowing, particularly in Canterbury. It is uncertain whether September rainfall and temperature interact together in their relationship with yield. The two are negatively correlated (r=-0.28, p=0.0484), which suggests that the tendency is for them not to be associated. If the effect of rainfall is a direct one in terms of delaying sowing then whether the rain is from cool, southerly airstreams or warm, moist easterlies which are the two dominant sources of rain in Canterbury is not so important. The correlation result suggests however that the relationship may be more with southerly conditions. Warmer than average weather conditions in Canterbury most frequently occur in spring time with a prevalence of unrestricted westerly airflow on to the South Island which can give hot, dry Fohn winds in Canterbury. Canterbury climate is reviewed in more detail in section 7.2.

An examination of correlation coefficients shows that December rainfall has a significantly positive relationship with yield and confirms the result that Malcolm (1947) obtained from earlier years. It is obviously a persistent and important relationship in Canterbury. December temperature is also significantly negatively correlated with yield, and temperature and rainfall have a highly significant correlation (r=-0.63, p=0.0001). Yield depression can therefore result from moisture deficit conditions, potentially compounded by warmer than average temperatures at this time. There is a similar association in November, but weaker. As with results from other districts drier conditions seem to be preferred after this critical stage. However the monthly analysis shows that warmer temperatures are not favourable to yield until February, which is usually the month of harvest.

The Otago result also verified fairly well. This is a good result when it is recalled that this district is a climatic transition zone between Canterbury and Southland. Until 1945 Vincent and Lake counties in Central Otago were the dominant growing areas in the Otago district. After this period Waitaki, in the north, began to dominate more. The former two fall into different rainfall and temperature response areas according to Salinger's (1981) classification. Both Central and North Otago are regarded as rainfall transition zones. The former is continental in its temperature response and the latter can tend towards semi-continental conditions. As with previous analyses climate stations representative of North Otago were used. Interestingly there are positive associations with both May rainfall and temperature. This may be partly representing conditions in Central Otago, if it is assumed that the climatic response in North Otago is at least similar to that in Central. In this latter area barley is autumn sown, because of the very dry conditions. A positive relationship with May rainfall and temperature is not necessarily contradictory to the result with Hawkes Bay. Both Central and North Otago are cooler and drier on average at this time than in Hawkes Bay.

Table 5.3.7 May rainfall and mean temperature

Station	Rain (mm)		Temperature (°C)	
	Mean	90 Percentile	Mean	Average Minimum
Napier	87	176	12.0	7.5
Oamaru	44	82	--	--
Waimate	--	--	8.8	3.8
Alexandra	28	54	6.4	0.9

Wetter than average conditions in both North and Central Otago are both below the mean for Hawkes Bay, as comparison of 90 percentile values from Table 5.3.7 shows. The average daily means in Waimate and Alexandra are both similar in magnitude to the average minimum for Napier. Warmer, wetter conditions could obviously be an advantage to autumn sown barley in Otago, particularly in Central Otago.

A positive association with December rainfall and a weaker, negative association with November to December temperatures are consistent with all previous results with barley, as is the relationship with January temperature.

5.3.4 Summary

The result with the P.C.A. multiple regression of district barley yields and climate highlights the value of this approach. Of the three crops examined barley is the one that gave a yield response that matched climatic response area characteristics most closely. This is perhaps a reflection of its wider ecological adaptability. The most interesting aspect of the result is the apparent geographic differences in response to spring temperature. This tends to be an indirect relationship with rainfall response area characteristics.

The selection of seasons for the P.C.A. was originally made to give consistency in the analysis of the three crops. Compiling seasonal data sets can also be a time consuming process, which influenced the decision to use a common seasonal climate data set for the P.C.A. of the three grain crops. The result with the weighted analysis reveals that there are risks involved in taking this approach.

Although barley is highly adaptable, it is also apparently much more sensitive to shorter term variations in climate. This appears to contrast with autumn sown wheat which appeared to be more strongly affected by more persistent seasonal variations. The relationship between barley yield and late spring and early summer temperature and rainfall is an important one, and is a particularly persistent relationship, from year to year, in Canterbury.

CHAPTER 6

Analysis of N.Z. fruit crop-climate interactions

6.1 Stonefruit: general introduction

The gold rush in Central Otago in the mid 19th century led to a recognition of the potential of that district for temperate fruit growing, most particularly stonefruit. As with the establishment of all such practices some areas proved more suitable than others, with Roxburgh and Alexandra establishing as the main centres of fruit production in Central Otago. As can be seen from Table 6.1.1 in the earlier part of this century Central Otago was the principal growing district for all stonefruit in New Zealand, particularly apricots, nectarines and cherries. In latter years North Island districts have come to dominate as the main producers of peaches, nectarines and plums, particularly Auckland and Hawkes Bay. Over the last two decades plantings of cherries have increased in Marlborough to make it the principal growing district for this crop. However Central Otago remains the main producing district for apricots, the continental type climate being well suited for this crop. Neighbouring Waitaki has in recent years become an important area for apricots also.

A summary of important developmental stages and general relations with climate are given for each crop analysed.

There has been no previous empirical analysis of crop-climate interactions for stonefruit in New Zealand and none sourced from overseas, with the exception of almonds (Granger, 1980) which are not grown commercially in New Zealand.

The Orchardist of New Zealand magazine was searched for the years 1963-1982 to give some insight into the frequency, and possible impact of drought, hail, frost, above average rain and at what stages these events may have critical impacts on stonefruit. Results from this search are tabulated and presented in Appendix C for the two principal stonefruit growing districts, Hawkes Bay and Central Otago.

6.2 Peaches and nectarines

6.2.1 Climate relationships and distribution in N.Z.

Peaches and nectarines are temperate fruits and will grow in all parts of New Zealand (Jackson, 1986). However they do best with a hot summer climate and are only moderately winter hardy (Westwood, 1978).

Table 6.1.1
Percentage distribution of stonefruit

District	Apricots	Cherries	Nectarines	Peaches	Plums
(a) Percentage of trees by district (1929)					
Auckland	5	-	24	29	28
Hawkes Bay	3	7	9	18	15
Nelson	8	7	9	6	10
Marlborough	-	1	1	-	-
Canterbury	6	29	10	6	12
Otago	77	55	44	38	30
(b) Percentage area by district (1963)					
Auckland	-	-	13	23	25
Hawkes Bay	6	9	13	41	31
Nelson	-	3	2	8	5
Marlborough	-	20	-	2	1
Canterbury	13	7	8	-	8
Otago	80	61	61	19	28
(c)Percentage area by district (1985)					
Auckland	3	1	20	33	33
Hawkes Bay	13	6	39	37	30
Nelson	3	-	3	3	5
Marlborough	7	55	4	1	-
Canterbury	4	2	8	7	6
Otago	65	34	20	11	18

Floral initiation usually begins in mid summer and continues for several weeks. As mentioned they tend to prefer moderate winters, and their winter chilling requirement is less than that for pipfruit.

Bud burst usually occurs about mid September in New Zealand and is on average three weeks before apples (Jackson, 1986). If early flowering occurs there can be the potential for frost damage. The trees have no tolerance for water logging at any time of the year. However the developing fruit require a regular supply of water, most particularly in the final fruit swell stage. Warm, humid conditions can lead to disease problems particularly with bacterial blast, brown rot and leaf curl. Near to harvest heavy rainfall can lead to cracking of fruit.

The earliest time of ripening is early summer and the harvest usually continues through until March, although the bulk of the crop is usually harvested by the end of February.

Peaches have traditionally been much more extensively grown in New Zealand than nectarines. In 1963 nectarines were grown on a total of 100 hectares compared with 1150 ha of peaches.

At this time the former crop was predominantly grown in Central Otago (61% of total trees), with Hawkes Bay being the main peach growing district (41% of total trees). While the relative distribution of peaches has remained fairly much the same there has been a significant shift in the distribution of nectarines. By 1985 Central Otago accounted for only 20% of the nectarine area with Hawkes Bay now the principal growing area with 37% of the area in 1985. Time series of national yield for peaches and nectarines are given in Figs. 6.2.1 and 6.2.2. It is useful to relate information drawn from the 'Orchardist' magazine with these time series.

In the years that nectarines were a predominantly Central Otago crop it appears that frost posed the greatest climatic risk to national yield. There were particularly damaging frosts in the 1968-1969 season and an even more severe one in the 1970-1971 season. Greater use of overhead sprinklers combined with an increase in plantings of nectarines elsewhere have contributed to a lesser impact of frost on national yield in more recent years. Another possibility is that there have been fewer severe frosts since 1971, which is reinforced by the seasonal summaries. Yields of nectarines haven't been as consistently high since the period of 1963-1968, although in more recent years similar yields have been obtained. This may have been a period of both favourable climate and stable production. Cold, wet conditions at blossom time reduced stonefruit yields in Hawkes Bay in 1974-1975, 1976-1977 and 1977-1978. Such conditions appeared to impact on national yield of peaches in 1975 and 1978 respectively.

From the phenology and empirical evidence the sensitive developmental stages and associated weather phenomena for peaches and nectarines are summarised below :-

1. They are intolerant of waterlogging at all times.

2. They are susceptible to frost, which can occur with early flowering or late frosts.

3. Cold, wet weather at blossom and fruit set is undesirable.

4. They are relatively drought tolerant, but need plenty of water in the final fruit swell stage.

5. Cracking of fruit can be a problem near harvest with too much rainfall.

6. They prefer hot, dry summers, provided that there is adequate moisture for fruit sizing.

Fig. 6.2.1 New Zealand peach yield 1963–1981

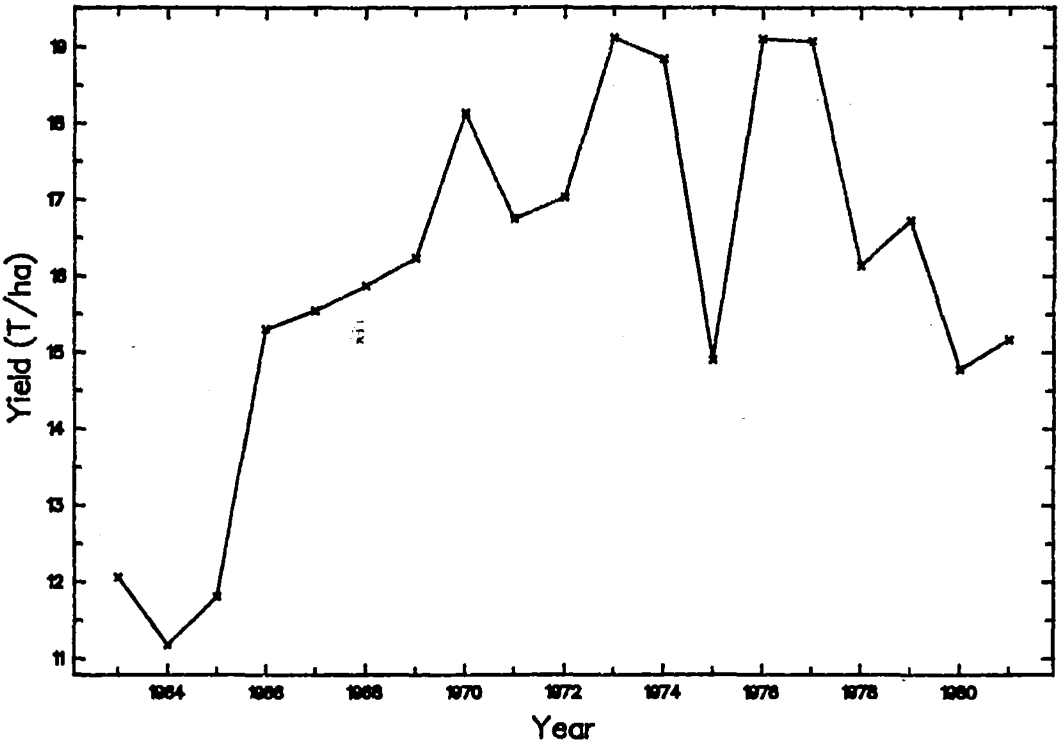
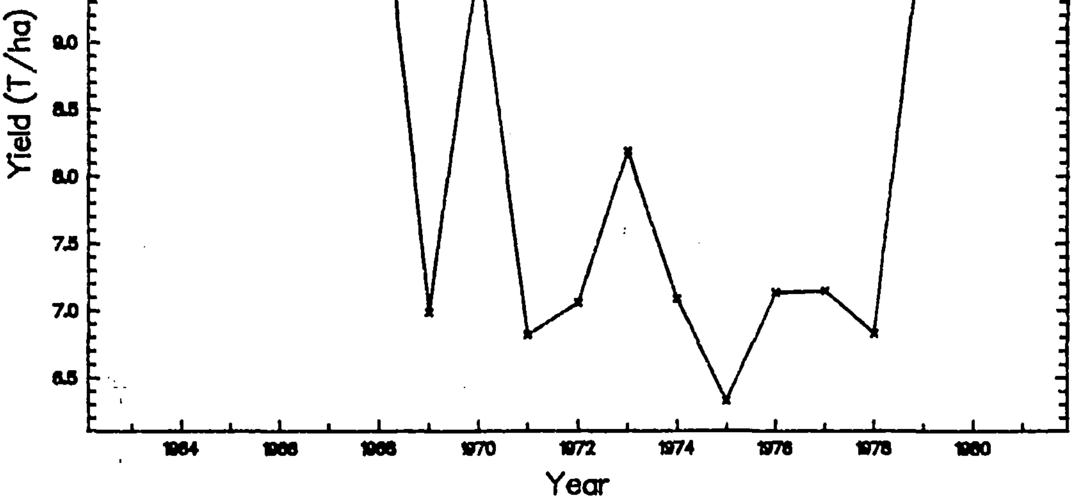


Fig. 6.2.2 New Zealand nectarine yield 1963–1981



6.2.2 Peaches and nectarines: results

Yield data for peaches and nectarines are presented graphically in Figs. 6.2.1 and 6.2.2. Weighting factors used for the climate data for peaches and nectarines are given in Tables 6.2.1a and 6.2.2a respectively. Results from the multiple regression analysis of peaches and nectarines are also presented in Tables 6.2.1 and 6.2.2. First glance of the summary of the results shows that the significant predictors for the two crops differ. This is most probably a result of varying geographical distribution of these crops and hence interactions with different weighted rainfall and temperature data.

Peaches

Using a forward selection stepwise procedure on all monthly values of rainfall and temperature two variables came up as significant predictors of yield. These were July rainfall and April temperature, which together gave an R^2 of 0.70. The result suggests that above average July rainfall is deleterious to yield and that warmer than average April temperatures have a positive effect on yield in the following summer. The result with July rainfall is explainable in terms of the intolerance of peach trees to water logging. Another possibility is insufficient winter chilling with above average rainfall suggesting the possibility of a milder winter although the literature suggests that peaches have a low winter chilling requirement. There is also the possibility of cooler winters resulting from above average rainfall, depending on the prevailing air streams.

Warmer than average April temperatures may be important for the the promotion of photosynthetic activity, and thus assimilation of nutrients, prior to the dormant phase. This would prepare the tree well for the coming spring when active growth begins, and a good reserve could make the difference between a low and high yield.

Application of the backward elimination procedure, to a reduced set of predictors gave some apparent anomalies. July rainfall and April temperature remain significant predictors. Temperatures for all three winter months showed a negative relationship with yield. It is possible that as the trees are only moderately winter hardy colder than average winters could be damaging to dormant buds. The anomalies are September and October rainfall which show a positive relationship with yield, and December temperature which shows a significant negative relationship. Expectations would have been for the reverse. September-October covers the blossom period so that it would be expected that rainfall at this time would be generally undesirable. In early summer warm temperatures would seem necessary for fruit development. There is the possibility that this reflects a moisture sensitive stage, which can be made worse by warmer than average temperatures. It is a time when there is a high potential for the soil to be in moisture deficit, particularly in east coast regions and Central Otago, where production is centred.

Table 6.2.1

(a) Peaches; weighting factors for climate data

District	Weighting
Northland	0.005
Auckland	0.177
Waikato	0.028
Bay of Plenty	0.016
Manawatu/Taranaki 0.002	
Wellington/Wairarapa0.001	
Poverty Bay	0.041
Hawkes Bay	0.539
Nelson	0.052
Marlborough	0.011
Canterbury	0.023
South Canterbury 0.003	
Oamaru/Dunedin	0.002
Central Otago	0.100

(b) Multiple regression model for peaches
(from forward selection and max R^2)
Model R^2=0.70; F=18.65; P>F=0.0001

Variable	B value	F	P>F
Intercept	-3.084		
JUL RAIN	-0.059	24.12	0.0002
APR TEMP	1.640	13.44	0.0021

(c) Multiple regression (backward elimination) model
R^2=0.95; F=24.24; P>F=0.0001

Variable	B value	F	P>F
Intercept	32.021		
JUL RAIN	-0.054	35.19	0.0001
SEP RAIN	0.053	31.54	0.0002
OCT RAIN	0.028	9.88	0.0105
APR TEMP	1.618	37.63	0.0001
JUN TEMP	-0.978	10.65	0.0085
JUL TEMP	-0.844	7.74	0.0194
AUG TEMP	-0.720	5.97	0.0346
DEC TEMP	-1.001	13.10	0.0047

Nectarines

A forward selection regression incorporating all monthly values of rainfall and temperature gave only one significant predictor. That was September rainfall, which showed a negative relationship with yield. With bud burst normally occurring around mid September it seems probable that above average rainfall in this month has a direct effect on blossoming and subsequent fruit set.

The later blossoming of nectarines, compared to apricots, and the reduction in relative significance of Central Otago as a growing district for these crops would explain the absence of any significant relationship with spring temperatures.

Table 6.2.2

(a) Nectarines; weighting factors for climate data

District	Weighting
Auckland	0.096
Waikato	0.020
Bay of Plenty	0.020
Poverty Bay	0.010
Hawkes Bay	0.356
Nelson	0.043
Marlborough	0.016
Canterbury	0.031
Oamaru/Dunedin	0.001
Central Otago	0.407

(b) Forward selection multiple regression model
Model R^2=0.48;

Variable	B value	F	P>F
Intercept	12.381		
SEP RAIN	-0.067	13.78	0.001

(c) Backward elimination multiple regression model
Model R^2=0.68; F=7.54; P>F=0.0019

Variable	B value	F	P>F
Intercept	12.812		
JUN RAIN	-0.030	7.51	0.0159
JUL RAIN	0.048	6.30	0.0250
SEP RAIN	-0.056	11.71	0.0041
OCT RAIN	-0.036	5.25	0.0380

Application of a backward elimination procedure to a reduced number of predictors gave four significant predictors. A negative relationship with October rainfall is consistent with the relationship with September rainfall, and the evidence which suggests that wet springs affect blossom and fruit set. The other two significant predictors appear anomalous. While a negative relationship with June rainfall is consistent with the result for peaches, it is directly contrasted with a positive relationship with July rainfall. The only possibility, if it is a true effect is the greater bias of the weighted climate data towards Central Otago. Central Otago winters are cold and dry by Hawkes Bay standards. So a positive anomaly with July rainfall may provide much needed soil moisture for the following spring. Too much rain earlier in winter may increase the risk of freezing injury wheras later, when the plants may be more cold hardy, it may boost soil moisture for the following spring. One or the other, or both, may be a "black box" statistic.

6.3 Apricots

6.3.1 Climate relationships and distribution in N.Z.

Apricots are temperate fruits with a preference for a mediterranean or continental climate (Jackson, 1986). Floral initiation occurs in late summer, and where conditions are warm and moist initiation is poor. They generally require less winter chilling than the peach but following warm winters in California can be subject to bud drop (Westwood, 1978). The buds swell and deharden early, making them susceptible to late frosts. Frost free sites are an advantage. In New Zealand the time of bud burst is from mid to late August to early September. Dry conditions are preferred at blossom time (Jackson, 1986). It appears that adequate moisture is required for fruit sizing, but warm, dry conditions are preferred close to harvest. Rain at this time can lead to fruit cracking, and brown rot is a problem with warm, moist conditions. The fruit generally reach maturity from mid December to mid January.

Apricots have a long history as a major crop in Central Otago, probably dating from the mid to late 19^{th} century. Table 6.3.1a shows the average district weightings over the period of analysis, clearly demonstrating the dominance of Central Otago. This has lessened somewhat in recent years, with expansion of production into the neighbouring Waitaki Valley. The time series of national yield is shown in Fig. 6.3.1.

The most dramatic feature of this time series is the very low yield in 1971. This is attributable to the snow storm on 23 September 1970 and following freezing conditions, as summarised in Appendix C. Apart from susceptibility to frost, cold, wet weather at blossom and fruit set and rain over the harvest period have led to reduced yields of apricots in Central Otago.

From all sources of information a summary of sensitive stages and associated weather conditions is given below for apricots:-

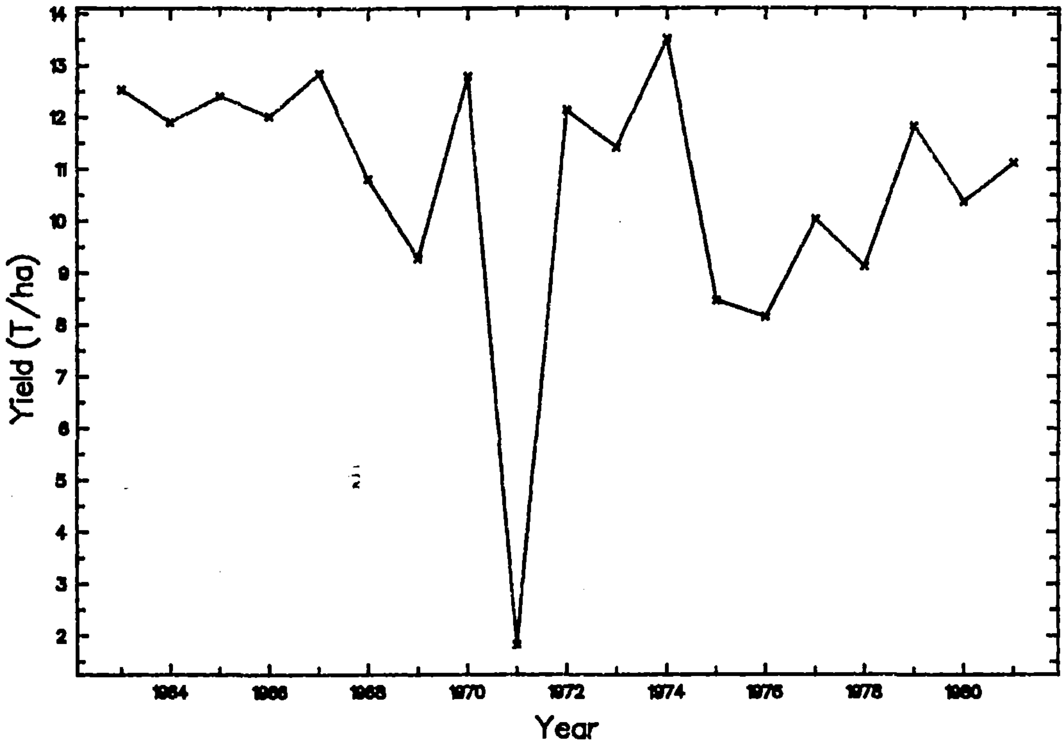
1. They are susceptible to early spring frosts.

2. Cool, wet conditions can adversely affect blossom and fruit set.

3. An adequate moisture supply is required for fruit sizing.

4. Rain close to maturation can cause fruit cracking and lead to brown rot problems.

Fig. 6.3.1 New Zealand apricot yield 1963–1981



6.3.2 Apricots: results

Results are presented in Table 6.3.1

The most significant predictor from the forward selection of all monthly values of rainfall and temperature was November rainfall, which gave a positive relationship with yield. The next most significant predictor was August temperature which was negatively related to yield. This result was repeated using a maximum R^2 procedure. An F=2 model is also included for discussion. This incorporated the above two predictors as well as showing negative relationships with April and August rainfall and a positive relationship with May temperature.

It is possible that rainfall in November is beneficial to early fruit development, although prolonged periods of wet, cool weather can delay fruit maturation. This is more likely to be a problem if such conditions are persistent over the summer months. With increased use of overhead sprinklers for frost protection and irrigation, moisture deficits may cease to be a problem. In fact in Central Otago where overhead sprinklers are widely used for frost protection, waterlogging of soils has become a limiting factor in more recent years (R. Rowe, pers. comm.).

Warm temperatures in August may stimulate earlier breaking of dormany, increasing the risk of frost damage. Following this rationale cooler temperatures would tend to prolong the dormant period, delay flowering and thus reduce the risk of frost damage. A weaker negative relationship with August rainfall is possibly connected to this temperature interaction. Wetter conditions may have a moderating effect on temperature, encouraging early bud break and increasing the risk of damage from late frosts.

There is no apparent explanation of the relationship with April rain and May temperature in the literature. At this time soil temperatures are dropping rapidly in Central Otago, as Table 6.3.2 shows.

Table 6.3.1

(a) Apricots: weighting factors for climate data

District	Weighting
Poverty Bay	0.004
Hawkes Bay	0.069
Nelson	0.004
Marlborough	0.006
Canterbury	0.038
Oamaru/Dunedin	0.061
Central Otago	0.818

(b) Forward selection and Max R, F=4, model
R^2=0.35; F=4.40; P>F=0.030

Variable	B value	F	P>F
Intercept	15.682		
NOV RAIN	0.089	5.34	0.0346
AUG TEMP	-1.250	4.25	0.0558

(c) Forward selection, F=2, model
R^2=0.68; F=5.52; P>F=0.0061

Variable	B value	F	P>F
Intercept	4.162		
APR RAIN	-0.081	5.45	0.0363
AUG RAIN	-0.062	3.89	0.0702
NOV RAIN	0.122	12.03	0.0042
MAY TEMP	2.079	11.78	0.0045
AUG TEMP	-1.229	5.86	0.0309

Table 6.3.2 Average ground temperature (10cm) at Alexandra

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp.	16.4	15.4	13.2	9.0	4.8	1.9	1.3	2.6	5.9	9.7	13.0	15.6

At a time when temperatures are generally falling rainfall would tend to have an overall cooling effect. Soil heat capacity and conductivity would be increased with more rainfall, but more latent energy exchange would be required for soil warming to occur. Any acceleration of the drop in soil temperature would then have a net effect in reducing active photosynthesis and promoting the onset of dormancy. This would reduce the potential store of nutrients for the dormant phase and the following spring when active growth begins again. The end result could be reduced yields as the tree would have to work harder to satisfy the demands of the developing crop. A positive association with May temperatures may be related to the risk of early winter frost damage. It has been pointed out (R. Rowe, pers. comm.) that Central Otago fruit growers often employ frost protection at this time in the belief that early winter frosts can damage plant tissues which can lead to problems with disease in the following spring.

Although not presented in Table 6.3.1 results from a preliminary investigation using a backward elimination procedure gave a positive association between September and October temperatures and yield. This is the period when frosts can be particularly damaging so such a relationship is not surprising. Warm temperatures at this time would also encourage bee activity for pollination, raise soil temperatures more quickly and thus boost photosynthetic activity. A negative association with January temperatures, from this same analysis, defies explanation as this is the time when warm, dry conditions are generally desirable for fruit maturation.

6.4 Cherries

6.4.1 Climate relationships and distribution in N.Z.

Cherries fruit well in cooler climates than are tolerated by peaches or apricots (Westwood, 1978). In general the most desirable climate is one with good winter rains followed by dry, cool summers. Cherries are not successful in warm, humid areas.

Floral initiation usually occurs after cropping, in January. Cherries need more winter chilling than peaches or nectarines, so require fairly cold winters. Bud burst is the latest of the stonefruit, in late September to mid October. At blossom time rain can be a problem, affecting fruit set and increasing the chances of disease. Lack of water is generally not a problem as cropping is usually over by the beginning of summer. Rain close to, and at harvest is highly undesirable as spoiling of fruit can result.

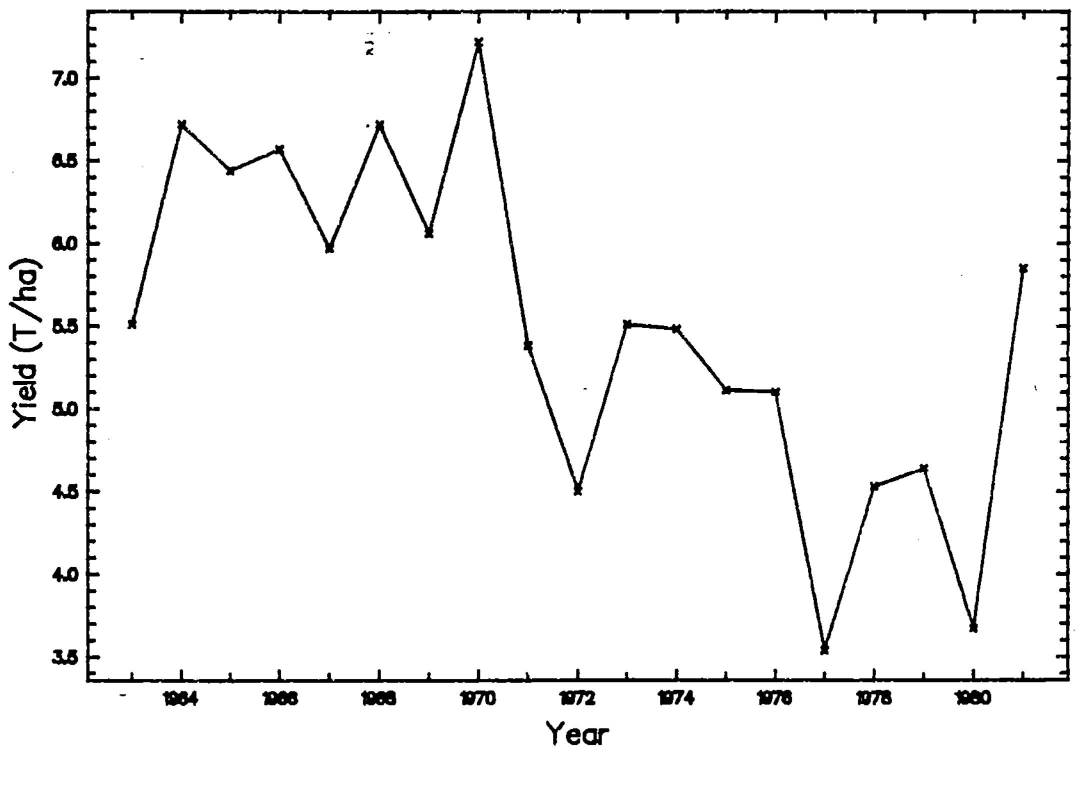
With their winter chilling requirement and the desirability of relatively low rainfall, particularly in spring and summer, cherries are predominantly grown in Central Otago and Marlborough and to a lesser degree in Canterbury and Hawkes Bay. The latter district would be approaching the limits in terms of suitable climate. Weighting values are given in Table 6.4.1a and show the dominance of Marlborough and Central Otago. Searching the Orchardist of New Zealand gave the general impression that cold, wet weather at blossom time and rain at harvest are the principal climatic factors limiting to yield of cherries in New Zealand. The time series of yield is shown in Fig. 6.4.1. Reduced yield apparently resulting from wet blossom or harvest conditions have occurred in the 1968-1969, 1971-1972, 1976-1977 and 1979-1980 growing seasons. Important climatic factors limiting to production are summarised as follows :-

1. Insufficient winter chilling

2. Rainfall at blossom time (late September to mid October)

3. Rainfall near to or at harvest

Fig. 6.4.1 New Zealand cherry yield 1963–1981



6.4.2 Cherries: results

Initial analysis was carried out using all monthly values of rainfall and temperature in a forward selection procedure. Only two predictors were significant at the 5% level, as shown by the result in Table 6.4.1b. These were October rainfall and December rainfall which both gave a negative relationship with yield. October rainfall on its own accounted for 37% of the variance. Analysis with other multiple regression procedures, gave the same result. The consistency of the result suggests that it has some validity. This is reinforced by making reference to section 6.4.1. Rainfall at blossom time and at harvest both came through as potentially strongly limiting to yield in New Zealand. This is quite an encouraging result.

Table 6.4.1

(a) Cherries; weighting factors for climate data

District	Weighting
Waikato	0.003
Poverty Bay	0.004
Hawkes Bay	0.081
Nelson	0.011
Marlborough	0.400
Canterbury	0.026
Oamaru/Dunedin	0.063
Central Otago	0.412

(b) Forward selection and backward elimination, F=4, model
R^2=0.58; F=11.25; P>F=0.0009

Variable	B value	F	P>F
Intercept	7.593		
OCT RAIN	-0.024	12.64	0.0026
DEC RAIN	-0.021	8.19	0.0133

(c) F=2 model
R^2=0.73; F=9.66; P>F=0.0006

Variable	B value	F	P>F
Intercept	12.490		
AUG RAIN	-0.012	3.28	0.0915
OCT RAIN	-0.020	11.05	0.0050
DEC RAIN	-0.023	12.68	0.0031
APR TEMP	-0.349	4.07	0.0634

A look at predictors that are at least 10% significant gives two additional predictors and an R^2=0.73. These are August rainfall and April temperatures, both negatively related to yield. This result was repeated using several different regression procedures and again suggests some biological connection. However this result is treated with more caution because of its lower statistical significance and the lack of supporting evidence from the literature. With cropping finished, usually by early January, cherry trees have ample time to recover and build reserves before the dormant phase, for the next spring. A negative relationship with April temperatures suggests that by this time the tree may have built up sufficient reserves and be ready to enter the dormant phase. This would be most likely to occur in this month in Central Otago, where temperatures at this time are colder than any other cherry growing district. With cherries having a higher chilling requirement than peaches, winter chilling may possibly be a problem in warmer districts such as Marlborough and Hawkes Bay. The chilling period may be longer in these districts to satisfy the chilling requirement. A negative relationship with April temperatures may relate to years when this requirement is satisfied to a greater degree and conversely relate to years when warmer then average Aprils effectively shorten the chilling period, particularly if followed by mild winters.

There is no immediately apparent explanation for a negative relationship with August rainfall. One possibility is a moderating effect on temperature, before the chilling requirement has been fully met. There is no significant correlation between rainfall and temperature for this month, with the weighted data set, which tends to negate this as a possibility. If anything a positive relationship might have been expected, with above average rainfall at this time providing a boost to soil moisture prior to the spring growth flush.

6.5 Plums

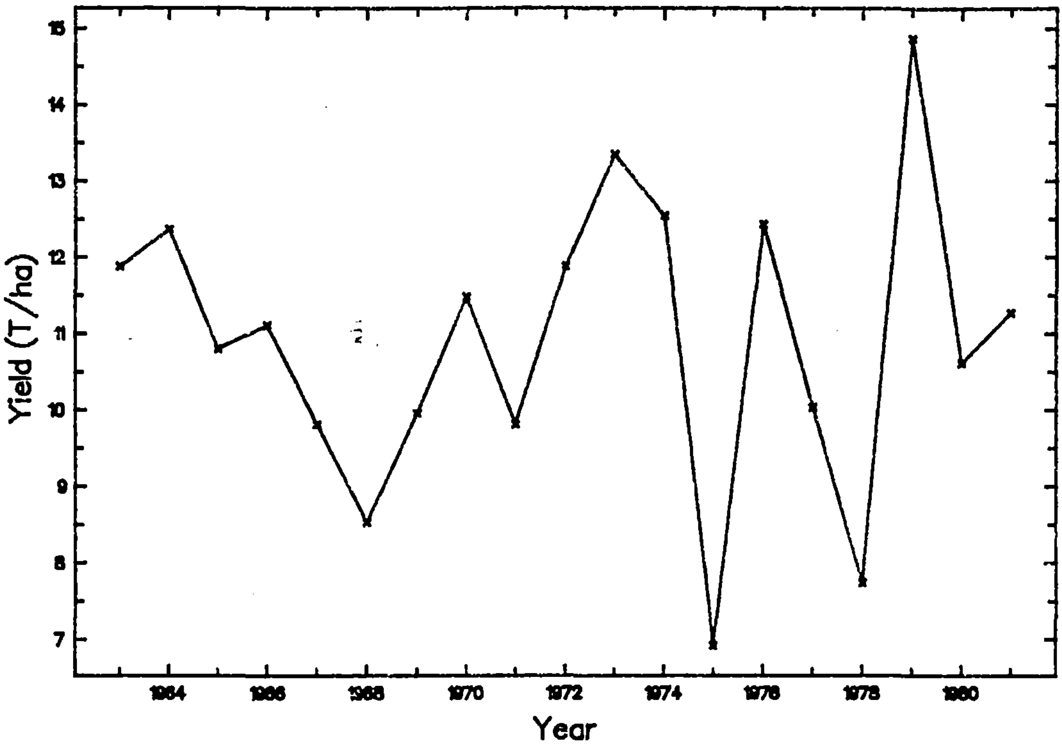
6.5.1 Climate relationships and distribution in N.Z.

There are two main species of plum that are grown commercially. These are European and Japanese plums. In New Zealand Japanese plums are predominantly grown, and are grown in all districts. European plums are generally not grown in the warmer districts of New Zealand, the main area of production for these being Central Otago. Unfortunately the yield data available is for all plums combined, so it is not possible to look at these two species separately. However with Japanese plums being by far the dominant crop the results can be taken as more of a reflection of relationships with this species. The North Island is the main centre of production, accounting for 70% of the crop on average, over the period of record. Hawkes Bay is the principal growing district, followed by Auckland and Central Otago. This is shown by the weighting factors in Table 6.5.1a.

In general warm, dry climates are the most suitable for plum production (Westwood, 1978). Flower initiation usually occurs in late summer. The two species have different winter chilling requirements. Japanese plums have a lower requirement for winter chilling than European plums. This accounts for the differing geographical distribution in New Zealand, and in particular the concentration of European plums in Central Otago. Most Japanese plum varieties flower in early September in New Zealand, which can make them subject to spring frosts. Other varieties, plus the majority of the European varieties flower in mid to late September (Jackson, 1986). Maturity is usually reached in the months of December to January. In humid conditions brown rot can be a problem, particularly at blossom and maturity. This is most likely to occur in Auckland and other warmer, wetter parts of New Zealand.

The Orchardist of New Zealand didn't yield a lot of direct references to plums. However there were enough such references, combined with general information on stonefruit to deduce some possible climatic causes of lower than average yields. The severe frost in Central Otago in the 1970-1971 season is a possible cause of low yield in that year, although without district yield data this cannot be verified. Two other low yielding years can be attributed to cold, wet spring conditions having significant impacts on fruit set. These are the seasons 1974-1975 and 1977-1978 and correspond to yield depressions in the time series of plum yield shown in Fig. 6.5.1.

Fig. 6.5.1 New Zealand plum yield 1963–1981



6.5.2 Plums: results

The only significant predictor using the forward selection procedure was May temperature which was positively related to yield. Application of the backward elimination procedure to a reduced number of variables gave all as being significant, until it was reduced to about five variables, by selection of the most significant, from which May temperature emerged as the only significant predictor.

Application of stricter selection criteria to a model beginning with ten predictors gave significant five and six predictor models. Very similar results were achieved using a maximum R^2 procedure. Results of these analyses are presented in Table 6.5.1.

The result with May temperature is more significant than any other, but has no apparent explanation. The data is biased towards Japanese plums which have a lower chilling requirement. Without knowing the average time of autumn leaf fall in each of the three main districts it is difficult to know whether this result might relate to winter storage, photosynthetic activity, or susceptibility to early frost. The autumn transition is earlier and more pronounced in Central Otago. However the climate data is weighted more towards the warm temperate areas of Hawkes

Table 6.5.1

(a) Plums; weighting factors for climate data

District	Weighting
Northland	0.002
Auckland	0.210
Waikato	0.016
Bay of Plenty	0.008
Manawatu/Taranaki	0.003
Wairarapa	0.001
Poverty Bay	0.012
Hawkes Bay	0.447
Nelson	0.031
Marlborough	0.014
Canterbury	0.039
South Canterbury	0.001
Oamaru/Dunedin	0.002
Central Otago	0.216

(b) All methods, F=4, model
R^2=0.22

Variable	B value	F	P>F
Intercept	-0.208		
MAY TEMP	1.001	4.69	0.0448

c) Max R^2, 6 variable, F=4, model
R^2=0.79; F=7.73; P>F=0.0014

Variable	B value	F	P>F
Intercept	-17.370		
JAN RAIN	-0.049	17.56	0.0013
APR RAIN	-0.084	28.44	0.0002
NOV RAIN	-0.059	15.07	0.0022
APR TEMP	2.349	20.99	0.0006
MAY TEMP	2.169	32.45	0.0001
NOV TEMP	-1.152	8.65	0.0123

Bay and Auckland, so that late autumn photosynthetic activity is not improbable, although likely to be minimal. Both of these explanations are highly speculative.

The favourability of a warm autumn is reinforced by a positive relationship with April temperature. In this month there is a greater chance of enhanced photosynthetic activity, which would be favourable to yield in the following growing season. A negative relationship with April rainfall suggests that above average rainfall at this time may have a negative feedback effect, possibly lowering soil temperatures, reducing soil aeration and thus slowing down metabolic activity. A negative relationship with August temperature is possibly connected to the early flowering habit of Japanese plums. Cooler August temperatures could delay flowering and reduce susceptibilty to late frost. A negative relationship with November rainfall and temperature in the six variable model is plausible if warm, humid conditions occur relativley frequently at this time, which is close to maturity. As mentioned in the brief review such conditions can lead to problems with brown rot. According to Westwood (1978) brown rot is mostly a mature fruit problem with Japanese plums. Conditions conducive to this disease are most likely to prevail in the Auckland district, of the three principal growing districts. A negative relationship with January rainfall may have a similar explanation, as well as perhaps generally interfering with harvesting of the crop.

6.6 Stonefruit: summary

The lack of analysis at the district level proved to be a major limitation in the interpretation of the results with stonefruit. The shortness of the time series also precluded any statistical verification as carried out with the grain crops. Despite these obvious limitations and some apparently anomalous results, overall it was a relatively encouraging exercise. The information drawn from the "Orchardist" magazine reinforced that drawn from the reviews of Westwood (1978) and Jackson (1986).

While it was not always easy to deduce biological connections in the analyses, knowledge of crop distribution facilitated the process. Differences in distribution gives a probable explanation for the different relationships for peaches and nectarines, although some, such as the anomalous results identified for peaches, are beyond reasonable explanation. However the statistical significance of the F=4 predictors for both crops gives some encouragement, despite the obvious criticism that they are only black box statistics. Analysis of district data would provide some form of verification for these results.

The concentration of apricots in Central Otago provided some hope for a good result with this crop, but in the context of other results was not as good as expected. The negative relationship with August temperature did suggest a connection with susceptibility to late winter or early spring frosts. From the literature this is a dominant limiting factor to apricot yield.

The most easily explainable result was that with cherries. The two most significant predictors of yield were October and December rainfall. Negative relationships with both highlighted the susceptibility of this crop to rainfall damage at blossom and harvest time. Such conditions can be a problem in both Marlborough and Central Otago, the two principal cherry growing districts.

Plums gave the least satisfactory result, with the relationship with May temperature. However further analysis revealed some relationships with possible biological connections. Autumn temperatures are apparently favourable to yield. Cool, dry conditions appear to be preferred close to the beginning of the harvest period, near Christmas. Rainfall later in the harvest period, in January, also appears to be detrimental.

In summary the results with stonefruit offer some encouragement. More detailed analysis is required. This should preferably be done with both district data and longer time series. The former is more attainable than the latter.

6.7 Pipfruit: general introduction

Pipfruit, in particular apples, were the principal fruit crop grown in New Zealand until the development of the kiwifruit industry in the 1970s. They still remain, along with kiwifruit a major export earner.

Apples and pears, along with other temperate fruits were introduced with the European settlers in the early 19th century. The N.Z. fruit growing industry was not formally established until the early 20th century. However it is probable that apples and pears were widely distributed around the country by the early settlers. Canterbury was one of the first districts to organise its apple growing activities, being the first to export fruit, to Chile in 1888 and the U.K. in the 1890s. The potential of Hawkes Bay as an apple growing region was recognised in the 1890s. In Central Otago apple orchards were probably established in the wake of the gold rush in the mid to late 19th century. The other principal apple growing regions of Auckland and Nelson became more established in the early 20th century. In Auckand an influx of Yugoslavs boosted fruit growing. In Nelson development began in earnest in 1911 under a "grow apples for export" slogan. As can be seen in Table 6.7.1 Nelson quickly established as the principal apple growing region, largely as a result of this entrepreneurial endeavour. It remained the principal growing district until the mid 1970s when Hawkes Bay progressively began to dominate as an apple growing district. These two districts collectively account for 70% of the total area of apples and 65% of pears at present.

6.8 Apples

6.8.1 Apple-climate relationships

The domestic apple is one of the hardiest, and consequently one of the most widely grown of the temperate zone fruits (Westwood, 1978). He states that the great genetic diversity of the apple makes it difficult to make general statements about specific climatic requirements. However it is possible to make some general comments about general climatic requirements at different developmental stages of the fruit.

Floral initiation occurs in the early summer for the next years crop. A warm autumn generally favours the production of fruit buds (Landsberg, 1977) until the onset of dormancy.

Table 6.7.1

Distribution of pipfruit in New Zealand

District	Percentage trees 1929	Percentage area 1963	1985
	(a) Apples		
Auckland	18	15	12
Hawkes Bay	11	18	39
Nelson	38	42	29
Marlborough	3	5	3
Canterbury	11	8	5
Otago	14	9	6
	(b) Pears		
Auckland	17	7	14
Hawkes Bay	27	36	43
Nelson	28	34	22
Marlborough	1	1	-
Canterbury	10	7	4
Otago	14	12	9

Generally apples need a cool winter, to satisfy the winter chilling requirements of the dormant buds. Extended flowering normally results where winters are mild (Jackson, 1986). Temperature is considered to be the most important weather factor in winter and spring (Landsberg, 1979). It governs the breaking of dormancy and subsequently influences the rate of bud growth to full bloom. For successful pollination warmer temperatures and absence of wind and rain are considered crucial by Landsberg (1977). Hot dry conditions at fruit set can increase fruit drop, but low temperatures can delay fruit development (Landsberg, 1979). Lack of water through the fruit development period can reduce the crop, particularly in its effect on fruit size.

Two related studies carried out in England revealed some interesting crop-climate interactions. Beattie and Folley (1978) examined long term variations in the English apple crop. Their regression analysis showed a significant negative relationship between mean maximum temperatures in the pre-blossom period, and yield. They postulated that hormonal confusion may result from warmer winters with the trees needing a decisive dormancy break between winter and spring. The other possibility they proposed was that warmer winters may lead to a greater risk of frost damage, but they could find no association between the two. For some cultivars they also found a positive relationship between early summer temperature and yield. Jackson and Hamer (1980) and Jackson et al (1983) carried the analysis further using dates of full bloom. They considered that high pre blossom temperatures adversely affected yield through adverse effects on flower quality and fruit setting potential. High yields were associated with high temperatures immediately after full bloom, which are considered favourable for rapid completion of pollen tube growth.

6.8.2 Apples in New Zealand

In New Zealand bud burst normally occurs in mid to late September with the main flowering period around mid October. The crop reaches maturity from January through to April-May, depending on the cultivar (Jackson, 1986).

John Wilton (pers. comm.), MAF deciduous fruit expert, has reviewed what he considers to be the principal climatic factors limiting to production of apples. These are summarised below.

Frosts below -3.5°C in late September can be damaging, this is 2-4 weeks prior to blossom. At blossom, around mid October, frosts below -2°C can be damaging and from the end of October onwards, frosts below -1°C can be damaging. Hail storms can be damaging to the crop at any time from blossom to harvest. All of the principal growing districts have suffered hail damage at some time or another, with some particularly extensive and severe ones in Hawkes Bay and Nelson. The latter district was classified as a climatic disaster area as a result of hail damage in 1977 (Appendix C).

Prolonged periods of wet weather can favour the development of Black Spot and Glomerella. Fruit russet problems appear to be in part related to heavy rain in the post blossom period. It was concluded that rainfall in the October-December and February-April periods in excess of 250 mm could be damaging to yield. Over the first period this is critical for fruit finish and disease, in the latter for harvest and internal quality. In the former it is considered desirable for this rain to fall on less than 12 days per month. In the latter period it is desirable for the rain to fall on less than 10 days per month. In April to May less than 200 mm on less than 25 days is critical for tree health.

Temperatures in New Zealand fall within the desired range for apples. Temperatures over the 6 weeks after bloom (cell division period) are possibly critical to ultimate fruit size. Fruit size is generally lower in Central Otago which may be temperature related. Daily maximums greater than 32°C near to harvest can cause sunburn problems. Cool night temperatures prior to harvest are important for colour, particularly with the red varieties.

In New Zealand Maunder (1965) used seasonal rainfall, temperature and sunshine data to examine apple yield/tree relationships with climate. Apple yield data used were mean yields over all varieties.

From his multiple regression he considered the following climatic factors to have significant positive influences on yield per tree :-

1. A dry autumn.
2. A dry, warm, cloudy winter
3. A dry, cloudy spring
4. A wet, warm summer

Some of these appear to be inconsistent with the literature, although district responses can vary. However warm winters appear to be undesirable as shown by the research in England. Wet, warm summers may potentially promote disease and as Wilton (pers. comm.) noted rainfall in excess of 250 mm over the summer period could be damaging to yield. Maunder (1965) acknowledged the relatively incomplete nature of his analysis and also the limitations of the data base. Perhaps part of his lack of succes could be attributed to the use of seasonal climate data in the analysis. The quality and availability of the data hasn't improved significantly since Maunders (1965) study. It was also recognised that extreme short term events such as frost, hail and storms can have significant effects on yield although no assessment was made of this.

A review of the "Orchardist" magazine for the two principal growing districts, Hawkes Bay and Nelson, (Appendix C), highlights the potential impact of short term extremes. Hail appears to be more of a problem in Nelson, most dramatically in the 1976-1977 season. Drought also appears to be a recurrent phenomenon in Nelson. Cold, wet springs can adversely affect yield in both districts. Both are subject to non-periodic storms which have resulted in yield losses.

Figure 6.8.1 shows the time series of yield per tree from 1941-1981. A strong year to year fluctuation is evident, demonstrating the biennial bearing behaviour of apples. The 1963-1973 period is particularly consistent with this. It is much less apparent since then as seen in Figs. 6.8.2 and 6.8.3. This is perhaps in part related to increased use of varieties that are less strongly biennial bearing and improved management such as more effective thinning in heavy cropping years. The important question is, is this year to year fluctuation soley a reflection of biennial bearing characteristics, or at least in part related to climate. Beattie and Folley (1978) added a biennial bearing factor to their model as a first-order then a second-order lag. Neither proved significant and were dropped from their final model. No such factor was incorporated in the analysis presented here. Empirical evidence drawn from the Orchardist magazine shows some strong climatic relationships over the 1963-1981 period. Wet springs appear to be related to low yielding years in at least two years (1963, 1977), with drought conditions over summer also a problem at times in Nelson. The greater use of irrigation has probably reduced the impact of drought in more recent years, although drought affected some Nelson orchards as recently as the 1980-1981 season. In other low yielding years extreme events such as hail, gales, frosts and persistent wet periods all appear to have contributed to low yields.

Fig. 6.8.1 New Zealand apple yield (kg/tree) 1941–1981

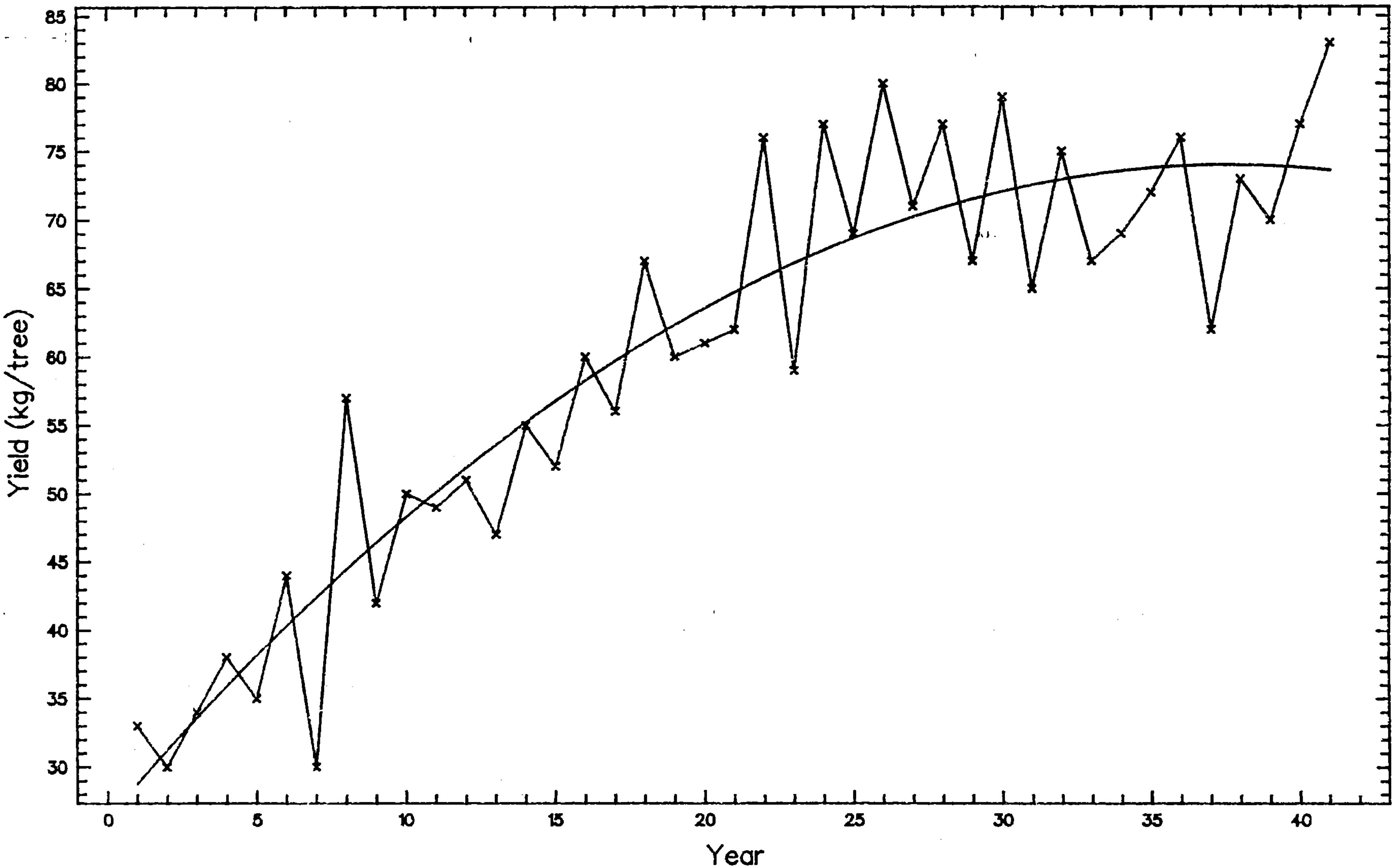


Fig. 6.8.2 New Zealand apple yield (kg/tree) 1963–1981

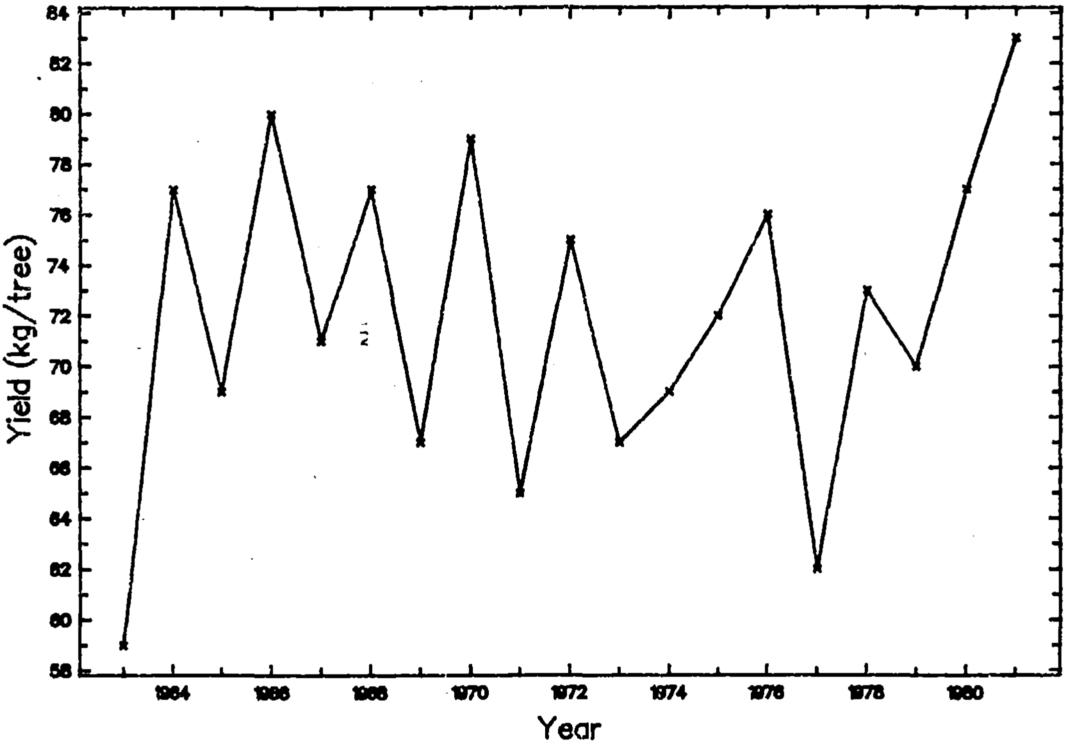
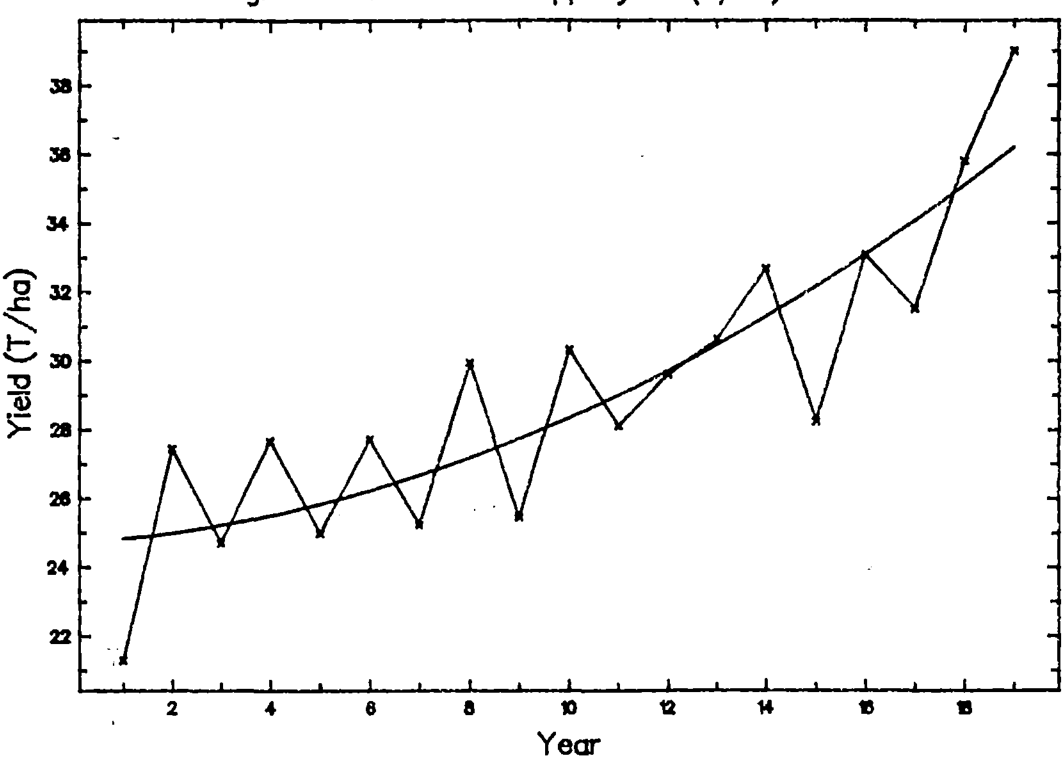


Fig. 6.8.3 New Zealand apple yield (T/ha) 1963–1981



6.8.3 Apples: results

Initially an analysis of yield per hectare was carried out for the 1963-1981 period, using weighted temperature and rainfall data. Weighting factors are presented in Table 6.8.1. Similar weightings were given to Nelson and Hawkes Bay districts. It should be noted that over this period there has been a relative decline in area in production in Nelson and a relative increase in Hawkes Bay. There was an obvious trend in yield per hectare which was accounted for by the fitting of a quadratic trend line, as shown in Fig. 6.8.3. Analysis was carried out on the residuals. It is of value to compare yield per tree for the same period, Fig. 6.8.2, which shows no trend. Yield per tree has remained relatively unchanged whereas yield per hectare has shown a steady increase. This is attributed to the move to more intensive plantings that has taken place over this time, which have obviously optimised use of the photosynthetic resource without being detrimental to yield per tree. There is also a possible effect of an increased proportion of young trees over recent years, which has resulted from a period of relatively constant orchard expansion and the move to higher density plantings (Wilton, pers. comm.). This second data set provided a unique opportunity to test the accuracy of the trend removal procedure. The fitting of trend lines is a bit of a grey area in crop-climate multiple regression analyses. Normally there have been a range of factors contributing to trend which are not easy to quantify or assess in terms of their relative contribution to trend.

Table 6.8.1

Apples; weighting factors for climate data

District	Weighting 1941-1965	1963-1981
Northland	0.00	0.004
Auckland	0.13	0.108
Waikato	0.02	0.038
Bay of Plenty	0.00	0.015
Manawatu/Taranaki	0.01	0.011
Wellington/Wairarapa	0.01	0.008
Poverty Bay	0.01	0.013
Hawkes Bay	0.16	0.267
Nelson	0.41	0.353
Marlborough	0.04	0.034
Canterbury	0.08	0.053
South Canterbury	0.01	0.008
Oamaru/Dunedin	0.01	0.004
Central Otago	0.10	0.084

The results for the analysis of these data are presented in Table 6.8.2. A four predictor model is given. Both selected the same four predictors and had similar R^2 values. All predictors except for February rain in the apple/tree model were at least 5% significant and all conformed to the F=4 criteria. July temperature came through as the strongest predictor with both, showing a negative relationship with yield. This suggests that this may be an important month in the winter chilling of apples, which could lead to poor bud break. Another possibilty is that warmer temperatures at this time may lead to the adverse effects on flower quality as suggested by the English research. If this is so then this is possibly a Southern Hemisphere verification of their result.

Table 6.8.2

Apples (1963-1981) regression model (F=4) max R procedure

Variable	B value	F	P>F
	(a) Apples/tree (no trend) R^2=0.64; F=6.32; p=0.004		
Intercept	119.315		
FEB RAIN	-0.092	4.47	0.0530
MAR RAIN	0.074	8.37	0.0118
JUN RAIN	0.100	6.80	0.0207
JUL TEMP	-7.165	18.76	0.0007
	(b) Apples/ha (trend removal) R^2=0.65; F=6.48; p=0.0036		
Intercept	16.458		
FEB RAIN	-0.037	6.73	0.0212
MAR RAIN	0.019	5.40	0.0357
JUN RAIN	0.032	6.54	0.0228
JUL TEMP	-2.364	19.27	0.0006

The other three predictors have less obvious explanations. A positive relationship with June rainfall may be indicative of a need for sufficient winter rainfall to maintain soil moisture levels for the following spring and the active growing period. Wilton (pers. comm.) suggested that June rainfall may generally have a cooling effect, leading to more winter chilling than might otherwise be experienced in a drier June.

The negative relationship with February rain and positive relationship with March rain is interesting in light of Wilton's (pers. comm.) observations. As mentioned earlier, he considered a February to April rainfall in excess of 250 mm to be damaging to internal quality, and interfering with the harvest. This could in part explain the negative relationship with February rainfall. Another possible explanation is that rainfall at this time could tend to promote vegetative growth at the expense of fruit development (Wilton, pers. comm.).

If the summer has been relatively dry then March rainfall could be of some benefit to mid and late season varieties. This pattern has been documented for at least one year, 1981, in Nelson. Examination of the rainfall data for Appleby (Nelson) and Napier (Hawkes Bay), and the national weighted set, showed on average five years out of nineteen with below average summer rainfall

(Dec-Feb) followed by a wetter than average March. For the weighted rainfall data four out of five of these years had positive yield anomalies. Nelson and Hawkes Bay each showed three years in which a positive national yield anomaly was associated with a drier than average summer period and a wetter than average March. There is at least a tendency towards higher yields following such a rainfall sequence, which makes such a hypothesis at least plausible.

Analysis of yield per tree data for the 1941-1965 period allowed for evaluation of regional interactions with climate. Contrary to the 1963-1981 period there was an upward trend in yield per tree over this earlier period. This can be related to a time of improving management, improved varieties, changes in rootstocks and perhaps more effective control of pests and diseases. A linear trend proved satisfactory for both the national yield data and the five main districts that were examined; Auckland, Hawkes Bay, Nelson, Canterbury and Central Otago. Analysis was carried out on the residuals. Table 6.8.3 provides a summary of the five predictor models for New Zealand and these five districts. Although not all fit the F=4 statistical selection criterion they are included for the sake of comparison.

Contrary to the result for the 1963-1981 period, a negative relationship with March rainfall showed up in the national yield relationship. One or the other may be an anomaly, or related to the different average proportional distribution of apples over the two periods and thus different weighting factors. Climate data for the earlier period was weighted more to Nelson. Another possiblity is that in different years the rainfall response has varied. A wet March following a wet summer may have detrimental effects on yield, whereas after a dry summer the effect may be the opposite. The former scenario may have been a more dominant pattern over this earlier period. This hypothesis is supported by a negative relationship between March rainfall and yield in Auckland and a positive relationship in Central Otago. The former district has the highest rainfall of the five main districts, as seen from Table 6.8.4, and is more likely to have rainfall in excess to requirements. The latter is more likely to be in deficit so that rainfall in March, particularly after a dry summer could be very beneficial.

Close examination of the results shows that in all districts rain in the October to November period is detrimental to yield. This time corresponds to blossom and early fruit development. After this time it appears that lack of summer and autumn rainfall is limiting in South Island districts, most obviously in Central Otago. In Auckland and Hawkes Bay December rainfall is negatively related to yield.

Hawkes Bay, although drier on average than Nelson, generally had more orchards under irrigation over this earlier period. In Nelson district the Moutere hills in particular have a history of being prone to summer drought. With ample rainfall and more irrigation in Hawkes Bay it appears plausible that rainfall would tend to have been more in excess to requirements in Auckland and Hawkes Bay than in the less well irrigated Nelson district.

Table 6.8.3

N.Z. and district apple yield models (1941-1965); maxR procedure

Variable	B value	F	P>F
	(a) New Zealand R^2=0.607; F=5.87; P>F=0.0019		
Intercept	-5.272		
MAR RAIN	-0.005	8.89	0.0077
DEC RAIN	-0.007	15.93	0.0008
NOV TEMP	0.328	5.42	0.0311
FEB TEMP	-0.173	11.69	0.0029
MAR TEMP	0.275	17.85	0.0005
	(b) Auckland R^2=0.662; F=7.44; P>F=0.0005		
Intercept	1.109		
MAR RAIN	-0.002	4.53	0.0466
MAY RAIN	0.003	5.11	0.0357
SEP RAIN	-0.002	3.84	0.0649
OCT RAIN	-0.006	21.15	0.0002
DEC RAIN	-0.004	8.10	0.0103
	(c) Hawkes Bay R^2=0.780; F=13.48; P>F=0.0001		
Intercept	3.615		
NOV RAIN	-0.013	10.83	0.0038
DEC RAIN	-0.015	22.40	0.0001
APR RAIN	-0.009	30.96	0.0001
JUN TEMP	0.337	4.26	0.0529
JUL TEMP	-0.542	12.17	0.0025
	(d) Nelson R^2=0.631; F=6.51; P>F=0.0011		
Intercept	-2.241		
SEP RAIN	0.004	5.85	0.0258
OCT RAIN	-0.004	6.06	0.0236
DEC RAIN	0.006	16.23	0.0007
JAN RAIN	0.003	11.28	0.0033
AUG TEMP	0.212	5.65	0.0281
	(e) Canterbury R^2=0.563; F=4.90; P>F=0.0048		
Intercept	1.939		
NOV RAIN	-0.007	5.09	0.0360
JAN RAIN	0.005	10.35	0.0045
OCT TEMP	0.086	3.09	0.0948
NOV TEMP	-0.120	3.98	0.0605
APR TEMP	-0.103	3.38	0.0817
	(f) Central Otago R^2=0.640; F=6.76; P>F=0.009		
Intercept	-2.631		
JAN RAIN	0.004	2.82	0.1097
MAR RAIN	0.009	15.36	0.0009
APR RAIN	0.009	9.96	0.0052
JUL RAIN	0.014	11.49	0.0031
NOV TEMP	0.120	9.44	0.0063

Table 6.8.4 Summer (Dec-Feb), Autumn (Mar-May) and annual rainfall

	Dec-Feb	Mar-May	Annual
Auckland	238	304	1204
Hawkes Bay	189	229	839
Nelson	216	257	979
Canterbury	152	178	659
Central Otago	108	95	343

An interesting contrast is that between Auckland and Central Otago, the extremes of wet and dry climates of the major apple districts. In the former district excess rainfall appears to be limiting to yield, whereas in the latter lack of rainfall appears to be a major limiting factor.

It should also be noted that in the most significant one predictor model, for New Zealand yield, the predictor was October rainfall, which was again negatively related to yield. Both Auckand and Nelson gave October rainfall as the strongest single predictor, and Hawkes Bay had a negative relationship with November rainfall as the most significant single predictor. This strongly suggests that October to November is a critical rainfall sensitive period, corresponding to flowering and early pollen tube growth.

A positive relationship with November temperatures is consistent with Wilton's (pers. comm.) hypothesis that the post bloom period is a critical temperature sensitive time. He believed that temperatures over the cell division period can have a significant effect on ultimate fruit size and crop, as also stated by Jackson and Hamer (1980). Central Otago is the only district to show a significant positive relationship with November temperature. This suggests that temperatures at this time may be potentially most limiting to yield in this district. Again this is borne out by Wilton's (pers. comm.) observations that trees in this district generally give a lower fruit size for a given crop load, which he believed may be temperature related. This could be compounded by moisture deficit, later in the season, as shown by the negative relationship with March rainfall.

Canterbury district showed quite a different response, with a positive relationship with October temperature and a negative one with November temperature. There may possibly be some interaction between the two months. Development may be slightly more advanced in Canterbury, than Central Otago, perhaps with earlier blossom and the early growth requirements being met earlier. Temperatures may be more limiting after this time, particularly if associated with a period of moisture deficit. A negative relationship with November rainfall suggests this not to be so.

The strong negative relationship of February temperature with national yield, and strong positive relationship with March temperature is not reflected in any of the district analyses. Temperatures in February have greater potential to be limiting than in March, being on average a warmer month.

March is cooler and more into the main harvest period, so that warmer temperatures may be desirable for maturity and harvest of the crop.

There are two other temperature relationships, for Hawkes Bay and Nelson that didn't come through at a national scale. The most significant one is July temperature in Hawkes Bay. This relationship came through in the 1963-1981 models. The climate data for this period had a greater weighting on Hawkes Bay than the earlier period. The suggestion is that this is a district response. If the response is related to phenomena suggested from the work of Beattie and Foley (1978) and Jackson and Hamer (1980) then it would appear that there is greater potential for this to occur in Hawkes Bay than any other district. The positive relationship with June temperature is difficult to explain, particular in light of the response to July temperature. It may be an anomalous result, which is given some weight by its lower level of significance.

The positive relationship, in Nelson, with August temperature is also difficult to explain, particularly in light of the English work. Again it may be a black box statistic.

As a final step in the analysis of apple yields, the two separately sourced data sets were combined into one, to give national yield/tree for the 1941-1981 period. This allowed for model verification. Trend over the two periods has previously been discussed. A quadratic trend line was fitted to the data as shown in Fig. 6.8.1. Every two years out of three were retained for verification, as with the grain crops. This in part compensated for the changing distribution of the crop over this period, with the climate data being weighted for the two separate periods.

Results of the verification of the calibration model are presented in Table 6.8.5, as is the F=4 model using all of the data. The model verified well considering changes in the distribution of the crop and different regional yield responses to climate. It is important to note the relative strength of the relationship with July temperatures, which was the single most significant predictor. This was shown earlier to be a significant predictor of Hawkes Bay yield, but perhaps is also of some importance in other districts. Even if it is a response just in this district it is a very important one with this now being the principal apple exporting district in New Zealand. The negative relationship with December rainfall was earlier reflected with Auckland and Hawkes Bay yields and reinforces the suggestion that rainfall at this time may be excess to needs. Warm March temperatures appear to be desirable and may relate to maturing and ripening of the crop.

Table 6.8.5

(a) Verification of N.Z. apple yield/tree (1941-1981) model
Correlation coefficients

Calibration	Verification
0.542	0.278
p=0.0029	p=0.3579

b) F=4 model, max R procedure
R^2=0.312; F=5.59; P>F=0.0029

Variable	B value	F	P>F
Intercept	-3.387		
DEC RAIN	-0.064	4.04	0.0517
MAR TEMP	2.203	6.91	0.0124
JUL TEMP	-3.809	10.70	0.0023

6.8.4 Summary

There are no consistently strong relationships over all years and districts, although July temperatures, October rainfall, December rainfall and Autumn temperatures appear to be important determinants of yield. It is apparent that there are some quite strong regional interactions between climate and yield. Some caution must be taken in interpreting national yield models because of these apparent differences.

In summary rainfall appears to be generally surplus to requirements in Auckland and can be detrimental to yield, particularly in spring, early summer and autumn. Rainfall appears to be surplus to needs in late spring early summer and mid autumn in Hawkes Bay, possibly due to wider use of irrigation.

July temperatures are also critical in this growing district. This predictor appeared strongly in the 1963-1981 analysis of national yield and in the analysis of national yield from 1941-1981. It appears to reflect the increased dominance of Hawkes Bay as an apple growing district. However the relative strength of the relationship has increased, which doesn't appear to be solely related to this shift in dominance and may suggest an increased frequency of warmer winters above the optimum.

In Nelson lack of rainfall appears to be limiting to yield over the summer period and is perhaps related to the lesser use of irrigation over the years examined. January appears to be a critical moisture sensitive period in Canterbury, although it appears that a drier November period is desirable. In direct contrast to Auckland, lack of rainfall is quite limiting in Central Otago. Wet winters, mild summers and autumns appear to be favourable. Post blossom temperatures are also important in this district.

6.9 Pears

6.9.1 Pear-climate relationships

Pears are generally less hardy than apples (Westwood, 1978). However they still require a cool winter, with extended flowering being a problem in areas where little winter chilling occurs (Jackson, 1986). Bud burst normally occurs from early to mid September and flowering in about late September to early October. Frost can be a problem around this time. The crop reaches maturity from January to May, depending on the cultivar. The trees have a moderate drought tolerance suggesting that irrigation could be necessary in low rainfall areas. In general relationships with climate are similar to those for apples and the synopsis given for apples in New Zealand could be taken as a broad guideline for pears.

6.9.2 Pears: results

Pear data was available over the same time periods as the apple data and methods of analysis were the same.

For the 1963-1981 period a linear trend was fitted to both yield per tree and yield per hectare, Figs. 6.9.2 and 6.9.3. It is apparent that pear production has not become as consolidated as apple production has. The period from 1941-1981, Fig. 6.9.1, shows a fairly consistent upward trend suggesting that optimum pear yields have yet to be attained.

Weighting factors for the climate data are given in Table 6.9.1. Regression analysis of pears was carried out on residuals for yield per ha and yield per tree data. Results for the 1963-1981 period are presented in Table 6.9.2, for a five predictor model. Three predictors are common to both models, being the most significant ones in both cases. Spring rainfall, particularly in September, has a very strong negative relationship with yield. This reinforces results with stonefruit crops and apples, that rainfall at blossom time is detrimental to yield. A negative relationship with February rainfall is consistent with the result for apples over the same time period, and with Wilton's (pers. comm.) observations. Warm temperatures in September, the pre blossom time, seem to be important. For the yield per ha data there is also a weak relationship with August temperature. This suggests the possibility of a need for a sharp winter to spring transition and would add support to the general theory for apples put forward by Beattie and Foley (1978) and Jackson and Hamer (1980). Without this sharp transition extended flowering may become a problem, which Jackson (1986) noted can result in areas with insufficient winter chilling.

Positive relations with May rainfall and temperature also appear. These are for the current season. They would appear anomalous as this is the end of the harvest period and it would be difficult to imagine serious yield losses arising from conditions in this month.

Fig. 6.9.1 New Zealand pear yield (kg/tree) 1941–1981

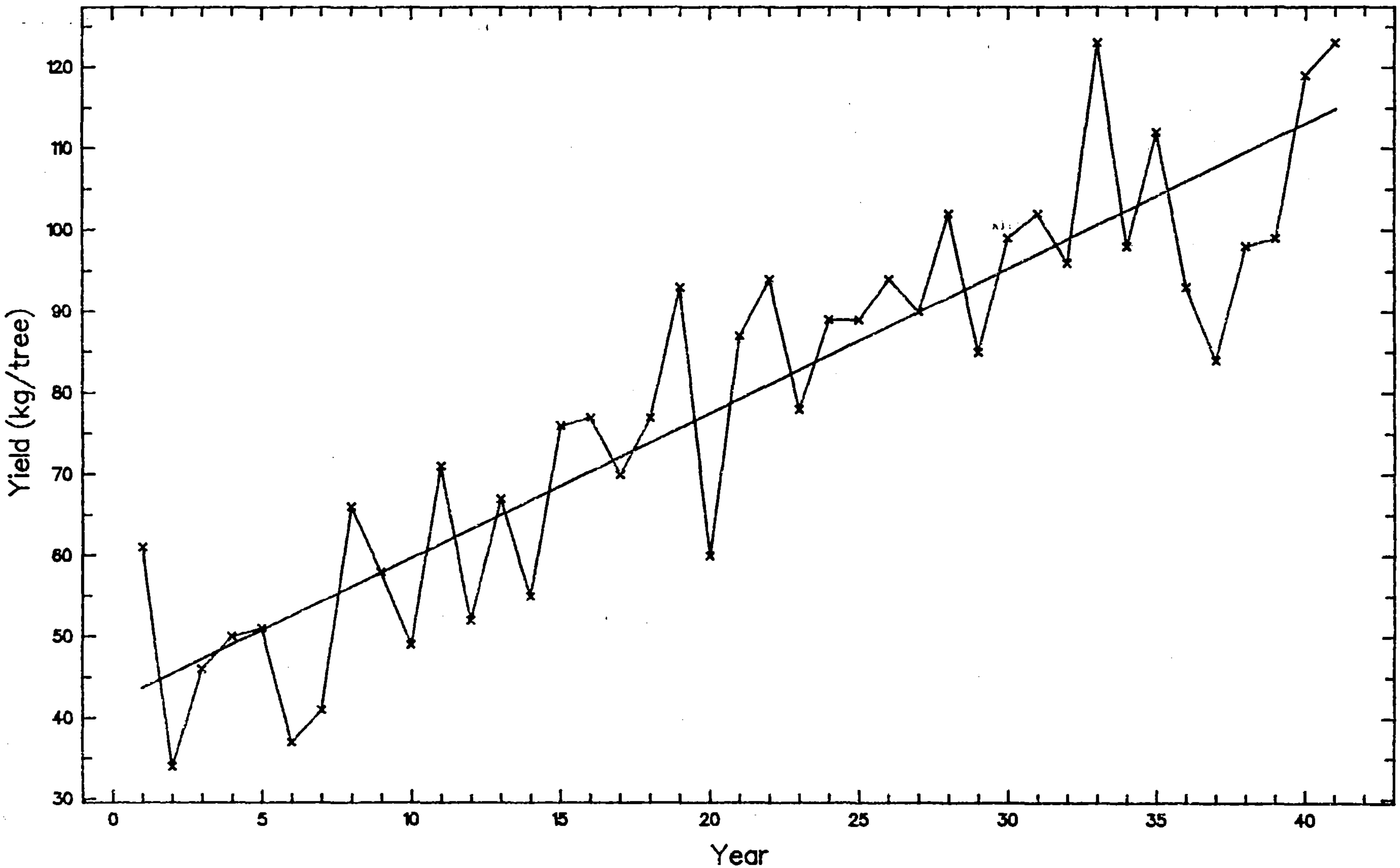


Fig 6.9.2 New Zealand pear yield (kg/tree) 1963–1981

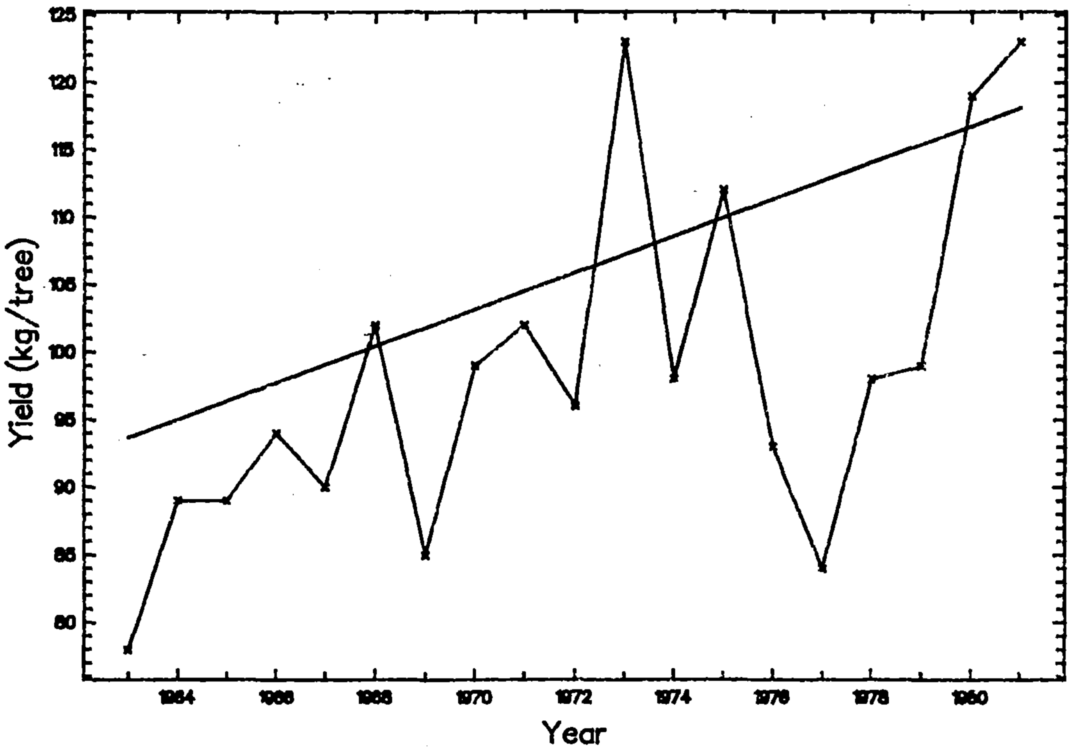


Fig. 6.9.3 New Zealand pear yield (T/ha) 1963–1981

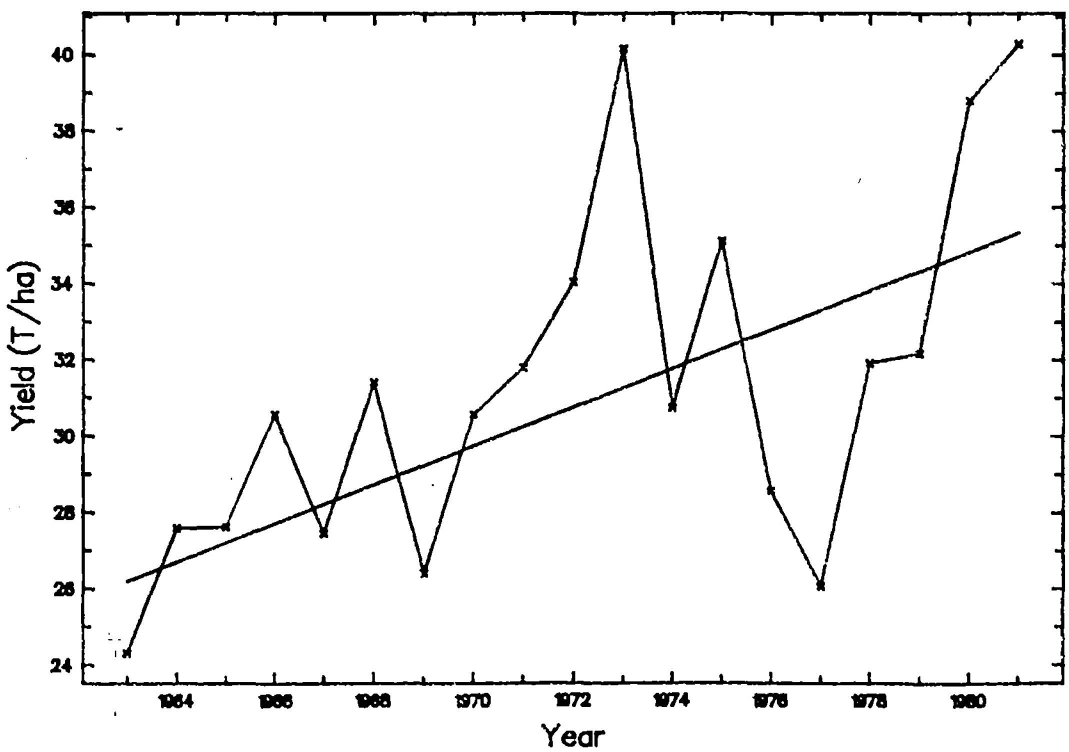


Table 6.9.1

Pears; weighting factors for climate data

District	Weighting 1941-1965	1963-1981
Northland	0.01	0.003
Auckland	0.08	0.062
Waikato	0.02	0.038
Bay of Plenty	0.01	0.011
Manawatu/Taranaki 0.01	0.005	
Wellington/Wairarapa0.01	0.003	
Poverty Bay	0.01	0.014
Hawkes Bay	0.33	0.458
Nelson	0.32	0.227
Marlborough	0.01	0.008
Canterbury	0.06	0.043
South Canterbury 0.01	0.005	
Oamaru/Dunedin	0.00	0.002
Central Otago	0.13	0.120

Table 6.9.2

Pears; regression yield models (1963-1981)
max R method

Variable	B value	F	P>F
	(a) pears/tree R^2=0.87; F=16.89; p=0.0001		
Intercept	-89.979		
FEB RAIN	-0.162	11.44	0.0049
SEP RAIN	-0.187	14.37	0.0022
OCT RAIN	-0.097	6.26	0.0265
MAY TEMP	4.144	7.13	0.0193
SEP TEMP	6.600	21.76	0.0004
	(b) pears/ha R^2=0.84; F=13.30; p=0.0001		
Intercept	-1.067		
FEB RAIN	-0.082	23.34	0.0003
MAY RAIN	0.045	5.24	0.0395
SEP RAIN	-0.093	14.54	0.0022
AUG TEMP	-1.209	3.13	0.1005
SEP RAIN	1.782	7.99	0.0143

For the 1941-1965 period a linear trend was fitted to both the district and national yield data. Results of analysis for 5 predictor models is given in Table 6.9.3, and allows for evaluation of possible regional relationships and their relative impacts on national yield over this period.

Rainfall at blossom time is apparently detrimental to yield, as could be expected. This relationship is apparent both with national yield and with the Nelson data. With a greater proportion of the crop grown in this district over this period than in 1963-1981 this is probably a reflection of the bias of the weighted climate data towards Nelson. As with apples lack of summer rainfall can be limiting to yield in Nelson and again reflects in the national model. Highly significant is the positive relationship with January rainfall at the national scale. Four out of five of the main growing districts, all except for Central Otago, showed a positive relationship with January rainfall. This obviously explains its strong presence in the national yield model. January is obviously a critical moisture sensitive stage and may relate to when the fruit is approaching maturity and requires moisture for sizing, particularly if the conditions in the preceding months have been relatively dry. There are apparent regional differences in response to rainfall in late summer and autumn. Some of these relationships may be anomalous, but may also be true reflections of regional rainfall relationships. Perhaps because of no apparent consistency between regions none of these months reflects in the national yield model.

December temperatures are positively related to yield, both nationally and in Hawkes Bay and Nelson, the two principal pear growing districts. Warm temperatures at this time, although not within the six week critical post bloom period identified by Wilton (pers. comm.), may still be important for early cell division and fruit development. Adequate moisture at this time also appears to be important. Closer to harvest warm March conditions appear important. This could be an association with final stages of maturity and perhaps with warm, dry conditions for harvest. A negative relationship with March rainfall in Auckland attests to the undesirability of rainfall at this time in this district and may be related to delayed harvest or reduced yield through disease arising from humid conditions.

It is questionable whether rainfall in May could have any significant impact on yield in the current season, as most of the harvest would have been completed by this time. In Hawkes Bay a negative association with April rainfall is not so easy to explain and may be anomalous. However in the dry Central Otago district rainfall in the months of March and April is positively related with yield. It is recalled that even above average rainfall in Central Otago is below the average of wetter districts such as Auckland, so this is not necessarily an inconsistency. With fruit size generally smaller than in other districts rainfall at this time in Central Otago would be beneficial to yield by delaying harvest and allowing fruit to increase in size a bit more. The interpretation is made more difficult with a negative association with February rainfall in Central Otago. Either this is a very moisture sensitive period under Central Otago conditions, or some or all of these results are anomalous.

Table 6.9.3

Pears; N.Z. & district yield/tree models (1941-1965)
max R procedure

Variable	B value	F	P>F
		(a) New Zealand	
		R^2=0.828; F=18.34; P>F=0.0001	
Intercept	-9.645		
OCT RAIN	-0.006	11.17	0.0034
DEC RAIN	0.005	7.78	0.0117
JAN RAIN	0.015	47.56	0.0001
DEC TEMP	0.191	8.89	0.0077
MAR TEMP	0.346	13.36	0.0017
		(b) Auckland	
		R^2=0.607; F=5.86; P>F=0.0019	
Intercept	-26.928		
JUL RAIN	-0.009	4.38	0.0499
JAN RAIN	0.022	12.82	0.0020
MAR RAIN	-0.006	2.11	0.1629
FEB TEMP	0.612	4.48	0.0478
MAR TEMP	0.807	4.79	0.0412
		(c) Hawkes Bay	
		R^2=0.737; F=10.67; P>F=0.0001	
Intercept	-16.009		
JAN RAIN	0.013	14.92	0.0010
APR RAIN	-0.006	4.27	0.0528
MAY RAIN	0.008	12.89	0.0020
DEC TEMP	0.527	14.25	0.0013
MAR TEMP	0.335	3.84	0.0650
		(d) Nelson	
		R^2=0.626; F=6.36; P>F=0.0012	
Intercept	-4.549		
OCT RAIN	-0.006	6.91	0.0166
DEC RAIN	0.009	7.90	0.0111
JAN RAIN	0.008	9.39	0.0064
MAY RAIN	-0.005	7.24	0.0145
DEC TEMP	0.287	5.17	0.0347
		(e) Canterbury	
		R^2=0.448; F=3.08; P>F=0.0333	
Intercept	3.674		
AUG RAIN	-0.003	2.06	0.1671
NOV RAIN	-0.005	2.91	0.1042
JAN RAIN	0.009	5.08	0.0363
MAY RAIN	0.003	3.38	0.0816
FEB TEMP	-0.236	4.50	0.0472
		(f) Central Otago	
		R^2=0.592; F=5.52; P>F=0.0026	
Intercept	0.358		
JUL RAIN	0.023	13.89	0.0014
FEB RAIN	-0.007	9.83	0.0054
MAR RAIN	0.008	6.16	0.0226
APR RAIN	0.013	8.17	0.0101
AUG TEMP	-0.213	6.37	0.0207

As with apples the two separately sourced data sets were combined into one to give a 41 year record of yield per tree, from 1941-1981. Both periods had shown a fairy consistent linear trend, and this was again the case with the combined data. A linear trend was fitted, shown in Fig. 6.9.1, and analysis performed on the residuals. Correlation coefficients from actual yield versus yield estimated from the calibration model, for the calibration and verification periods are shown in Table 6.9.4. The result is similar in magnitude to that achieved with apples. Although not statistically significant it is encouraging all the same given the apparent different regional responses of yield to climate.

Table 6.9.4

(a) Verification of N.Z. pear/tree model (1941-1981) correlation coefficients

Calibration	Verification
0.756 p=0.0001	0.274 p=0.3659

(b) F=4 model, 2 predictors, max R procedure
R^2=0.293; F=7.86; P>F=0.0014

Variable	B value	F	P>F
Intercept	-129.284		
OCT TEMP	5.004	8.20	0.0068
DEC TEMP	3.801	5.00	0.0314

(c) F=4 model, 5 predictors, max R procedure
R^2=0.458; F=5.92; P>F=0.0005

Variable	B value	F	P>F
Intercept	-96.857		
JAN RAIN	0.102	4.37	0.0439
MAR TEMP	4.672	8.22	0.0070
JUL TEMP	-3.963	4.06	0.0516
AUG TEMP	-4.081	4.25	0.0467
OCT TEMP	6.062	12.47	0.0012

October and December temperature were the significant predictors in a two predictor model, which satisfied the F=4, 5% significant criteria. Both were positively related to yield. Temperatures in the blossom and post blossom period are apparently quite important, and this adds weight to the theory put forward by Wilton (pers. comm.) for apples. It is further reinforced by a positive association with November temperature in a five predictor, F=2 model. The importance of a well defined winter to spring transition is highlighted by negative associations with July and August temperatures. Warm conditions at this time may result in hormonal confusion, as with apples (Beattie and Foley, 1978; Jackson and Hamer, 1980) and lead to delayed flowering (Jackson, 1986). The presence of January rainfall in the F=2 model is probably a reflection of the strength of this relationship in the earlier, 1941-1965, period.

6.9.3 Pears: summary

As with apples there was no apparent consistency with the results achieved over the two separate periods. This is probably a reflection of changes in orchard management, wider use of irrigation and also importantly shifts in relative importance of the two principal growing districts. The analysis of national yield was biased more towards Nelson district in the earlier period and towards Hawkes Bay in the latter.

The strong regional differences in yield response to rainfall that were apparent with apples, were not so with pears. The reverse is true to a degree with the consistency of the response to January rainfall in the earlier years. The interesting contrast is the negative association with February rainfall in the latter period. If both are true relationships then this is apparently another important moisture sensitive period. One explanation may be that lack of January rainfall has become less limiting because of wider use of irrigation. It could then follow that above average rainfall in February could have a negative effect, if there is already an abundance of available moisture. Central Otago remains an anomaly, but perhaps the nature of the response to rainfall in this dry district may add weight to the hypothesis that late summer to early autumn is a very moisture sensitive period for pears, and generally important for fruit sizing.

The importance of temperature in the winter to spring transition is highlighted more in the latter period. There are two possible explanations of this. One is that temperatures have universally become warmer. Temperature means for Appleby and Napier climate stations for the 1941-1965 and 1963-1981 periods show an increase of about 0.2°C. More significant is the difference between the two stations which would show up in the different weightings for the two periods, the latter being more weighted towards warmer Hawkes Bay. The inference is that late winter temperatures are more likely to be warmer than desirable in this district than in Nelson. However if this were the case it could be reasonably be expected that temperature in these months would appear as a significant predictor of yield in the Hawkes Bay yield model derived from the earlier data. Perhaps there is a combined effect of proportionately more pears being grown in this district and temperatures being universally warmer, so that there are more years that are warmer than optimum. This is given weight by the result with apples which suggests that the July temperature response has become stronger over the latter period. This obviously requires further investigation as it could have important implications for the pipfruit industry. Yield data by district for the latter period combined with dates of full bloom in each district would help satisfactorily resolve this more.

As a general summary it appears that summer rainfall conditions were dominant limiting factors to national yield over the 1941-1965 period, fairly strongly reflecting relationships in both Hawkes Bay and Nelson. Over the latter period conditions in late winter and spring appeared to dominate as the main climatic factors limiting to pear yield.

CHAPTER 7

The Canterbury food-climate system: review and analyses

7.1 Introduction

Canterbury is the largest plains region in New Zealand. It's climate is unique, influenced by the Southern Alps and in coastal areas, by the oceanic locale. Early white settlers found both the climate and soils well suited to temperate grain crops. Rapid expansion of cropping in the 19^{th} century led to soil erosion problems. This highlighted the need for careful land management practices to optimise the benefits from the climatic resource. The recent Canterbury drought has shown that the lessons from the past have not been fully learnt. This Chapter addresses some of these issues, providing some assessment of the Canterbury agroclimate resource base. This is a necessary preliminary to an evaluation of the potential local and regional benefits of shelter.

Topographically the plains of Canterbury appear to offer a homogenous environment. A spatial analysis of climate in Canterbury is presented and demonstrates that there are potentially significant sub regional response areas. This is an important consideration for planning future land use. County yield data for wheat allows for a study of the spatial response of yield in relation to spatial variations in climate.

With the importance of Canterbury as a cropping region, and a growing interest in horticulture it is important to evaluate potentially limiting climatic factors. Empirical analyses of temperate grains, in Chapter 5, suggested that agricultural drought can be a significant limiting factor in Canterbury. Closer analysis of drought, and its impact on yield was carried out and results are presented and discussed.

7.2 Physical features and climate

Canterbury is situated east of the Southern Alps, in the South Island. Close to the mountains are several inland basins, the largest and highest being the McKenzie to the south in the area now known as Aorangi. The main range gives way to the foothills which tend towards the east coast in both the north and south. Inland to the north is the Amuri plain. To the east as far as the coast are the Canterbury Plains. The latter cover an area of some 5000 km^2. Rising to the northeast of the plain is the Banks Peninsula. These features, with the exception of the McKenzie basin, can be seen in Fig. 7.2.1, adapted from McKendrey et al (1987).

New Zealand climate was briefly described in section 3.2. Both the axial ranges and the oceanic locale have a dominant influence on the climate of Canterbury. The seasonal variations in the mean latitude of the anticyclonic belts influences the general seasonal weather patterns as experienced in Canterbury and described by McGann (1983).

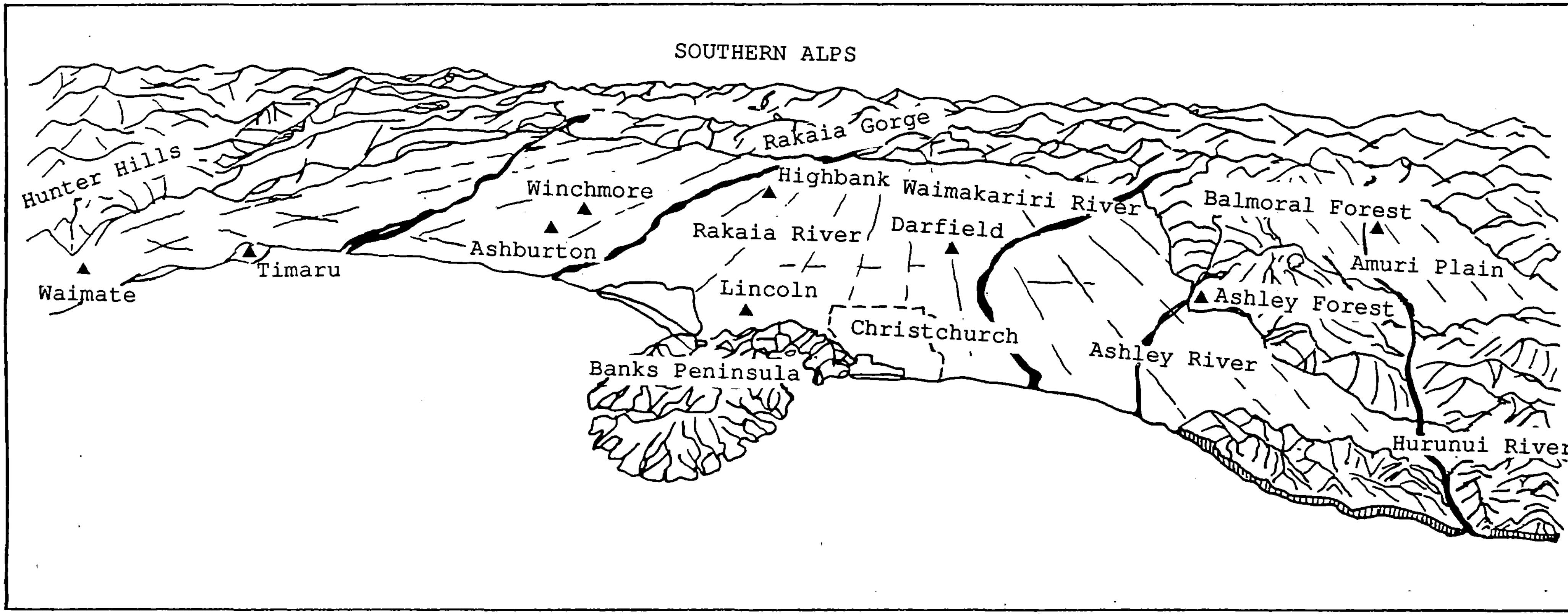


Fig. 7.2.1 Oblique view of the Canterbury Plains, showing major topograpical features (modified from McKendry et al., 1987)

Winds from the east to northeast are a dominant characteristic in Christchurch. This is often the result of undisturbed westerly airflow being channeled around the northern end of the South Island. It can be augmented, particularly in summer months by local sea breeze effects. In winter months there is generally a higher frequency of winds from the south and southwest, often bringing cold Antarctic air to the region. These winds arise from the passage of anticyclones at lower latitudes, with the often associated cold fronts moving onto the South Island. A common and dramatic feature in spring, but also occurring in other seasons, is the Fohn or northwest wind known as the Canterbury nor'wester. This arises from undisturbed westerly flow. If this flow is fairly moderate and stable, it is mostly diverted around the northern end of the South Island as described earlier. In intermediate conditions there may be some passage of the air mass over the Southern Alps as well as around the north of the South Island. This can result in upper winds being from the west or northwest with surface winds from the northeast. When the flow is strong and unstable most of the air mass passes over the Alps and the Fohn wind is experienced over the whole of Canterbury. In cases where wind passes over the Alps an orographic trough forms on the lee side. This can result from adiabatic warming of the descending air on the lee side. An alternative explanation is that the vertical stretching of the air column on the lee side creates a low pressure zone which leads to horizontal convergence of air and thus generation of cyclonic circulation. A nor'wester can often precede a rapidly moving cold front resulting in a sharp transition from warm dry northwest conditions to cold showery southerlies. Rapid changes in temperature and relative humidity result. This can introduce a considerable degree of risk to such agricultural activities as spring lambing where losses are often high with rapid weather changes.

A much less dramatic feature of the climate on the plains are katabatic or drainage winds. These generally occur on clear nights, most commonly in winter time. Their flow is westerly or northwesterly, depending on the orientation of valleys and location of measurement sites.

7.3 The food resource

A summary of arable and horticultural crops, from 1930 and 1985 Agricultural Statistics publications is given in Table 7.3.1. A brief discussion follows.

7.3.1 Arable crops

The dominant crops in Canterbury have been, and remain, the temperate grains. Wheat is a relatively less important crop than it was in 1930, both in area grown and as a percentage of the national area. The area in oats has halved and barley has increased ten fold. Peas have also become a relatively more important crop. Maize remains a minor crop in Canterbury, with the growing season generally too short for consistently good yields.

The changes in area of the temperate grains tend to reflect shifts in commodity price rather than any significant climate changes.

Table 7.3.1

Summary of principal crops grown in Canterbury; 1930 & 1985

(a) Arable crops

Crop	1930 statistics Area(ha)	1985 statistics % of N.Z. total	Area(ha)	% of N.Z. total
Wheat	80704	84	49158	68
Oats	12055	44	5638	42
Barley	9114	50	91281	60
Peas	2138	54	18852	85
Maize	5	0.15	19	0.1

(b) Horticultural crops

Crop	1930 statistics Tree number	1985 statistics % of N.Z. total	Area(ha)	% of N.Z. total
Apples	143610	11	393	5
Pears	13398	12	30	5
Apricots	4412	7	35	5
Nectarines	2146	13	92	8
Peaches	7951	7	89	7
Plums	7111	14	23	6
Cherries	5172	29	3	1.5
Strawberries			72	19
Blackcurrants			346	46
Kiwifruit			4	0.02

However as shown in Chapter 5, and will be demonstrated further with wheat, climate does have a significant influence on year to year variability in Canterbury grain production.

In more recent years there has been increasing research into other crops. A lot of attention has been paid to pulses, and lentils have become an increasingly popular crop that is apparently well suited to the climate. However the traditional crops still predominate.

Generally the climatic resource of Canterbury has been well exploited for cropping, and there is on going research to improve cultivars and identify new crops that may have potential. The district analysis of wheat, oats and barley yields in relation to climate identified significant limiting factors. Above average rainfall in winter appeared to be detrimental to Autumn sown crops, particularly wheat. Spring temperatures can be limiting to wheat and late spring to early summer conditions can be limiting to oats and barley. These temperature relationships appear to be related to moisture deficit conditions, which suggests that agricultural drought can be limiting to these crops. This is examined in more detail in section 7.8.

7.3.2 Horticultural crops

Fruit growing in Canterbury has been relatively stable over time, generally catering to local demand. Lack of area statistics for 1930 precludes direct comparison with 1985. However percentages of national totals provide some useful contrasts. The most dramatic change has been with cherries. Canterbury was a significant growing area for this crop in the early part of the 20th century, although still secondary to Central Otago. Marlborough has since become the dominant growing district for this crop. Spring and early summer rainfall were shown, in section 6.4.2, to be the dominant limiting factors to yield with cherries. There is little difference in rainfall over this part of the growing season between Canterbury and Marlborough, although there is uncertainty as to timing and intensity in relation to rainfall sensitive stages. Yield per tree was virtually the same for these two districts, on average, from 1925-1930. It appears likely that there were factors other than climate that led to the decline in cherry production in Canterbury.

Canterbury has also become relatively less important as a pipfruit growing district, although this is being reversed with recent large increases in plantings of apples. Grapes are another horticultural crop to show potential, with the development over the last decade or so of a fledgling wine industry.

The climate resource has been under exploited for horticultural production, which may partly reflect the traditional dominance of cropping. Lack of district data for stonefruit precluded identification of limiting factors for these crops. There appears to be potential for cherries, as discussed earlier, perhaps the main barrier being the capital investment required. Apricots require careful management, and although grown in some frost free areas in Christchurch do not appear to perform well. Jackson (1986) noted that careful selection of cultivars suited to a district will increase cropping potential and reliability. Peaches and nectarines generally do well in Canterbury. Lack of rainfall at sensitive fruit development stages could be limiting to stonefruit, but this could be overcome with irrigation. There is the risk of frost, but overhead sprinklers would overcome this. Generally the risk is lower than in Central Otago. The summers are generally warm and dry which are well suited to stonefruit production, providing water is available at sensitive stages.

The main limiting factor for pipfruit in the district analysis of Canterbury yields, shown in sections 6.8.3 and 6.9.3, was January rainfall, which was positively related to yield. This attests to the need for irrigation, particularly over persistently warm, dry summers. The temperature relationships were generally less clear and of uncertain significance. The effect of drought on these crops is examined further in section 7.8.

Canterbury is presently the southern limit for kiwifruit, with this crop being grown on a very small scale. Wind would be a major limiting factor. Shelter is critical for all horticultural activities in Canterbury, primarily for protection from wind damage.

7.4 Spatial variability of climate: a review

Five main climatic zones were identified in Canterbury by Ryan (1987). These are the plains region; the eastern foothills; the high country near the main divide; the Banks Peninsula and the northern coastal hills; and the inner basins, some sheltered valleys and the foothills to the south of the plains. Rainfall is highest near the main divide, with a moderate rainfall on the Peninsula and in the eastern foothills and northern coastal area. The Plains and South Canterbury generally have lower rainfall. The temperature range on the Plains and to the south is high compared to most other areas of New Zealand, leading Salinger (1981) to comment that the climate of this area is semi continental in nature. The extremes are characterised by the warm Fohn conditions and the potentially very cold southerlies. The climate of Banks Peninsula and the northern coastal area is more moderate, being temperate maritime. Frosts are a frequent occurrence in the winter months in most parts of Canterbury. Their frequency and severity generally increases with distance from the coast and altitude. As might be expected the Peninsula and the northern coastal strip generally experience fewer and less severe frosts. Coastal areas experience a high frequency of east to northeast winds, particularly in north and mid Canterbury. Northwest winds are more frequent and stronger in inland North Canterbury. There is also a high frequency of northwest winds in the south, as recorded at Timaru airport (N.Z.Met.Service, 1982). These winds are largely locally generated katabatic winds, being channelled through nearby valleys. This area, being closer to the foothills, experiences quite a high degree of sheltering from the west. This results in a high frequency of recorded calms at Timaru airport.

Although drying northwest winds are generally of low frequency over the north and central Canterbury Plains, their greater frequency in spring and summer has a significant impact on agricultural activity and productivity. These drying winds, combined with the low rainfall and relatively shallow soils over large areas, gives a high potential for agricultural drought in the Plains area and also in inland North Canterbury. Ironically, this can occur at times when record rainfalls are being recorded on the West Coast of the South Island. This has been graphically illustrated in 1988 with Canterbury experiencing its driest year on record and the West Coast experiencing record rainfalls and some of the worst flooding on record.

Salinger (1981) determined climatic response areas for New Zealand. He applied cluster analysis methods to delineate temperature and rainfall response areas. His results for the Canterbury region are briefly summarised here.

Five temperature response areas were defined for the South Island. The whole of Canterbury, with the exception of the McKenzie basin, was incorporated into a single response area, also including the rest of the east coast to the north and the eastern top of the Island.

A total of eleven rainfall response areas were delineated for the South Island. Canterbury was characterised by three response areas. These were the alpine spillover, North and Mid Canterbury, and South Canterbury. The inner hills can experience high rainfall under westerly conditions, with the air drying as it descends to the Plains. Salinger (1981) noted that Canterbury and South Canterbury are affected by similar synoptic events. High rainfall can be associated both with moist east to northeast air streams and southerly or southwest winds. Nearly half of the annual rainfall in Christchurch is associated with southwest winds (McGann, 1983).

The distribution of rainfall over Canterbury and its relationship with circulation patterns was examined by Sturman (1986). Using a stepwise regression he identified the most significant circulation index for each of 137 rainfall stations. The influence of westerly air flow was limited to the main divide and was consistent with Salinger's (1981) alpine spillover zone. In the intermediate basins, the eastern foothills, South Canterbury and in the Christchurch locale cyclonicity was the most significant index. Easterly airflow was the dominant source of rainfall over the plains and northeast Canterbury. This was quite a different result to the Canterbury/South Canterbury divisions made by Salinger (1981).

A mesoscale study by Trewinnard and Tomlinson (1986) showed the importance of Banks Peninsula in influencing rainfall gradients in Central Canterbury. They also showed the existence of distinct rainfall gradients over Christchurch City.

7.5 Spatial analysis of Canterbury climate

7.5.1 Introduction

The purpose of the study reported here was to examine more closely patterns of variability over the plains areas of Canterbury. This was to highlight the influence of local geographic features on climate and to build a more comprehensive picture of the climatic resource.

The data base used was more spatially limited than that of Salinger (1981), being largely confined to the plains. Data from some stations on the periphery of the plains were also included. The methods used were cluster analysis and principal component analysis, described in Chapter 4. Monthly data covering stations from the Amuri plain and the main Canterbury plain as far south as Waimate were entered on the VAX. Variables selected for analysis were mean temperature, rainfall, days of screen frost, sunshine hours and pan evaporation. For the first three variables a good spread of spatial and temporal data were available. For the latter two the time series were generally shorter and the number of climate stations fewer.

The longest period for which data were analysed was 1955 to 1986. This was chosen because data recording was superior and more stations were coming into operation over this period. All data were compiled into seasonal data sets. The three main periods chosen for analysis were 1955-1986, 1965-1986, 1975-1986. Analyses for the latter two periods allowed for inclusion of more climate stations, thus allowing for greater spatial representation. Data for each variable and each time period were transformed into single columns for each climate station and then the columns merged into one file for the analysis. All data were standardised, with mean equal to zero and variance equal to one. The rainfall data was normalised prior to standardisation.

Cluster analysis was carried out using both a hierarchical and a disjoint procedure from the SAS statistical package. In all cases the disjoint procedure failed to assign any of the variables to new clusters, reflecting the high degree of correlation within each data set. This was partly a result of the standardising but also reflected the similar spatial responses over the region to climate. The results discussed here, therefore, are from the hierarchical clustering and principal component analysis procedures. Both methods gave consistently similar results. In light of this only eigenvectors from the P.C.A. are presented to illustrate apparent divisions. Results are discussed for each variable in turn.

7.5.2 Mean temperatures

The temperature data were analysed over the three time periods, given earlier. The first principal component in all cases accounted for approximately 99.5% of the variance. This is a confirmation of Salinger's (1981) result, which assigned all of the area covered in the current analysis to the same temperature response area. In general the region as a whole is affected by the same synoptic phenomena. The magnitude of the response will vary according to site location. Local variations in altitude, proximity to the coast, sheltering from foothills, or effects from human modified environments were reflected to varying degrees in both the clustering and the second and third principal components. Eigenvectors, for the 1955-1986 and 1975-1986 periods are presented in Table 7.5.1.

An obvious anomaly, from the P.C.A., is apparent with the Ashley Forest and Highbank climate stations over the 1955 to 1986 time period. This is seen in the second eigenvector. In the cluster analysis these two stations again appeared to be anomalous, this time in combination with the Lincoln climate station. It was noted by Salinger (1981) in his site descriptions that Ashley Forest did not reflect the strong regional warming trend apparent from all other Canterbury climate stations used in his analysis. Because of this sites good exposure and faultless record he took the record as being true. The Ashley site is located on downland rising from the northern end of the Canterbury Plains. To the west of the site is the exotic Pinus radiata forest planted over the slopes. To the east the ground slopes gently down to the northern end of the Plains. The coast is clearly visible. Its elevation (100m), proximity to the coast and aspect (facing to the east north east) make this site unique. It is considered that these site features combined with down slope air drainage have an ameliorating effect on this site. Interestingly Ashley contrasts most strongly with Balmoral Forest, to the north and inland on the Amuri plain. The latter has warmed relative to Ashley.

Table 7.5.1

Eigenvectors from P.C.A. of temperature data

Climate station	PRIN1	PRIN2	PRIN3
	(a) 1955-1986		
Balmoral forest	0.301313	-0.380907	-0.125552
Ashley forest	0.301305	0.453389	-0.262812
Darfield	0.301749	-0.089883	0.189367
Eyrewell forest	0.301766	-0.133969	-0.200024
Christchurch airport	0.301836	-0.093419	-0.322064
Christchurch	0.301930	-0.135106	-0.161589
Lincoln	0.301712	0.071936	-0.344620
Highbank	0.300587	0.701764	0.303961
Winchmore	0.301848	-0.211190	0.133072
Ashburton	0.301168	-0.227642	0.684856
Waimate	0.301408	0.047655	0.107562
	(b) 1975-1986		
Balmoral forest	0.223558	-0.068894	-0.431342
Waiau	0.223658	0.094613	-0.355854
Ashley forest	0.223394	-0.345450	0.204622
Rangiora	0.223996	0.000083	-0.144504
Darfield	0.223754	-0.102407	-0.086307
Eyrewell forest	0.223667	-0.127209	-0.249926
Christchurch airport	0.223932	-0.036373	-0.142708
Christchurch	0.223826	-0.020741	-0.077810
Bromley, Christchurch	0.223662	-0.153375	0.127231
Lincoln	0.223472	-0.377856	-0.020623
Highbank	0.223087	-0.398420	0.388995
Hororata	0.223854	0.028568	-0.225262
Winchmore	0.223953	-0.036196	0.035220
Ashburton	0.222419	0.530229	0.272709
Timaru airport	0.223698	0.178158	0.116899
Peel forest	0.224006	0.066520	0.000074
Orari estate	0.223756	0.279613	-0.006992
Geraldine	0.223678	0.289780	-0.017907
Waimate	0.223152	0.023344	0.429569
Ikawai	0.223609	0.177119	0.188097

This could be, in part, influenced by the maturing forest in the locale of this latter station. Being in a flat environment the effects on surface roughness of a growing forest are likely to be significant. As will be shown later this roughening of the landscape can have a significant effect on both wind speed and mean temperature.

Again the unique exposure of the Highbank station makes for a strong local microclimate. The station is elevated above the Rakaia river and is also exposed to the nearby Rakaia gorge. From the latter it would be exposed to funnelling of westerly and katabatic winds. Air drainage therefore appears to be significant at this site and again leads to an apparent anomaly.

It is not so straight forward to explain the association of Lincoln with these two stations over the shorter time series. The Lincoln temperature data was adjusted to a more exposed site, there having been two site changes at Lincoln over the 1955 to 1986 time period. This may therefore be an association of more exposed sites.

While the second eigenvector over the 1955-1986 period highlighted the anomalous stations, as did the cluster groupings, the third eigenvector suggested a general north south division with the division being south of Lincoln. This general pattern is repeated over the 1965-1986 period. Over the same two time periods while the clustering highlighted the anomalous stations it also tended to reflect inland and coastal differences.

The 1975-1986 time series gave a more consistent result between the two methods, probably facilitated by the greater number of South Canterbury climate stations that were in operation over this period. The presence of these stations in the analysis reinforced the north/south contrast, which was the dominant secondary feature in both the clustering and P.C.A. The anomalous stations, discussed previously were still apparent in both the clustering and as a dominant feature in the north/south contrast, apparent from the loadings in the second eigenvector, all associating more with stations north of the Rakaia river. An exception was Hororata which is just to the north of Highbank but in the lee shelter of the ranges and clear of the gorge.

While the temperature response over the district as a whole is similar there are some important local differences. These largely reflect the effects of both site location and exposure on microclimate. Coastal exposure versus inland contrasts are weak, but apparent. The general north/south contrast possibly reflects slight differences in synoptic phenomena and also geographic differences. In the south the plains narrow to a coastal strip and all sites are either close to the hills or nestled in the downs. It is recalled that there is a high frequency of both katabatic winds and recorded calms in this area, as recorded at Timaru airport, which would particularly affect minimum temperatures. This north/south contrast is more strongly apparent with rainfall.

7.5.3 Rainfall

Again the rainfall data were analysed over three different time scales, with more stations in the analysis over the shorter time period. The periods used were the same as for the temperature data, with the stations being mostly the same. In all cases the first P.C. accounted for approximately 80% of the variance. This was obviously not as strong a result as achieved with the temperature data. However it still suggests that the region as a whole is affected by similar patterns of climate, with some potentially significant sub regional effects. As with the temperature data eigenvectors for the 1955-1986 and 1975-1986 periods are presented, in Table 7.5.2.

Table 7.5.2

Eigenvectors from P.C.A. of rainfall data

Climate station	PRIN1	PRIN2	PRIN3
(a) 1955-1986			
Balmoral forest	0.264955	-0.210786	-0.560687
Ashley forest	0.294074	-0.036617	-0.302892
Darfield	0.303124	-0.048910	-0.216910
Eyrewell forest	0.305901	-0.091566	-0.247067
Christchurch airport	0.294416	-0.329550	0.238042
Christchurch	0.279411	-0.401852	0.389653
Lincoln	0.287836	-0.297837	0.346912
Highbank	0.292131	0.297367	-0.177742
Winchmore	0.307543	0.085009	0.037995
Ashburton	0.304053	0.121545	0.101225
Orari estate	0.276862	0.466677	0.111515
Waimate	0.247457	0.506402	0.318176
b) 1975-1986			
Balmoral forest	0.190841	-0.195922	-0.294917
Waiau	0.195672	-0.292864	-0.176772
Waipara	0.211432	-0.176419	-0.284312
Ashley	0.228173	-0.090459	-0.212011
Rangiora	0.229561	-0.108727	-0.076832
Darfield	0.229362	-0.104845	-0.079735
Eyrewell forest	0.236067	-0.113649	-0.086243
Christchurch airport	0.215769	-0.220027	0.259868
Christchurch	0.213030	-0.218568	0.325228
Bromley, Christchurch	0.198136	-0.243532	0.356071
Lincoln	0.212858	-0.187119	0.278345
Highbank	0.228266	0.092451	-0.187118
Hororata	0.233765	-0.033483	-0.126239
Winchmore	0.233559	0.000698	-0.013538
Ashburton	0.229145	0.008971	0.047053
Timaru airport	0.205463	0.325807	0.107447
Peel forest	0.156789	0.378729	-0.279851
Temuka	0.214743	0.281934	0.054708
Orari estate	0.220303	0.226520	-0.063098
Geraldine	0.214186	0.246894	-0.122068
Waimate	0.191809	0.284646	0.274443
Ikawai	0.181846	0.279625	0.343986

Over the 1955 to 1986 time period, for which there were data from 12 stations, the strongest division in the clustering was between North and South Canterbury. This was again reflected in PRIN2 which accounted for 6.6% of the variance. The result was repeated over the 1965-1986 period for which there were data from 17 stations, and again over the 1975-1986 period for which there were data from 22 stations. As more South Canterbury stations came into operation the amount of variance accounted for by PRIN2 steadily increased, so that for the latter period it accounted for 9.1% of the total. This was a reflection of both the greater number of South

Canterbury stations and the inclusion of two further North Canterbury stations which tended to intensify the contrast.

The general boundary between the north and south appears to be the Rakaia river, generally following the result with the temperature data. This fits well with Salinger's (1981) response areas. However closer analysis of the P.C. loadings reveals that the north/south contrast is strongest between stations in the locale of Christchurch and those south of Timaru airport. Banks Peninsula has a significant influence on rainfall patterns in the locale of Christchurch as shown in the work of Trewinnard and Tomlinson (1986). Annual rainfall is on average higher over the southeast side of the peninsula than it is over Christchurch to the north (Sturman, 1986). Although no similar study has been carried out in South Canterbury, it seems likely that again the nature of the landscape in this area has a considerable modifying influence. Both proximity to the coast and to the foothills are significant local features. The hills in South Canterbury tend to provide sheltering from the west, southwest and south (Sturman, 1986). It is suggested that it is these features that led to the differences in response between the Christchurch locale and South Canterbury, as apparent in PRIN2.

Less strongly contrasted in both the principal component and cluster analysis are coastal and inland areas. This contrast is reflected in PRIN3, which consistently accounted for about 4.5% of the total variance. For all of the time series examined the strongest contrasts were between the Christchurch locale and coastal South Canterbury, and inland and northern stations. Central plains areas appeared to be transitional. This pattern tends to follow more closely that identified by Sturman (1986).

The analysis presented here lacks the detailed spatial representation of Sturman's (1986) study. However it appears that there are two different rainfall response regimes over the plains, with that identified by Salinger (1981) dominating on the basis of this analysis.

It is also of value to note the strongly local nature of the clustering. In all cases, most graphically illustrated over the latter period, stations group most strongly with nearest neighbour stations. Rainfall patterns are therefore similar over large areas, but local features have a considerable modifying influence.

7.5.4 Days of screen frost

Spatial differences in screen frosts were also examined over the three time periods. The first principal component accounted for a high percentage of the variance over all time scales, being of the order of 94%. This is not unexpected, with a similar seasonal pattern of temperature variation occurring over the whole of the plains. Differences are mainly in frequency, and intensity of frost although the latter is not implicit in this data. However the clustering and second and third P.C.s did highlight some differences, that can be attributed to site location features. Eigenvectors from the P.C.A. over the 1975-1986 period are given in Table 7.5.3.

Table 7.5.3

Eigenvectors from P.C.A. of screen frost data, 1975-1986

Climate station	PRIN1	PRIN2	PRIN3
Balmoral forest	0.223374	-0.231872	-0.203319
Waiau	0.224601	-0.134772	-0.156394
Ashley forest	0.215085	0.200883	0.659175
Rangiora	0.227294	0.025128	-0.128894
Darfield	0.223839	0.249600	-0.115988
Eyrewell forest	0.220952	-0.326215	-0.134566
Christchurch airport	0.226137	0.033079	-0.209763
Christchurch	0.223978	0.217429	-0.163218
Bromley, Christchurch	0.212919	0.581067	-0.308600
Lincoln	0.222823	0.142185	-0.274111
Highbank	0.219564	0.321255	0.284375
Hororata	0.226818	-0.095190	0.016049
Winchmore	0.225405	0.089120	0.251472
Ashburton	0.225443	-0.037421	-0.009436
Peel forest	0.226051	-0.233838	0.001740
Geraldine	0.225754	-0.212373	0.046972
Orari estate	0.225993	-0.210296	0.089922
Timaru airport	0.225511	-0.029645	0.177818
Waimate	0.225115	-0.140071	0.038309
Ikawai	0.224868	-0.161341	0.150559

An interesting result was the fairly strong tendency of Ashley and Highbank to group together over all time periods. Both sites experience a lower frequency of screen frosts than might be expected given their elevation. However the unique features of these sites, particularly the high potential for air drainage, makes them less prone to frosts than would otherwise be expected. This can be most graphically illustrated by comparing these sites with nearest neighbour sites, Rangiora and Hororata respectively. Both of the latter show a substantially higher incidence of frosts reflecting lower potential for air drainage.

This strong contrast between Ashley and Highbank and other sites, most particularly Balmoral forest, was the most consistent feature of both the clustering and the principal component analysis. The former two tended to group with the Christchurch locale stations, as illustrated by the loadings in the second eigenvector in Table 7.5.3. There is a general contrast between these sites and those to the north and inland and those to the south. The results generally reflect differences in frost frequency. This can arise from differences in latitude, altitude, distance from the coast, effects of air drainage and possibly sheltering. Balmoral, to the north, while being at a relatively high altitude and the furthest from the coast of all sites is also surrounded by forest. The forest environs, on calm nights could lead to an intensification of inversions. This may impact more on intensity rather than frequency of frosts. To the south, the sheltering effect of the nearby foothills and resultant high incidence of calms as recorded at Timaru airport gives a greater potential for frost. In the locale of Christchurch, the proximity to the coast, lower altitude, and lower frequency of calms reduces the risk of frost. Inland from Christchurch increasing altitude and distance from the coast give a greater risk of frost, with the exception of the two anomalous sites.

7.5.5 Sunshine hours

There are only a limited number of climate stations in the study area that have a record of sunshine hours. Data from 8 stations were used in the analysis, covering a relatively short time period. The Waimate station ceased recording sunshine hours in 1975, with the Ashley record only beginning in 1969, so there was an overlap of only 7 years giving coverage of all relevant stations. Data from Hanmer Springs, which is at the northern limit of inland North Canterbury were included to give added contrast. The period of 1969 to 1975 was used for the final analysis to give as much spatial contrast as possible. This was done following preliminary analyses which suggested similar patterns of response over all time periods examined. Eigenvectors for the 1969 to 1975 period are given in Table 7.5.4.

Table 7.5.4

Eigenvectors from P.C.A. of sunshine hours, 1969-1975

Climate station	PRIN1	PRIN2	PRIN3
Hanmer forest	0.341298	-0.485543	0.507890
Ashley forest	0.362160	-0.207889	-0.007403
Christchurch airport	0.362416	-0.188994	-0.138462
Lincoln	0.362728	-0.210373	0.180474
Highbank	0.361298	-0.039322	-0.368066
Ashburton	0.362339	0.090954	-0.440327
Timaru airport	0.350362	0.430454	-0.214434
Waimate	0.323818	0.667791	0.561167

Again the first principal component accounted for a high proportion of the variance, being 91%, suggesting that the region as a whole follows a similar pattern. However in both the clustering and in PRIN2, which accounted for 5.2% of the variance, a strong north south division was apparent. There were four stations in each cluster. The transition zone appears to be broadly the same as with the temperature and rainfall data, being roughly along the Rakaia river. Highbank and Ashburton, located near the Rakaia, both appear to be transitional sites in PRIN2. The inclusion of Hanmer Springs in the analysis may have weighted the result to come degree, however its inclusion is warranted as it allows comparison between the geographical extremes. Its weighting effect is not likely to be substantially greater than that provided by Balmoral in the analyses of other variables. Certainly with PRIN2 the strongest contrast is between Hanmer and Timaru and Waimate to the south.

This north/south contrast is more likely a reflection of differences in cloud cover arising from influence of geographical location and surrounding topography on synoptic phenomena than more localised site features. The effect of Banks Peninsula has already been discussed in relation to rainfall. It is likely that it also has an influence on local cloud cover. This is evident locally with occasional differences between Lincoln and Christchurch. The Hanmer station is located in a valley in the lee of the main divide. It is on the boundary of the alpine spillover, but still tends to associate with the northern plains stations suggesting similar patterns. There is certainly more exposure of these sites to the northwest and less sheltering from the southwest.

7.5.6 Pan evaporation

Raised pan evaporation data were available for only 7 stations, basically covering Mid Canterbury. The first P.C. accounted for 96.9% of the variance, suggesting a similar pattern for all sites in question, which is not unexpected in light of the previous results. Eigenvectors from the P.C.A. of raised pan evaporation data are presented in Table 7.5.5.

Table 7.5.5

Eigenvectors from P.C.A. of raised pan evaporation, 1965-1986

Climate station	PRIN1	PRIN2	PRIN3
Darfield	0.407991	0.108164	0.827938
Christchurch airport	0.410202	-0.120864	-0.383648
Bromley	0.405825	-0.640300	-0.109525
Lincoln	0.410180	-0.097307	0.168951
Highbank	0.405129	0.744420	-0.251718
Winchmore	0.410130	0.008840	-0.251854

In the clustering, Christchurch airport, Winchmore and Lincoln all grouped most strongly together, suggesting a similar exposure with these sites in relation to the rest. Darfield grouped less strongly with these three, being slightly further inland and more sheltered as reported by Salinger (1981). Bromley, in Christchurch, also grouped weakly. Although evaporation is of a similar order of magnitude at this site, its greater coastal exposure suggests a different pattern from the rest. The station with the most different response was Highbank. The annual total evaporation is similar in magnitude, so obviously there are differences in seasonal response. Exposure to drainage winds from the Rakaia gorge is the most likely explanation. The result is certainly consistent with that achieved with the rest of the analyses. The second P.C. strongly contrasted Bromley and Highbank, possibly reflecting differences in exposure to coastal winds with the former and katabatic winds with the latter.

7.6 Canterbury wheat-climate interactions

7.6.1 Introduction

Two previous empirical studies of wheat crop-climate interactions have been carried out in Canterbury. The earliest reported work was that of Kidson (1929), who sought to interrelate wheat yield from Lincoln College, Canterbury with various climate variables using a correlation procedure, for the period 1883 to 1928. Climate data used were suspect due to changing site conditions relating to shelterbelt growth and erection of buildings over part of this period (Cherry, 1988). This was commented on by Kidson himself (1929). The tentative conclusions that he drew were that cool and dry winter conditions are probably favourable for winter sown wheat. In the growing period of spring and early summer warm, moist conditions are favourable. Heavy rains near to harvest, in February, can lead to considerable losses.

A later study by Tauheed (1948) came to similar conclusions. Above average rainfall in spring and summer were shown to be beneficial to yield. Mean temperatures appeared to show no consistent effect although high temperatures in spring and summer were considered detrimental to yield. Spring is a time when warm, dry Fohn type winds can prevail in some years in Canterbury. It is probably these type of conditions that Tauheed (1948) was alluding to.

A more recently unpublished abstract by Gallagher and Macken (1983) identified warm spring and summer temperatures and high winter and spring rainfall as weather variables that tended to reduce yields in Canterbury grown wheat.

The results of these studies are generally consistent with the review given by Claridge (1972) and the results of the analysis of the Canterbury district data, presented in section 5.1.3.

7.6.2 Data and methods

Using the P.C.A. multiple regression approach, as outlined in Chapter 4, a more detailed analysis of Canterbury wheat yields was performed. Yield data were available, on a county basis, over the period 1945-1982. Data were collated from the thirteen counties indicated on Fig. 7.6.1 and earlier records converted from Bu/acre to Tonnes/ha. This record is broken, with data available for the years 1945-1952, 1960, 1962-1982. A simple quadratic trend line was fitted to the time series of yield for each county and the yield residuals used for the analysis.

The nature of the yield data affected the choice of climate data. Rainfall data were available from eleven climate stations and mean temperature data from nine, over the period for which yield data were used, covering the Canterbury region. As with the climate data used in the district analyses, it was considered that all possible sources of inconsistency should be removed. The procedure was as outlined in Chapter 4.

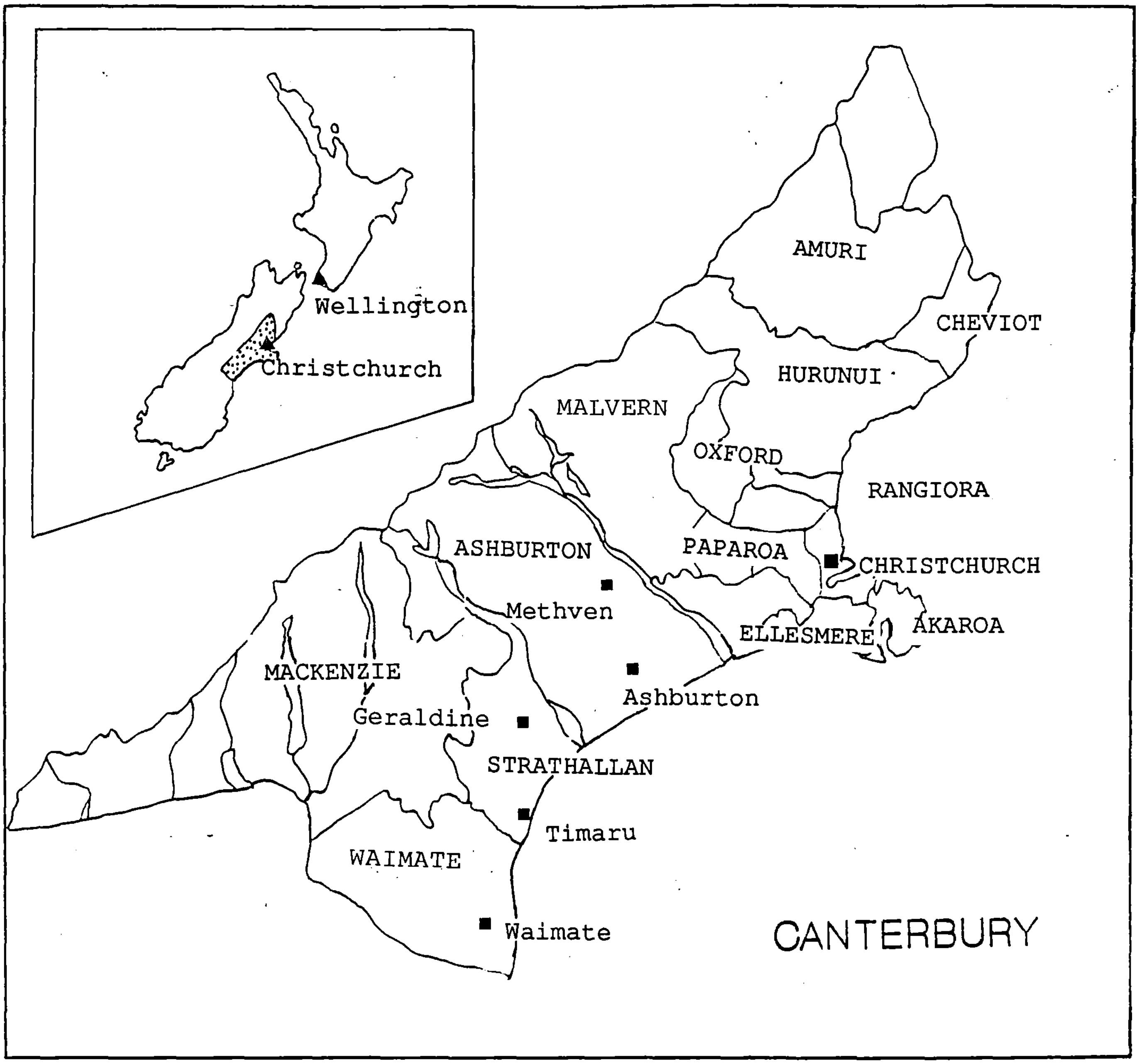


Fig. 7.6.1 Canterbury District and Counties from which wheat yield data was collected

The seasons chosen for the analysis of wheat were winter (June to August), spring (September to November) and summer (December to February). This covered the growing season of winter sown wheat which is the main wheat crop in Canterbury.

Rainfall data were normalized by a square root function after analysis of histograms showed some improvement by using such a procedure. Both rainfall and temperature data sets were then standardized as for the yield data.

Following the procedure of Wigley and Tu Qipu (1983), principal components analysis was carried out on the yield data and the temperature and rainfall data for each of the three seasons. In all cases the first three principal components accounted for approximately 80% of the variance or more. Details are given in the results section. Multiple regression analysis was then carried out for each of the yield principal components, using the total of eighteen climate principal components as predictors. A backward stepwise routine was used on SAS. Initially two thirds of the data were used as a calibration period, with two years out of every three being used for this purpose. The other third of the data was retained for verification. On the success of this result a regression using all of the data was carried out.

7.6.3 Results

Results of the principal components analysis are presented in Table 7.6.1. A high percentage of the variance was explained by P.C.1 for all of the variables indicating that the spatial responses are largely similar over the region as a whole. The result with the temperature and rainfall data is consistent with the results of Salinger's (1981) work and the more detailed analysis presented in section 7.5.

Given the general similarity in response to rainfall and temperature over the region as a whole it is not surprising that yield P.C.1 accounted for 61% of the variance. The eigenvector for P.C.2 had a high positive loading on North Canterbury counties, particularly Amuri and Hurunui, which encompass the inland Amuri Plain. The third eigenvector had a high positive loading on the southern extremes of Canterbury, most particularly in the Waimate area. As already discussed the southern counties fall in the South Canterbury rainfall response area delineated by Salinger (1981).

The results of the correlations, resulting from the verification procedure are presented in Table 7.6.1b and the regression equation for YIELD1 for all years in Table 7.6.1c.

Table 7.6.1

(a) Variance accounted for by the first three P.C.'s for the yield and climate data

Variable	P.C.1	P.C.2	P.C.3
Yield	61.2	71.0	79.8
Winter Rain	81.0	87.9	92.9
Spring Rain	73.8	83.6	88.5
Summer Rain	82.3	88.5	92.3
Winter Temp.	84.0	89.7	93.1
Summer Temp.	92.1	95.6	97.8

(b) Correlation coefficients from wheat model verification

County	Calibration	Verification
Amuri	0.80	0.48
Hurunui	0.73	0.31
Cheviot	0.86	0.71
Rangiora	0.78	0.60
Eyre	0.80	0.42
Oxford	0.82	0.44
Malvern	0.76	0.90
Paparua	0.74	0.79
Ellesmere	0.74	0.81
Ashburton	0.61	0.90
Strathallan	0.70	0.39
Mackenzie	0.45	0.79
Waimate	0.60	-0.17
YIELD1	0.85	0.86
YIELD2	0.52	-0.18
YIELD3	0.86	-0.56
Overall	0.73	0.41

(c) YIELD1, F=4, multiple regression model
R^2=0.673; F=8.21; P>F=0.0001

Variable	B value	F	P>F
Intercept	0.000		
WRAIN1	-0.353	7.84	0.0099
WRAIN2	-0.502	11.60	0.0023
SPTEMP1	-0.455	12.54	0.0017
SPTEMP2	-0.443	8.62	0.0072
SPTEMP3	-0.356	8.16	0.0087
SUTEMP2	0.512	12.29	0.0018

Some of the counties correlated better over the verification period than the calibration period. These were mainly Central Canterbury counties which comprise the largest part of the Canterbury wheat growing district. The poorest was Waimate, which is an obvious anomaly. Overall the yield P.C.1 model was the only one that verified well.

The results of the multiple regression show a negative influence of winter rainfall and spring temperature and a less marked positive influence of summer temperature. The second P.C. for summer temperature (SUTEMP2) had positive loadings on Balmoral and Ashburton climate stations, the latter representing the main wheat growing county.

The results are generally consistent both with previous research and with results from the district analysis. A cooler, drier winter appears to be favourable for autumn sown wheat. This is certainly reflected in the strong negative effect of winter rainfall, with the first two winter rain P.C.s gaining entry to the model. The strength of the relationship with spring temperature is also shown with inclusion of all three P.C.s in the regression model.

There is an apparent secondary effect with summer temperature. With a positive loading for Ashburton climate station it is possible that warm conditions over the ripening and harvest period are an important determinant of yield in this, the principal growing area.

The climatic factors limiting to wheat yield appear to have changed relatively little over the last one hundred years in Canterbury. It is also important to note the consistency with which South Canterbury appears anomalous, both with the climate data and the yield data. There is an apparent climatic connection with the anomalous yield response as shown by the poor verification of the P.C.1 model for Waimate county.

7.7 Drought in Canterbury

7.7.1 Definitions of drought

Drought has numerous definitions. It can be generally classified as a period of moisture deficiency. Maunder (1983) pointed out the required size of the deficiency is determined by the season, geographic location and activity affected. Human perceptions play a big part in determining what constitutes a drought. A warm, dry summer has a totally different meaning to a farmer and a holiday maker for instance.

The various definitions of drought are put into four main classes, as summarised by Finkelstein (1971). These are :-

1. Absolute and partial drought. These are British definitions. An absolute drought is a period of 15 days without any appreciable rain.

2. Broader definitions which may refer to rainfall being below a specified percentage of normal over a period of a few months.

3. Definitions which refer to a period of moisture deficiency in the soil.

4. Definitions which refer to the effects of drought.

In more recent years the N.Z. Met. Service has adopted a soil moisture balance approach to defining agricultural drought. A description of their approach and summary data has been published (N.Z. Met. Service, 1986). Rainfall and evapotranspiration data are used with an assumed available water capacity for the soil. A fairly straightforward budgeting approach is used to determine when the soil is in deficit and when it is at or below wilting point. The number of deficit days at or below the wilting point are an often used index of agricultural drought.

7.7.2 Spatial variation in Canterbury

Deficit day data, with an assumed available moisture capacity of 75 mm were obtained from the N.Z. Met. Service. The data used were for nine Canterbury climate stations ranging from Balmoral in the north to Waimate in the south.

A spatial analysis of this data was carried out using P.C.A. to see how consistent patterns of variability were with the observed climatic variables. The years examined were for the period 1955-1975. Seasonal totals were derived and analysis was carried out for autumn, spring and summer. There were no recorded deficit days recorded over the winter. An analysis of these three seasons combined was also carried out. Eigenvectors from the analysis of all seasons combined are given in Table 7.7.1.

Table 7.7.1

Eigenvectors from P.C.A. of deficit days, 1955-1975

Climate station	PRIN1	PRIN2	PRIN3	PRIN4
Balmoral	0.317501	-0.035050	0.565585	-0.572031
Ashley forest	0.342888	-0.179461	0.274881	-0.231762
Darfield	0.349825	0.180706	-0.236440	-0.121657
Christchurch airport	0.343993	-0.364400	0.059785	0.289730
Christchurch	0.334827	-0.404991	0.096720	0.407431
Lincoln	0.355968	-0.160268	-0.219021	0.206948
Winchmore	0.354605	0.187121	-0.405306	-0.110118
Ashburton	0.348410	0.272639	-0.360316	-0.237197
Waimate	0.234426	0.708571	0.440058	0.493059

For all analyses the first P.C. accounted for from 72 to 78% of the variance. Weightings were similar for all districts, with Waimate appearing as a slight anomaly.

In all cases P.C.2 accounted for 9 to 11% of the variance. In all seasons and overall there was a consistent and strong contrast between Waimate and Christchurch. The Rakaia river appears to be a general transition zone, with Ashburton and Winchmore associating with Waimate, and Lincoln associating with Christchurch. An exception was Darfield, inland from Christchurch which associated with the south. This result is generally consistent with the dominant sub regional response areas apparent from the analyses of other climate variables, in section 7.5.

A pattern more similar to Sturman's (1986) result with rainfall tended to come through in PRIN3 in individual seasons, and more clearly in PRIN4 in the overall analysis.

A clearer pattern would be apparent with a greater spatial representation, but it tends to reinforce the view that there are quite strong mesoscale differences in climatic response between the Christchurch locale and South Canterbury. These tend to outweigh the similarities in response. It should be remembered however that most of the variance with all variables was accounted for in the first P.C. and that these mesoscale contrasts are secondary and tertiary response characteristics.

7.7.3 Analysis of low rainfall years

Analysis of rainfall data can also give indications of drought. Table 7.7.2 summarises the 10 percentile annual rainfall for Waimate and Christchurch. Rainfall recording did not begin at Waimate until 1898. Taking this into account the two driest years at Waimate correspond to the two driest at Christchurch this century. The only other 10 percentile dry year that appears for both is 1931. The suggestion is that drought becomes a regional phenomenon in very dry years. In other dry years the severity of the drought tends to vary within the region. In most years a 10 percentile dry year at one station is matched by a below average rainfall year at the other.

An analysis of Canterbury drought by Maunder (1983) showed that dry periods can become very persistent in this region. This was confirmed by an analysis of the recent Canterbury drought which began in November 1987 and persisted through at least to late autumn 1989. The analysis was carried out in the spring of 1988. It showed that of the 10 percentile dry years at Christchurch only two out of twelve had a wetter than average summer following the dry spell. In the four driest years the drought persisted through the summer. At the time of this analysis the year was the driest to date on record. Assuming that the drought persisted to the end of December the analysis suggested that there was only a 17% chance of a wetter than average summer. If it persisted to be the driest year on record then there was a zero chance of a wetter than average summer based on historical patterns. Looking at the following autumn there was no consistent pattern, with an equal chance of it being drier or wetter than average.

This analysis was also generally consistent with N.Z. Met Service predictions based on the Southern Oscillation Index. The drought persisted through the summer, and to the end of April 1989 rainfall was still below average.

Table 7.7.2

10 percentile rainfall (annual totals) for Christchurch and Waimate

Waimate 10 percentile≤490mm		Christchurch 10 percentile≤481mm	
Year	Annual rainfall	Year	Annual rainfall
1969	371 (379)	1897	304
1915	400 (404)	1878	363
1931	429 (452)	1969	379 (371)
1906	450 (758)	1890	398
1907	450 (497)	1915	404 (400)
1973	450 (494)	1964	420 (497)
1948	451 (492)	1971	441 (613)
1910	487 (640)	1958	444 (563)
		1931	452
		1982	461
		1880	476
		1933	479 (560)

NOTE: bracketed values are totals in the same year for the station with which comparisons are being made i.e.:
Waimate (Christchurch); Christchurch (Waimate)

Although droughts of this severity are rare events in Canterbury, dry years are a recurrent phenomenon which can lead to persistent periods of below average rainfall. Apart from these persistent droughts there can also occur shorter periods, of a month or more, of below average rainfall. In spring and summer months this can lead to a high number of deficit days. If this occurs over critical moisture demand periods for a particular crop then there can be potential for significant yield reductions.

7.8 Impact of drought in Canterbury

7.8.1 Introduction

Both grain crops and pipfruit show sensitivity to periods of low rainfall in Canterbury. This was discussed briefly in section 7.3 and shown in the empirical models developed in Chapters 5 and 6 and the more detailed analysis of Canterbury wheat yield in section 7.6.

This section explores the impact of drought in more detail by assessing relationships between deficit days, as an index of agricultural drought, and yield. The yield data were the same as used in the district regression analyses, with trend removal carried out using a quadratic function. Deficit day data were for Christchurch. Crops examined were wheat, oats, barley, apples and pears. The period of analysis for the grain crops was 1930 to 1983 and for pipfruit it was 1941-1965. Simple correlation analysis was carried out. Results are shown in Table 7.8.1.

Table 7.8.1

Correlation of yields with monthly deficit days and rainfall and temperature for wheat

Month	Wheat	Oats	Barley	Apples	Pears	Wheat vs rain	Wheat vs temp.
Jun	-0.049	-0.129	-0.066	0.000	0.000	-0.142	-0.044
Jul	0.000	0.000	0.000	0.000	0.000	-0.311*	-0.108
Aug	0.000	0.000	0.000	0.000	0.000	-0.253+	-0.151
Sep	0.267+	-0.032	0.089	-0.100	0.103	-0.326*	-0.236+
Oct	0.320*	0.183	0.430**	0.030	0.089	-0.022	0.009
Nov	-0.116	-0.303*	0.132	0.209	0.148	0.186	-0.189
Dec	-0.040	-0.337*	-0.326*	0.340+	0.080	0.021	-0.233
Jan	-0.057	-0.169	-0.106	-0.334	-0.370+	0.119	-0.212
Feb	-0.041	-0.023	0.210	-0.059	-0.063	0.028	0.047
Mar	-	-	-	-0.224	-0.296	-	-
Apr	-	-	-	-0.100	-0.205	-	-
May	-	-	-	0.103	0.275	-	-

NOTE:
+ =10% significant
* = 5% significant
**= 1% significant
Apples are not quite 10% significant in January

7.8.2 Grains

The result with wheat initially appeared anomalous. It was clarified by carrying out a correlation analysis of yield with rainfall and temperature. Regression analysis of wheat crop-climate interactions in Canterbury gave winter rainfall and spring temperatures as having significant negative relationships with yield. This is also apparent from the correlation coefficients. It further appears that a wet winter followed by a wet spring could have a negative effect on yield. Dry conditions in spring, particularly after a wetter than average winter appear preferable. This is at least true in September and October, although the correlation with rainfall is very weak in the latter month. At the same time, cooler than average temperature conditions are preferred, particularly in September. The strength of the temperature relationship in the regression analyses suggested that this is a highly temperature sensitive period. Although the preference is for drier conditions, above average temperatures, particularly if associated with warm Nor'west conditions, could soon lead to physiological stress and a yield depression. As summer approaches lack of rainfall and warmer temperatures can be limiting, but the relationships are weaker.

The results with oats and barley are consistent with those from the regression analyses. Oats are particularly sensitive to soil moisture deficit conditions in November and December. For barley the only month when yield is affected by a high number of deficit days is December, which was the critical month in the regression analysis and in the study of Malcolm (1947). Of interest with barley is a highly significant positive correlation with October deficit days. It appears that in early developmental stages water is generally not limiting and that warm, dry conditions are preferred. Water becomes limiting at the crucial flowering stage, but as shown previously dry conditions are preferred nearer to harvest, shown by a weaker positive correlation with February deficit days.

7.8.3 Pipfruit

The shorter time series of data for apples and pears may in part explain the relatively lower significance of the correlations. These crops are highly sheltered, both with planted shelterbelts and some self sheltering amongst established trees. This would provide benefits in terms of moisture conservation. Their deeper and broader root systems would allow them to draw more moisture from the soil. However a high number of deficit days in January can be limiting to both crops. With apples the relationship is not quite 10% significant. It is probable that increased use of irrigation in latter years, particularly in the Loburn area, where lack of irrigation often led to low yields, has reduced the impact of moisture stress in this month. However as the recent Canterbury drought has shown, water for irrigation can become a scarce resource in persistent drought periods. Some fruit growers in the Loburn area were affected in the recent drought with water restrictions imposed on them as their irrigation source, the Ashley river, was reduced to sub optimal flows.

Both apples and pears show a weak positive relationship with November deficit days, and apples show a significant positive relationship in December. The preference seems to be for relatively dry conditions in early fruit development stages.

Lack of soil moisture appears to be detrimental over the harvest period, in March and April. Rainfall at this time would delay harvest and allow the fruit to size up more, being of particular benefit to mid season varieties.

7.9 Summary

This Chapter has provided a broad review, and in depth analysis of the Canterbury agroclimate resource. Historically the climate and soils of this region have been exploited for the growing of temperate grains. Horticulture has been a secondary activity, mainly catering to local demand. Patterns of land use haven't changed dramatically since the earliest white settlers arrived in the mid 19th century.

The region is subject to climatic extremes, from warm, dry northwest winds to very cold, showery southerlies. The transition between the two can be very rapid. Longer periods of extreme conditions, such as drought, are also recurrent phenomena. The impact of the recent drought in Canterbury showed that lessons from the past have not been fully learnt.

A review of spatial variability in Canterbury climate highlighted five main geographic divisions, covering areas from the plains to inland basins. The Canterbury Plains appear to be climatically homogeneous. They are to quite a degree, as reflected in the results of Salinger's (1981) spatial analysis. Both the work of Salinger (1981) and Sturman (1986) highlighted significant, but different sub regional responses to rainfall.

Spatial analyses of a range of climate variables were carried out. Results with temperature, rainfall and sunshine data showed a general North and Mid Canterbury versus South Canterbury contrast. Some anomalous stations were apparent, particularly with temperature and frost data, highlighting the important effects of site location and microclimate. Closer analysis of the rainfall data showed the north, south contrast to be largely a result of local geographic features. The contrasts were greatest between climate stations in the locale of Banks Peninsula and those in the locale of the southern foothills. Generally the divisions were consistent with those identified by Salinger (1981), although a tertiary rainfall response regime, more consistent with Sturman's (1986) result, was also apparent.

Spatial analysis of yield and climate data for wheat in Canterbury reinforced results from previous work and those from the district analysis in Chapter 5. The verification procedure showed Waimate to be anomalous in its yield response to climate. This reinforced results from the spatial analysis of climate data.

Drought was identified as a recurrent phenomena in Canterbury. Spatial analysis of deficit day data showed a pattern consistent with analysis of other climate variables. This result was reinforced by a review of 10 percentile rainfall years in Christchurch and Waimate. It appeared that drought only becomes a regional phenomenon in the driest of the dry years. However a 10 percentile dry year at one station is almost always associated with a drier than average year at the other. Further analysis showed the recurrent droughts to be persistent. This was used as the basis for prediction for the 1988-1989 summer.

As a final step time series of yield data were correlated with time series of deficit day data for Canterbury. This provided a confirmation of what had been deduced from the empirical crop-climate analyses and further highlighted the significant impact of drought on crop yields in this region.

CHAPTER 8

The Value of Shelter: review and methods

8.1 Introduction

The importance of climate to food production in New Zealand is unquestioned. Relationships between temperature and rainfall were examined in Chapters 6 and 7. A more detailed evaluation of yield responses to climate in Canterbury was carried out in Chapter 8, particularly with wheat. From these analyses it is apparent that periods of water deficit, particularly if associated with periods of higher than average temperature, can be limiting to a range of crops. Different crops show greater sensitivity to climate at certain developmental stages, which on the basis of these findings, normally coincides with periods with the greatest potential for agricultural drought.

There are few options available to both arable farmers and fruit growers to respond to the inherent variability of climate. Sturrock (1984) commented that shelter and irrigation are the main options available to farmers for modification of the local environment. The value of shelter to primary production in New Zealand was highlighted in an excellent report by the National Shelter Working Party, edited by Sturrock (1984). Shelter has long been recognised as essential for high value horticulture crops, but there has been greater difficulty in convincing arable farmers of the benefits.

In Chapter 7 it was shown that drought is a recurrent and persistent phenomenon in Canterbury, as it is in other east coast regions of New Zealand. Shelter offers considerable potential to modify both the local and regional environment and provide greater security in terms of yield benefits and other flow on effects. A brief review of the physical and biological benefits of shelter is given. This provides the background for a field based study on shelter in Canterbury, which is then described.

8.2 Effects of shelter on microclimate

The microclimatic and yield effects of shelter have been well reviewed and discussed by van Eimern et al (1964), Grace (1977) and more recently Rosenberg et al (1983). A brief review is given here.

The effect of shelter on any climatic variable is subject to the influence of a range of factors. The main causes of variation are orientation and height of the shelter, position of measurement in relation to the shelter, as well as season, time of day and prevailing weather. It is also important to realise that the microclimate of a particular site has a regional, and even global context to it. Much of the research with shelter has ignored, or overlooked the importance of this regional and global context.

8.2.1 Wind

The most direct effect of shelter is to reduce wind speeds, mostly in the lee but also to a lesser degree to windward (McNaughton, 1986). The direct benefits of this can be a reduction in physical damage to plants, reduced wind erosion and for fruit crops a more conducive environment for pollination by bees.

Few studies have examined the regional effects of shelter. Jensen (1954) compared windspeed across an open, flat terrain and a rougher terrain with many hedgerows. The latter showed a greater wind reduction near the ground. It was considered by Kaiser (1959) (from van Eimern et al, 1964) that extensive shelter systems increase the roughness of the ground surface as a whole and that the resistance is greater than that of an unprotected surface. Guyot and Seguin (1975, 1978) examined in detail the interactions between microclimate and the regional effects of a sheltered landscape. This was initiated by concern over the impact of tree hedge removal from the Bocage landscape in Brittany, France on both local and regional climate. The local windspeed reduction was found to be larger than that generally observed from single shelterbelts, which was thought to be related to the roughness of the landscape. Examination of the vertical wind profile in sheltered areas showed evidence of the effects of regional roughness in the upper profile, and of local site characteristics in the lower profile. This "kink" in the profile was also evident in the measurements of Cherry and Smyth (1984) at Lincoln, New Zealand. More recently McAneney et al (1989, in press) were unable to reconcile their windrun measurements at a fixed height with the work of Guyot and Seguin (1975). The measurements at a fixed height were taken over a six year period when shelter trees were growing. Examination of Fig. 3 in Guyot and Seguin (1975) shows a transition height of approximately 7m for a large field. Assuming that the orchard site was in a similar environment at the time of orchard establishment it would have already been inside the local zone, which would explain the linear relationship shown in McAneney et al's (1989, in press) results. Their result is therefore not inconsistent with the work of Guyot and Seguin (1975) or Cherry and Smyth (1984). Concurrent vertical profile measurements may have demonstrated similar profile kinks, and probably a steady increase in height at which the sheltered site was 'decoupled' from the surrounding environment. This is supported by research presented here.

8.2.2 Temperature

The temperature range appears to be greater in sheltered environments. This is attributed to generally higher maximums and sometimes lower minimums. Both can be attributed to reduced turbulent mixing. In the daytime this results in greater retention of sensible heat at or near the surface. On clear nights inversions can be intensified leading to lower minimums in sheltered areas. Increased soil temperatures have been generally documented in sheltered sites and are supported by the findings of McAneney et al (1989, in press).

An important observation has been that differences in temperature gradients between sheltered and exposed sites are greatest near to the ground, becoming slight at or near standard screen height. This led both Rosenberg (1966a) and Guyot and Seguin (1974) to conclude that screen measurements are not a true representation of surface modifications of shelter.

8.2.3 Relative humidity and vapour pressure

Intensified vertical gradients of humidity and vapour pressure have also been commonly observed in sheltered environments (Rosenberg et al, 1983). This has been attributed to reduced transportation of water vapour from the surface. Differences in relative humidity can mainly be related to differences in the temperature regime.

8.2.4 Evaporation

One of the principal conclusions of van Eimern et al (1964) was that a major benefit of shelter was the direct reduction in soil moisture evaporation, as a result of reduced wind speeds. A later review by Grace (1977) considered this effect to be inconclusive on the basis of research done over the previous decade. More recently Rosenberg et al (1983) have stated that all reviewed studies show that with less wind there is reduced evaporation. McAneney et al (1989, in press) found no significant differences in pan evaporation between sheltered and exposed sites. This was attributed to the oceanic locale and the absence of large mountain ranges in Northland, New Zealand, where the measurements were taken.

In a sheltered tamarillo (Cyphomandra betacea) orchard in Northland Judd and McAneney (1984) found an apparent reduction in the influence of advection on evaporation, with a tendency toward the equilibrium rate. This is defined in section 8.5.4. A later study in Nelson by Judd et al (1986) showed advective enhancement of evaporation to contribute from 21 to 49% of daytime water use with well sheltered kiwifruit (Actinidia chinensis) plants. This was attributed to the combined effect of regional topography, droughted pasture upwind of the orchards and very windy conditions over the period of measurement. They considered their results to represent the likely upper limit of the contribution of advection to water use by kiwifruit under New Zealand conditions. However they suggested that the Priestley-Taylor formula (α=1.26) be used in all but strongly advective conditions in New Zealand.

8.2.5 Radiation

Generally only slight differences in net radiation have been observed and on a daily basis could be considered as the same between sheltered and unsheltered sites, assuming that measurement is not made directly in the lee of the shelter. A slight increase in infrared loss was observed to be compensated by an equal increase in absorption of solar radiation by Guyot and Seguin (1978). This latter effect was attributed to reduced regional albedo.

8.2.6 CO_2 concentrations

More rarely measured are CO_2 concentrations, the most frequently quoted study being that of Brown and Rosenberg (1972) whose results showed very slight differences in CO_2 concentration to occur. This has implications in terms of photosynthetic activity and consequently yield. The literature on yield effects almost universally documents yield increases with shelter. Given little difference in CO_2 concentrations between sheltered and unsheltered sites the suggestion is that the available raw materials for growth (i.e. H_2O and CO_2) are more efficiently exploited in sheltered environments, as generally concluded by Rosenberg et al (1983).

8.3 Biological effects of shelter

As the empirical analysis of crop-climate interactions showed, crops are variable in their response to climatic factors, both spatially and temporally. The temporal response depends on crop phenology and the physiological status of the plant at a time of potential environmental stress. All crops examined showed critical moisture and temperature sensitive periods.

Sturrock (1984) noted that it is a common misconception that increases in wind lead to greater water use by plants. He identifies the important mechanism as being the effect of wind speed on stomatal closure. Increases in wind speed increase the potential for greater water use by the plant. The plant response under such conditions is to close or partially close its stomata. Sturrock (1984) stated this "restricts photosynthesis, translocation of carbohydrates and growth regulators, uptake of minerals from the soil, and nitrogen metabolism, all of which impair plant vigour and growth."

Rosenberg et al (1983) concluded that water use efficiency of plants is either improved or unaffected by shelter, with the improvement greater in dry years and in periods of strong sensible heat advection. This was considered to be the principal benefit of shelter in arid and semi arid areas. Other benefits in both arid and humid regions include rapid seed germination, vigorous vegetative growth and physical protection (Rosenberg et al, 1983). The literature almost universally documents increases in yield in sheltered environments (Appendix D) and this was attributed to improved water use efficiency by Rosenberg et al (1983).

Changes in the thermal regime resulting from shelter were considered to potentially have a significant influence on the range of crops that could be grown (McAneney et al, in press). Their study was carried out in the warm temperate to subtropical Northland region of New Zealand. In areas such as Canterbury, where the incidence of frost in winter is high, an increase in continentality might be expected with shelter. This would have important beneficial effects for temperate crops which require cool winters for winter chilling and warm summers for fruit development and maturation.

Another important consideration is the potentially synergistic effect of shelter in combination with well timed irrigation. Both crop water use efficiency can be potentially improved, as well as production, to a greater degree than would be predicted by adding the individual effects of these factors. This effect is well reviewed by Sturrock (1984).

The value of shelter is widely recognised for horticultural crops in New Zealand. The principal benefits to horticulture from shelter are protection from the wind and the warming effects (Sturrock, 1984). Higher temperatures in spring will hasten germination of spring sown crops and also the early growth flush of deciduous fruit trees. Temperature is important for pollinating insects. As discussed in Chapter 6 warm temperatures in spring are also important for pollen tube growth in pipfruit. Use of irrigation, in conjunction with shelter, is widely recognised with horticultural crops. Sturrock (1984) commented that the high capital outlay required for both is one of the factors that has inhibited expansion of horticulture in Canterbury.

Most of the measured yield responses to shelter have been documented with arable crops. Use of shelter in cropping areas was largely a response to widespread problems with wind erosion of soil. Extensive plantings of shelterbelts occurred in the Great Plains region of the U.S. after the combined drought and wind erosion problems of the 1930s. In New Zealand there was a similar response to wind erosion problems with the establishment of the National Water and Soil Conservation Organisation. In more recent years questions have been raised about the yield benefits with arable crops, which has been the stimulus for much research, notably by Rosenberg in North America and Sturrock in New Zealand. Of relevance to this current research are the field trials carried out by Sturrock (1981, 1983) with spring sown oats and barley in Canterbury. The oat crop showed an average yield increase of 35% up to six times the height to the lee of the shelter, in a below average rainfall year. Barley also showed a yield increase with shelter. Responses are often variable, with yield reductions in some cases, as Sturrock (1984) noted. Generally the benefits to cropping appear to be greater in drier than average years.

8.4 A regional perspective

The use of trees for shelter in New Zealand was formalised by the passing of an Act of Parliament in 1941 which made provision for the planting of trees for wind and water erosion control.

Canterbury is a region in New Zealand that is particularly vulnerable to wind erosion. This particularly occurs in periods of persistently low rainfall. Soils are particularly vulnerable in late spring and summer when there is a greater frequency of drying nor'west winds and a high potential for soil moisture deficit conditions.

The North and South Canterbury Catchment Boards have been particularly active in promoting the planting of trees for shelter. There continues to be considerable resistance from farmers whose obvious concerns are with loss of land, interference with current activities and establishment and maintenance costs. As will be discussed in Chapter 10 there are more than crop yield benefits attributable to shelter. In the past many shelterbelts have been poorly designed and managed and therefore their potential hasn't been fully realised. More recently loss of Government subsidies and an economic downturn have discouraged farmers from planting trees. This has occurred in the driest period on record in Canterbury. This situation has again highlighted the need for well planned shelter in Canterbury.

In section 8.2 the review of the wind effects of shelter were discussed. Particularly of interest is the regional effect. The impression gained was that a regional mosaic of shelter can have a potentially significant effect on the region as a whole. Zakharov (1965), quoted in Miller (1981), suggested that where shelterbelts occupy 5% of the land area crop damage by wind can be reduced to nearly zero. In North Canterbury, out of an area of 370 000 ha of arable land 972 km of shelter had been planted by 31 March 1984 (Wethey, 1984). Assuming an average shelterbelt width of 3-5m this amounts to 292-486 ha or approximately 0.1% of the arable land area, a tenth of the desired regional total (Wethey, 1984) and well below the optimum given by Zakharov (1965).

The work of Guyot and Seguin (1975) in particular provided the stimulus for the current study. Although the field measurements were of shorter duration the general principles applied were similar. The primary interest was to contrast different sites of differing exposure in an attempt to assess the degree of decoupling that might occur from the regional climate. Each site was considered within the context of the regional environment as measured at a well exposed reference site. The physical measurements at each site are considered within the context of the effects of agricultural drought in Canterbury, as examined empirically and in the literature on shelter effects on yield.

8.5 An experimental program

8.5.1 Introduction

It was with a regional perspective in mind and a concern as to how individuals could respond to uncertainty that a field study of shelter was initiated. This was considered within the context of regional and national crop-climate interactions explored in Chapters 5 to 7, with particular attention to the persistence of drought in Canterbury. A principal concern was to explore one possible way in which individuals can respond to the inherent variability of climate which may also currently be associated with a period of climatic change.

The initial aim was to take simultaneous measurements from a 20m portable mast and a fixed 30m mast at the now closed Lincoln College climate station. This would have allowed for simultaneous comparisons of wind and temperature profiles. Unfortunately the instrumentation and data retrieval system for the 30m mast was not operational for the field work. This problem was overcome by selecting the Broadfields, Lincoln climate station as a reference site. Location of the mast at this site allowed for characterisation of the wind profile and calibration of the portable mast against the climate station. On the basis of these relationships it was then possible to make comparisons between the other, remote, sites and the Broadfields, reference, site. Apart from Broadfields, which is an exposed site, sites chosen were the Lincoln College Plant Science research plots (moderately exposed), the Lincoln Horticultural Research Area (well sheltered) and the new Lincoln Springs orchard (moderately sheltered). All sites chosen were grassed. The mast was located at each site for a single period of approximately one month. Details are given in Chapter 9.

Variables compared were mean, maximum and minimum temperatures, wind speed at 6m, saturated vapour pressure, vapour pressure and vapour pressure deficit, and evapotranspiration. Organisation of the data and the statistical basis for comparison is presented in sections 8.5.5 and 8.5.6. The characterisation of wind profiles and estimation of evapotranspiration warrant further discussion, which is given in sections 8.5.3 and 8.5.4 respectively.

8.5.2 The mast and data recording

A 20m portable mast was obtained on loan from the Mechanical Engineering Department, Canterbury University. A diagram of the mast and instrumentation and an accompanying photograph are given in Fig. 8.5.1. Anemometers were readily available as were temperature probes, net radiometer and relative humidity probes. Radiation shields for some of the temperature probes had to be built as did aspirated screens for the relative humidity probes. A wind vane was also built to allow characterization of the main wind sectors. Laboratory calibration of the temperature probes and anemometers was carried out, with a final field calibration of the former. The commercial calibrations of the RH probes and the net radiometer were used. The former were checked in the field against a whirling psychrometer. A discussion of instrument calibration and measurement is presented in Appendix E. A programming fault led to loss of net radiation data for the first measurement site. Values were estimated based on a derived relationship between net radiation and solar radiation. This is also described in Appendix E.

For data recording and storage a Campbell Scientific CR7 data logger was used. An execution interval of 10 seconds was chosen with hourly averages going to final output. Data were automatically downloaded to a C90 audio tape when the output buffer was full. At the end of measurement at each site data were downloaded through a Campbell Scientific interface to the VAX computer system at Lincoln. Data were then reformatted courtesy of a Fortran program from Peter Carran, NZAEI. This then allowed for data manipulation and analysis with the SAS and Minitab software packages.

8.5.3 Wind profile characterisation

The aim of the wind speed measurements was to determine the profile characteristics of individual sites, for the main wind sectors and for each site as a whole. Comparisons between Broadfields daily mean wind speed (6m) and the mast (6m estimated) were also made.

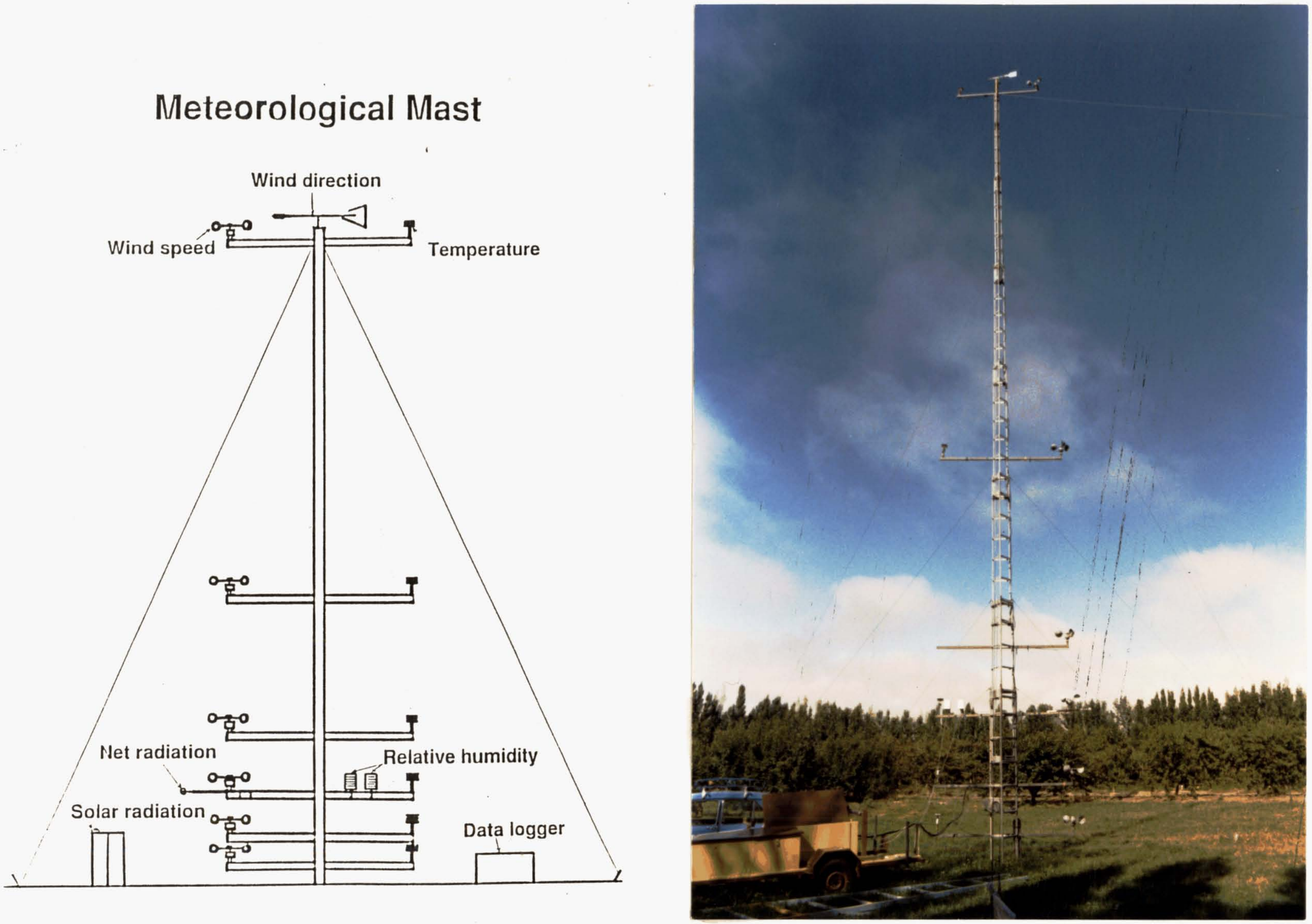


Fig. 8.5.1 Schematic and photograph of 20 m portable mast and associated meteorological instrumentation

It was anticipated that the upper part of the profile would give an indication of regional surface roughness and the lower part, local site roughness, based on the results from Guyot and Seguin (1975) and Cherry and Smyth (1984). The roughness length is characterized by the equation:

$$U_z = \left(\frac{U_*}{k} \right) \ln \left(\frac{z}{z_0} \right)$$

where U_z is the mean wind speed at height z, k is von Karmen's constant, U_* is the friction velocity and z_0 is the roughness parameter.

Alternatively, mean wind speed at each height can be plotted against the logarithm of height and straight line relationships extrapolated to give the roughness parameter at zero wind speed. The presence of two straight line relationships would be representative of the transition from regional to local surface effects.

Although instantaneous measurements were not possible from a reference and remote site comparisons are still possible. The important limitation can arises from differences in the frequency and strength of wind from different sectors over different measurement periods. Overall site comparisons should therefore be made with a greater degree of caution than those for specific wind sectors.

8.5.4 Evapotranspiration

Evaporation and evapotranspiration are well reviewed by Rosenberg et al (1983). This section gives a brief introduction to evapotranspiration estimation under New Zealand conditions.

Coulter (1975) examined methods for prediction of evapotranspiration from climatological data. He found the Penman combination method to agree well with estimates based on evaporation tank data. The Priestley-Taylor method was not evaluated in this study. Clothier et al (1982) measured evapotranspiration over a number of different crops near Palmerston North, New Zealand. They contrasted values derived from the Bowen ratio-energy balance method with daily estimates based on the Penman and Priestley-Taylor formulae. Both gave a similar level of accuracy, with errors of 15-20% for daily estimates. On the basis of the similar performance of these two methods of estimation it was concluded that the latter was more desirable because of its lower data requirement. A later study by Green et al (1984), in the same area over mixed pasture, confirmed the usefulness of the Priestley-Taylor method. They used a locally calibrated constant (α=1.21) for their estimation of evapotranspiration. Both studies were careful to point out that the reliability of meteorologically based formulae diminishes under conditions of water stress, most particularly in the presence of significant advection.

Comparisons between measured and estimated evapotranspiration have also been made in Canterbury by Jamieson (1982a) over a barley crop. The Priestley-Taylor estimates based on standard meteorological data, underestimated actual accumulated evapotranspiration by 9%. The Penman estimates overestimated by 17% as shown in a correction to the original paper (Jamieson,1982b). It was noted that under conditions of strong advection in Canterbury (associated with nor'west days) the aerodynamic term in the Penman method will become large due to the high vapour pressure deficit on such days, of the order of 30 mbar. The Priestley-Taylor method is not so strongly affected due to the absence of an aerodynamic term. Earlier in his thesis, Jamieson (1980) discussed in more detail the effect of high temperature and high vapour pressure deficit conditions on the ratio between actual and estimated evapotranspiration. It was observed that such conditions were associated with both a reduction in transpiration of the crop and an increase in estimated (or potential) evapotranspiration. The result of such conditions therefore is generally a sharp reduction in the ratio between actual and estimated evapotranspiration. It would seem that this reduction is more pronounced with the Penman than the Priestley-Taylor method, due to the effect of the aerodynamic term as discussed earlier.

Estimates of evapotranspiration from both the Penman and Priestley-Taylor methods were calculated for the field sites. In the absence of measurement of actual evapotranspiration it was decided to be consistent in the use of the empirical constants for both of the equations. This was decided in light of the previous research done in New Zealand. In application of the Penman formula the aerodynamic term has essentially been that originally used by Penman (Coulter,1975, Clothier et al,1982, Jamieson,1982). This is of the form:

$$Ea = f(u).vpd = 0.26(1 + 0.5u)(e_s - e_a)$$

where Ea is the aerodynamic term, f(u) is the wind function with wind speed u in ms^{-1} and $(e_s - e_a)$ is the vapour pressure deficit. The Penman formula is then:

$$ET = \frac{s(Rn - G) + \gamma Ea}{s + \gamma}$$

where s is the slope of the saturation vapour pressure curve as previously defined, Rn is net radiation, G is the soil heat flux and γ is the psychrometric constant (0.66 mbar $^\circ C^{-1}$, Monteith, 1973).

A constant of α=1.26 for daytime net radiation was used in the Priestley-Taylor equation so that:

$$ET = 1.26 * \frac{s(Rn + G)}{s + \gamma}$$

Although strongly advective conditions do occur in Canterbury at times, most particularly with nor'westers as previously mentioned, they do not predominate. Any such days are readily apparent in the data, represented by high wind speeds, high temperatures (25-30°C, or higher on occasion) and a high vapour pressure deficit (around 30 mbar). Estimates based on the formulae given were considered reasonable under all but extreme conditions of advection. As a matter of interest an empirical check on the consistency between the two methods of estimating evapotranspiration was carried out, using mast data from each site. On the assumption that the Penman equation will tend more towards actual evapotranspiration because of the aerodynamic term, a regression was carried out between Penman estimates and equilibrium values. Equilibrium evapotranspiration, ET_{eq}, is defined in Rosenberg et al (1983) as :-

$$ET_{eq} = \frac{s(Rn + G)}{s + \gamma}$$

It had been intended to check estimates from both the Priestley-Taylor and Penman equations against Bowen ratio values, but the RH probes were found to be not sufficiently accurate to derive such values.

8.5.5 Organisation of the data

Hourly means of all measurements were collected and recorded on the CR7, as mentioned earlier. Because the Broadfield climate station data is collected only once a day a rational method for comparing variables from the remote sites with the climate station data was required. This section describes how the data were organised. Individual variables had to be tailored to match the climate station as much as possible.

The station data is read at 9.00 am each day, or 8.00 am N.Z. Standard time when daylight saving is in force over the summer months. Wind run at 6 m and maximum temperature are assigned to the previous day. Minimum temperature is assigned to the current day and daily mean temperature is calculated from the daily minimum and maximum. There is the possibility that the recorded maximum and minimum are not the true values for the days to which they are assigned. This arise occasionally when there is a deviation from the normal diurnal variation of temperature, such as a warm Fohn wind occurring in the morning prior to the reading time. Vapour pressure is calculated from the 9.00 am readings of dry and wet bulb temperatures, such that

$$e_a = e_s(T_w) - \gamma^*(T_d - T_w)$$

where e_a is the actual vapour pressure, $e_s(T_w)$ is the saturated vapour pressure at the wet bulb temperature and γ^* is the psychrometric constant given a value of 0.85 for screen measurements above 0 °C. T_d and T_w are the dry and wet bulb temperatures respectively. As will be seen with the results vapour pressure is a fairly conservative value and not necessarily conducive to site comparisons. The relative humidity is the ratio between the vapour pressure and the saturated vapour pressure. At the dry bulb temperature.

$$RH = \frac{e_a}{e_s(T_d)} * 100\ \%$$

The vapour pressure deficit is calculated as the difference between saturated vapour pressure at the daily mean temperature and vapour pressure. For evapotranspiration estimation, net radiation is normally estimated from solar radiation. Wind run is estimated from the 6 m value.

Because of the occasional break from the normal diurnal temperature pattern, anomalies were apparent when making preliminary comparisons between the Broadfields climate station data and the data from the portable mast, for the period during which the mast was located at Broadfields. For a better comparison therefore, it was decided to use 24 hr "days" starting at 9.00 am and finishing at 9.00 am the next day. Mast temperatures were taken from each 9.00 am to 9.00 am period, as were screen minimum and maximum values. For comparison of mean temperatures, mast values were averaged over the 24 hour period and the screen values averaged for the same period. In hindsight it would have been more consistent to average the mast maxima and minima. As will be discussed in the next section some anomalies were apparent because of this approach. Even greater consistency could have been achieved, as was realised later, by programming the CR7 to record hourly maxima and minima.

A 6 m value for mean wind speed was estimated for each day from the daily mean wind profiles for comparison with the station values as derived from 24 hour wind run. Calms were included in averaging the mast data as they were implicit in the wind run data.

Vapour pressure was derived for the mast from the average of the 9.00 and 10.00 am mean temperatures, representing the mean of the 8.00 am to 10.00 am period. Saturated vapour pressure was calculated from standard daily mean temperatures. The rationale for this was to maintain consistency in evapotranspiration estimation, as the latter had as input daylight net radiation data.

Derived values are routinely calculated by the DSIR for Broadfield, however they were calculated again for the purpose of site comparisons to ensure consistency in computation.

8.5.6 Statistical basis for comparison

With inconsistencies in instrumentation, in some cases measurement heights and methods of averaging, some statistical basis for comparing sites with the reference site was required. The best option available was to calibrate the mast against the reference climate station. From this period of calibration regression relationships were developed, with mast values used as predictors of screen values. This effectively overcame problems associated with differences in instrumentation and data recording. Temperature was measured on the mast at 0.56 and 2.58 metres. Data from both heights were used as predictors of screen values. Both gave good correlation and therefore a single relationship was derived incorporating both as predictors. Simple regression relationships were derived for all other variables.

Data collected from the different remote sites were then input into the calibration equation, which yielded estimated screen values for those sites. These estimated values then provided the basis for making a comparison between each remote site and the reference Broadfields site, using estimated screen values for the former and recorded screen values for the latter. For each site, estimated remote site values were regressed against actual reference site values. Of interest statistically was the deviation of these relationships from the relevant 1:1 relationships, the latter indicating of no difference between sites. There are two possible types of deviation: in slope and in elevation. The first is examined by comparing the difference in slope between the regression line and the 1:1 line. The second involves comparing the elevation of the regression line with that of the 1:1 line.

For the comparison of the estimated slope $\hat{\beta}$ with the hypothetical slope of $\beta_0=1$, the appropriate statistic is:

$$\frac{\hat{\beta}-1}{se(slope)}$$

which has a t distribution with df=n-2 if the true slope is $\beta=1$.

For the comparison of the elevations of the regression line and that of the 1:1 line, the appropriate statistic is:

$$\frac{\bar{y}-\bar{x}}{se(\bar{y})}=\frac{\bar{y}-\bar{x}}{\sqrt{s^2/n}}$$

which is the difference in elevation at the mean x value, divided by the standard error of this difference. This statistic follows a t distribution with df=n-2 if the true difference in elevation is zero.

It was apparent when exploring the regression relationships between estimated site values and Broadfield screen values that outliers were present that were possibly distorting the relationships. In statistical terms outliers can exert high leverage on regression lines, particularly those outlying along the fitted line, thus affecting the slope. Such data points may carry a small amount of bias, but because of their position small changes are significant. Other outliers may not have a significant levering effect, but due to a high degree of bias, they can have a significant influence on the elevation of the fitted line. Where outliers were suspected of disproportionately influencing either the slope or the elevation the raw data were critically evaluated to assess whether this effect was true or biased in some way. Most of the examples arose with mean temperatures, with a flow on effect on saturated vapour pressure, vapour pressure deficit and estimated evapotranspiration. This was the result of the different methods of averaging the raw data, ie a 2-point versus a 24-point mean. In the extreme cases highlighted here this bias was carried through into the estimated screen values for each site. Individual examples are discussed in the presentation of the results. Data were only removed where there was a clear rationale for doing so. Often this led to a change in significance of the result. While outliers were removed from the regression analyses, the data points were included in the appropriate graphs and are clearly indicated.

CHAPTER 9

Results from field measurement of shelter effects

9.1 Location of the study area and prevailing weather

Measurements were made within the general vicinity of Lincoln. The Lincoln campus is situated 16 km from the city of Christchurch. The dominant feature in this area is the Banks Peninsula, which is to the east of Lincoln as seen in Fig. 7.2.1. Fig. 9.1.1 shows the Lincoln area, in which the field work was carried out. Three of the measurement sites are located within a 1.5 km radius of the campus. These are the Broadfield climate station, the Plant Science Department research block and the Horticultural Research Area. These sites are marked on Fig. 9.1.2. The fourth site, Lincoln Springs orchard, is located 6 km north of the campus, and is indicated on Fig. 9.1.1. All lie within a similar climatic zone, with the Peninsula having a significant local influence, particularly on rainfall as discussed in section 7.4.

Of interest is the microclimate of each site and the degree of variability that is present, largely as a result of human modification, in an otherwise fairly homogeneous environment. The sites are described and results presented in order of time when measurements were made. An exception is Broadfield which is described first as the reference site, but was not monitored first chronologically.

The field work began in mid-October 1987. This was a month of above average rainfall. The remainder of the measurement period, through until early May, was characterised by drier than average conditions. This marked the beginning of what was to become the worst drought on record in Canterbury. Temperature conditions were generally mild, with several cloudy months lowering the daily temperature range. A dominance of northerlies led to warmer than average conditions. The October to December period was characterised by generally cloudy weather. January was sunny, followed by a cloudy February. The remainder of the measurement period was characterised by mostly mild, sunny weather, although conditions were cooler than average in April and May. More detail is given for each site in the site descriptions.

9.2 The Broadfield site

9.2.1 Site description

The Broadfield site is part of the DSIR Crop Research Division research area and is located approximately 1 km north of the Lincoln campus. The climate station itself is fenced off in a small paddock. There is a low gully running east west to the immediate north of the site. Beyond this are the field research plots. To this east there is a large cultivated field, bounded by a single row shelterbelt on its eastern boundary. This is several hundred metres away.

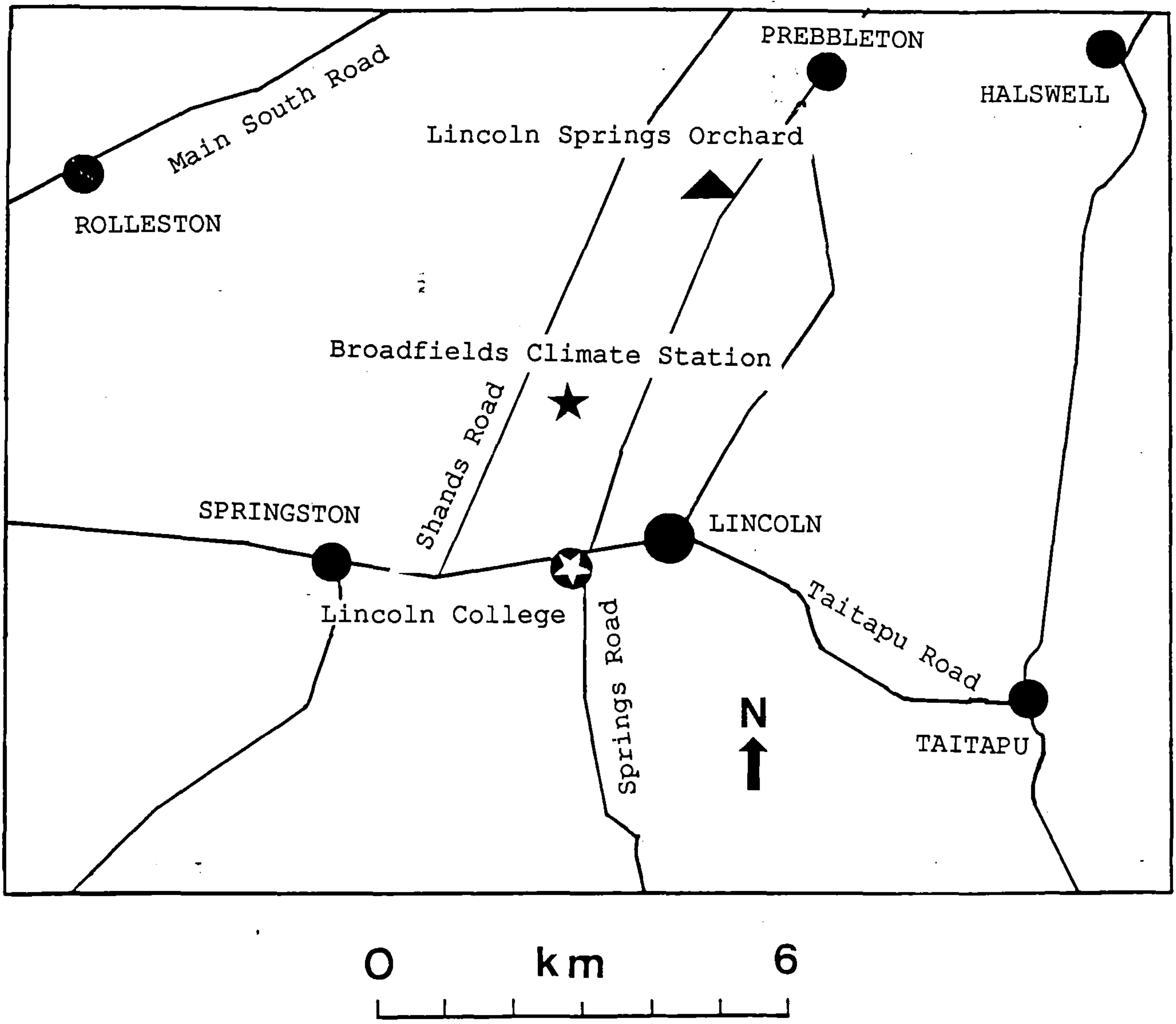


Fig. 9.1.1 Map of the Lincoln area with Lincoln Springs Orchard and the Broadfields Climate Station Indicated

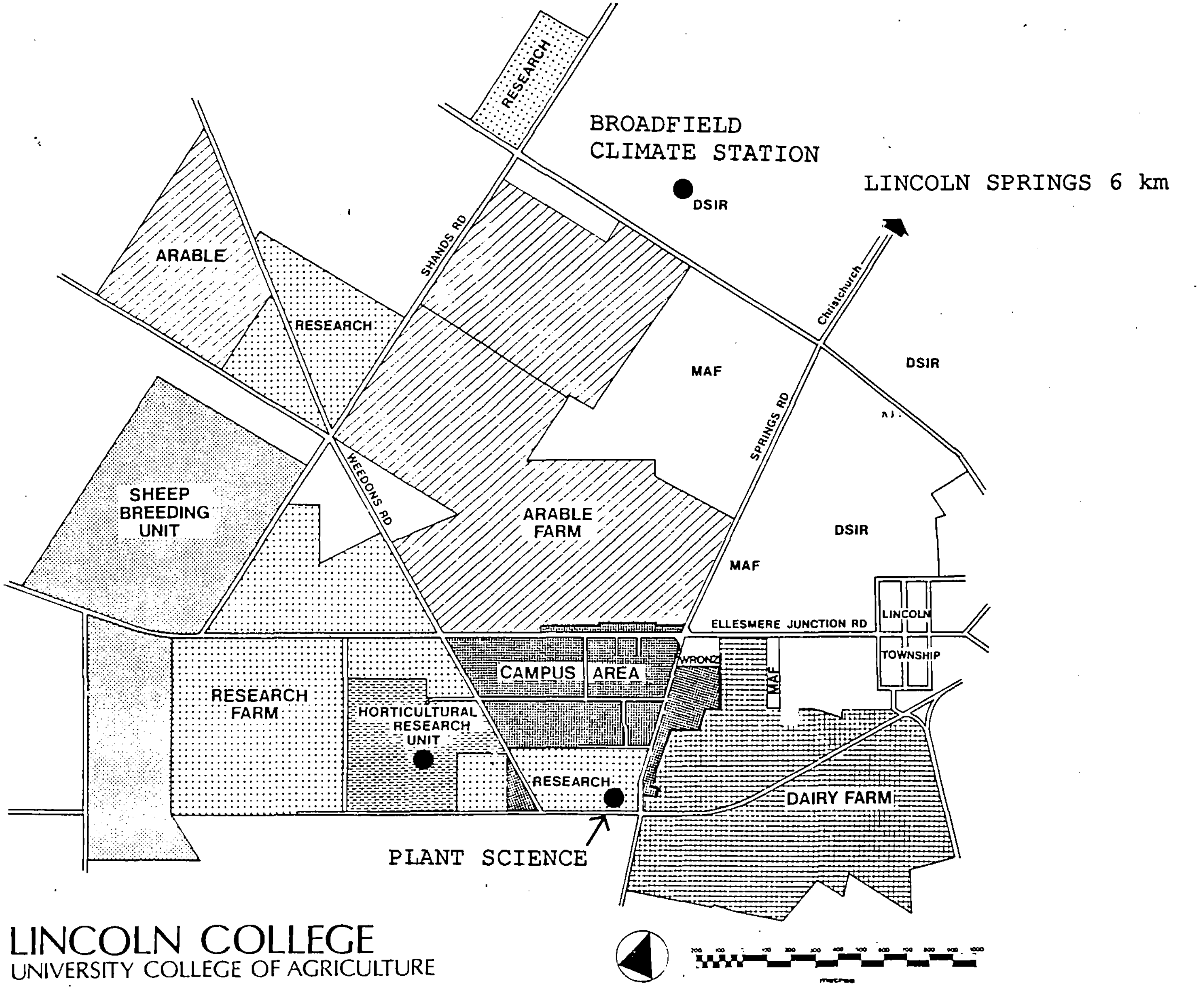


Fig. 9.1.2 Map of Lincoln College and associated research units, site locations at Broadfield, Plant Science and Horticulture Research Unit are indicated

To the west is a house, used as a field station and more to the northwest is a moveable rain shelter. These are both several hundred metres distant. Approximately 100 m to the south is a sealed road bounded on the north side by a low gorse hedge. Beyond that are open fields and the Lincoln campus. Around to the southeast, on the south side of the road, is a house surrounded by a tall hedge. Some of these features are evident in the aerial photograph in Fig. 9.2.1, taken over the period of measurement at this site. The climate station is clearly visible as a fenced off square and close examination to the left (west) reveals the mast. The gully is also apparent, as are the field house and rain shelter.

Fig. 9.2.1 Aerial photograph of the Broadfield climate station.

The period of measurement at Broadfield was from 11/2/1988 to 14/3/1988, being late summer. Weather conditions were generally mild and dry over the period of measurement at Broadfields, with higher than average wind speeds. Early February was cloudy, as a result of a sequence of depressions passing over the country. They brought little rainfall. High pressures over northern New Zealand in March resulted from a progression of anticyclones which gave more settled weather in this month and above average sunshine. February to March deficit days totalled 45, which was well above the average of 31 for this period.

As already stated this period served as a calibration of the mast against the climate station. The results of this period of calibration are presented below.

9.2.2 Site roughness

Two wind profiles were evident for the Broadfield site. Lower profile data for the south and southeast sectors were discarded because of an apparent interfering effect of the trailer located to the southeast. This housed the data logger. The second highest anemometer read higher than might be expected for the northeast and northwest sectors. This was attributed to the presence of the low gully to the immediate north of the site. There was a compensating effect with slightly reduced wind speeds with the third highest anemometer, at 2.58 m

Taking these sources of error into account, roughness coefficients for upper and lower profiles for each wind sector, and for the site as a whole, were calculated. Results are presented graphically in Figs. 9.2.2 to 9.2.9. Table 9.2.1 gives the frequency of wind from each sector over the period of measurement, and the z_0 values for each wind sector.

Table 9.2.1

Site roughness and frequency of wind from each sector

Wind sector	Frequency	Site roughness (z_0) Upper profile	Lower profile
N	0.2	0.014	0.00003
NE	0.24	0.0014	0.00003
NW	0.16	0.012	0.00006
S	0.16	0.008	-
SE	0.07	0.011	-
SW	0.11	0.005	0.00001
W	0.05	0.004	0.0002
Overall		0.008	0.0001

There is an obvious lack of data for the eastern sector, reflecting the effect of the Peninsula on winds from this sector. Generally easterlies are turned to become northeasterlies around Lincoln.

Fig. 9.2.2 Broadfield: wind profile for Northerly sector

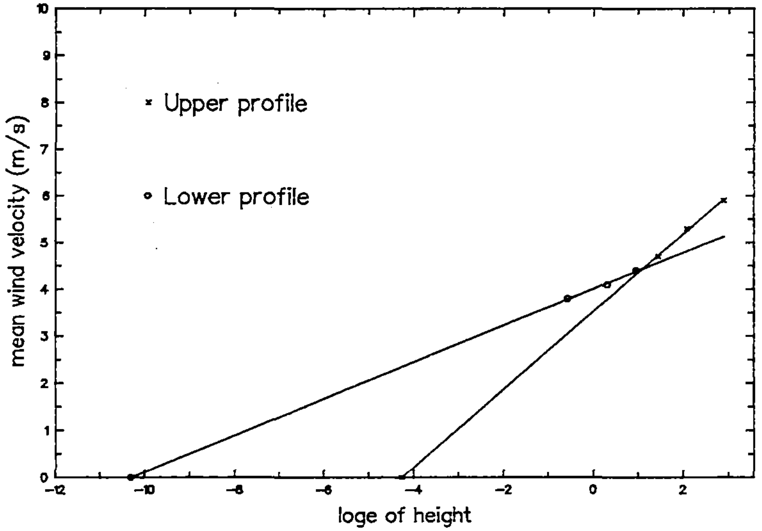


Fig. 9.2.4 Broadfield: wind profile for Northwest sector

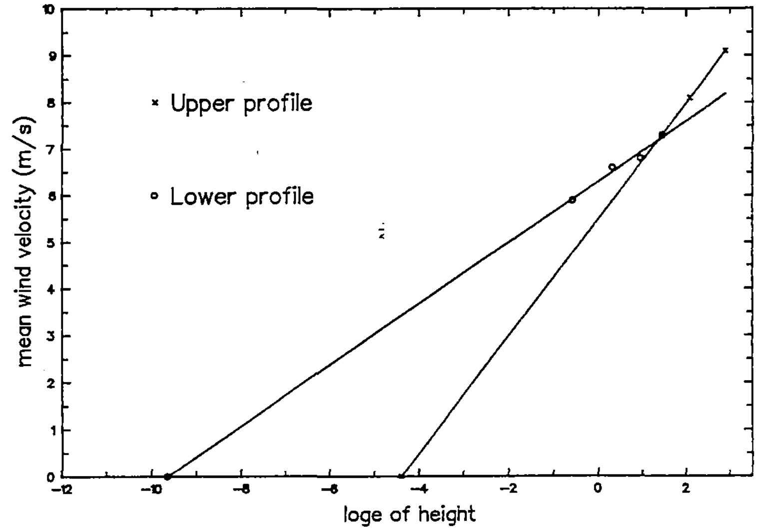


Fig. 9.2.3 Broadfield: wind profile for Northeast sector

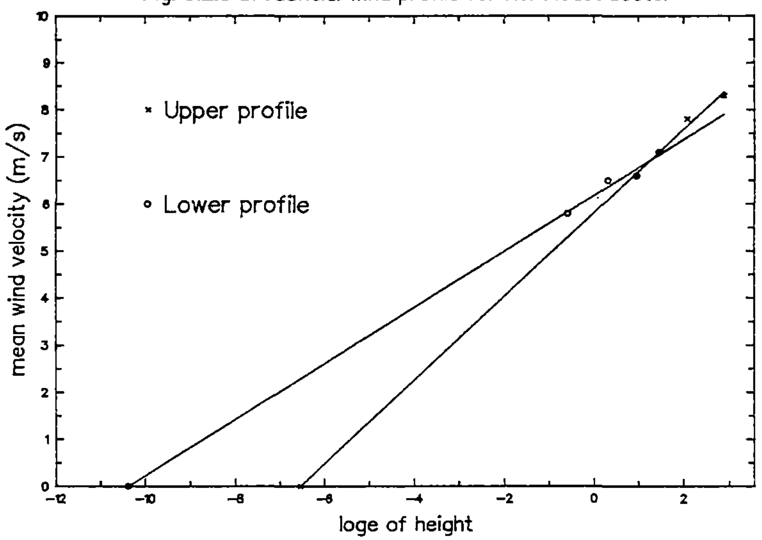


Fig. 9.2.5 Broadfield: wind profile for Southerly sector

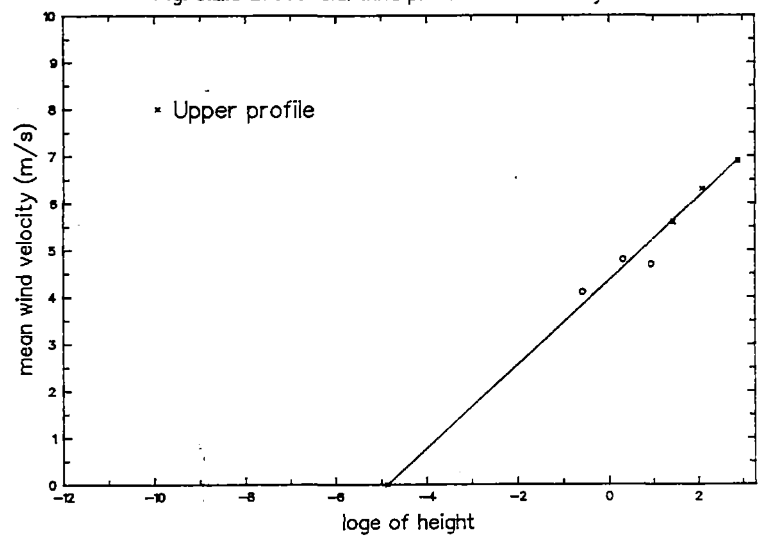


Fig. 9.2.6 Broadfield: wind profile for Southeast sector

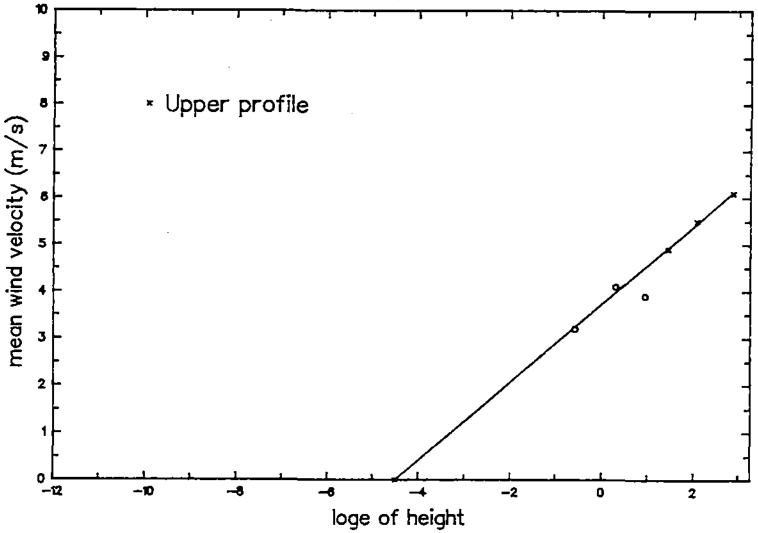


Fig. 9.2.8 Broadfield: wind profile for Westerly sector

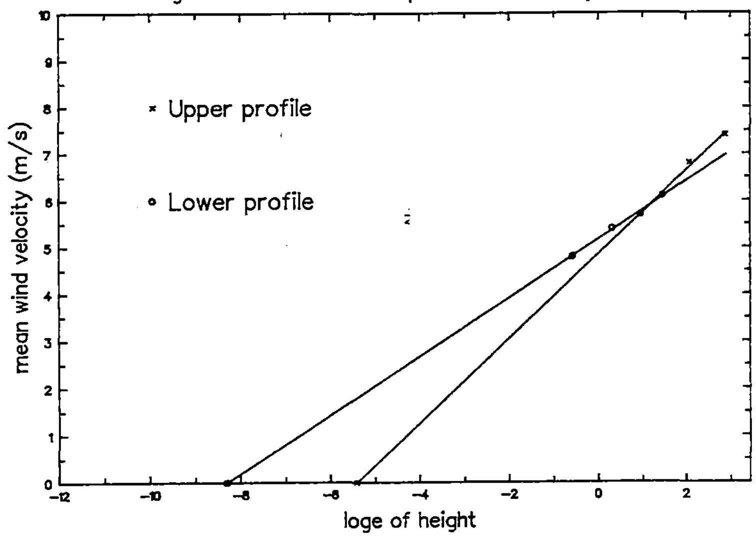


Fig. 9.2.7 Broadfield: wind profile for Southwest sector

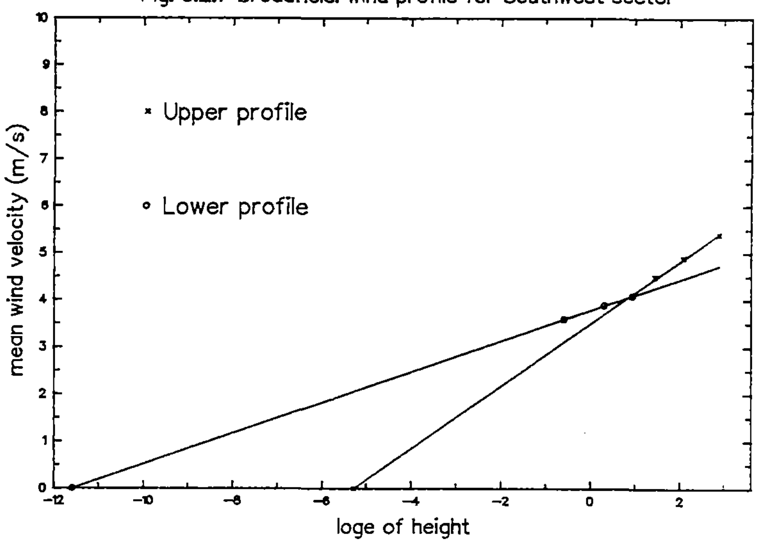
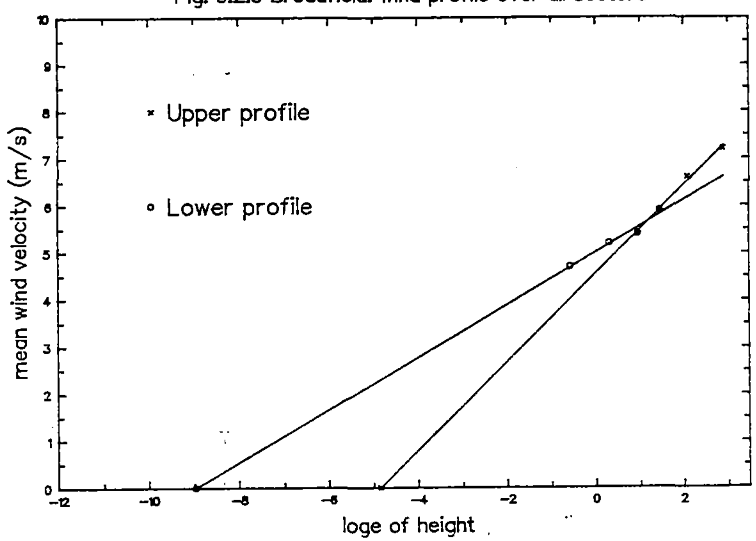


Fig. 9.2.9 Broadfield: wind profile over all sectors



The upper and lower profiles reflect regional and local site effects respectively. The roughness lengths are much lower than might have been expected, being comparable with very smooth surfaces. The wind reduction near the ground was not great, reflected in the relatively low transition height of approximately 3m, suggesting little obstruction to wind movement near the surface. This may be attributable to the generally dry conditions that were prevailing, in combination with this period being the end of the growing season. There were also sheep grazing in the environs for a couple of weeks over the measurement period, which further reduced what little ground cover there was. The gully to the north may have also distorted the result, but this doesn't explain the low value obtained from the southwest.

9.2.3 Calibration of the mast

The rationale and method for calibrating the mast against the Broadfield climate station was outlined in section 8.5. Details from the period of calibration are presented in this secton.

Temperature

A faulty temperature probe on the mast at 1.36 m ruled out comparisons at a uniform height. Temperature probes were maintained at 0.56 m and 2.58 m. This was to retain consistency in measurement between sites as much as possible and also to obtain measurements over a reasonable range of heights. The regression relationships between screen values of mean, maximum and minimum temperatures and mast values at 0.56 and 2.58 m are presented in Figs. 9.2.10 to 9.2.15. For all of the temperature relationships the correlation coefficients were highly significant ($p>0.01$). With the exception of minimum temperatures at 0.56 m, all proved not to be significantly different from a 1:1 relationship. The latter was significantly different with $p>0.05$. Overall data from the mast temperature probes proved to be good predictors of screen values. Given the significance of the linear relationships data from heights 0.56 and 2.58 m were combined into a single predictive equation for each of the temperature variables. These combined equations are

$$\text{Screen } T_{mean} = 1.96 + 1.20(T_{0\cdot 56m}) - 0.288(T_{2\cdot 58m})$$

$$\text{Screen } T_{max} = 2.89 - 0.536(T_{0\cdot 56m}) + 1.48(T_{2\cdot 58m})$$

$$\text{Screen } T_{min} = 0.609 + 1.11(T_{0\cdot 56m}) - 0.167(T_{2\cdot 58m})$$

Wind speed

Mean wind speeds correlated well, with a significant correlation of 0.975. The regression line is given in Fig. 9.2.16. There was no significant difference in slope from a 1:1 relationship.

Fig. 9.2.10 Broadfield: calibration of mast ● 0.56m vs std screen (mean temp)

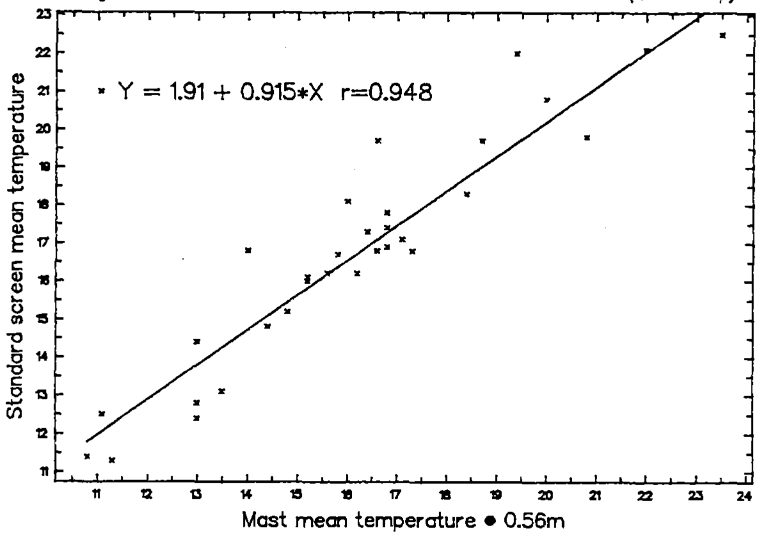


Fig. 9.2.12 Broadfield: calibration of mast ● 0.56m vs std screen (max temp)

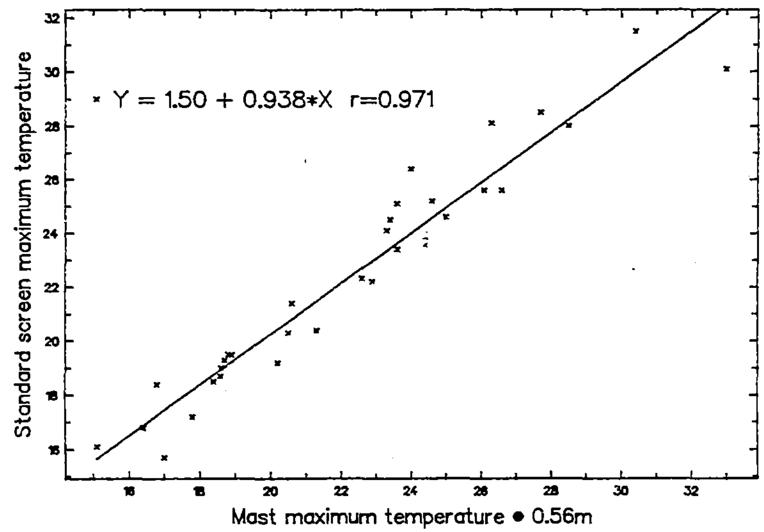


Fig. 9.2.11 Broadfield: calibration of mast ● 2.58m vs std screen (mean temp)

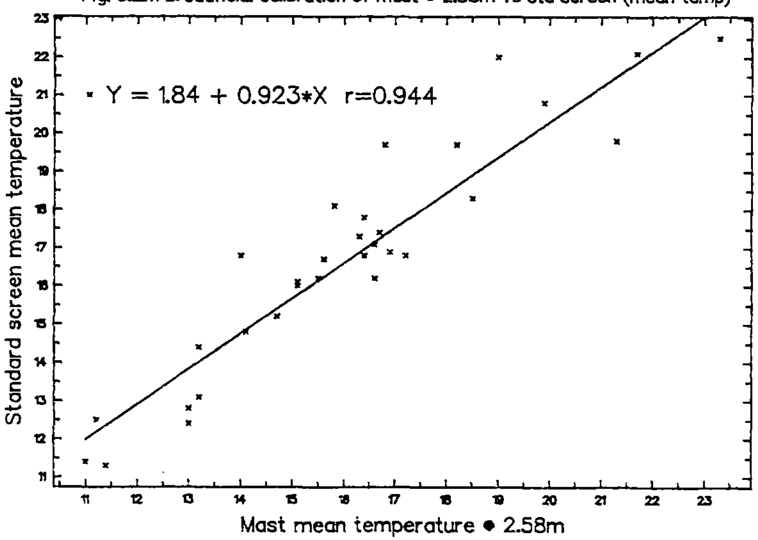


Fig. 9.2.13 Broadfield: calibration of mast ● 2.58m vs std screen (max temp)

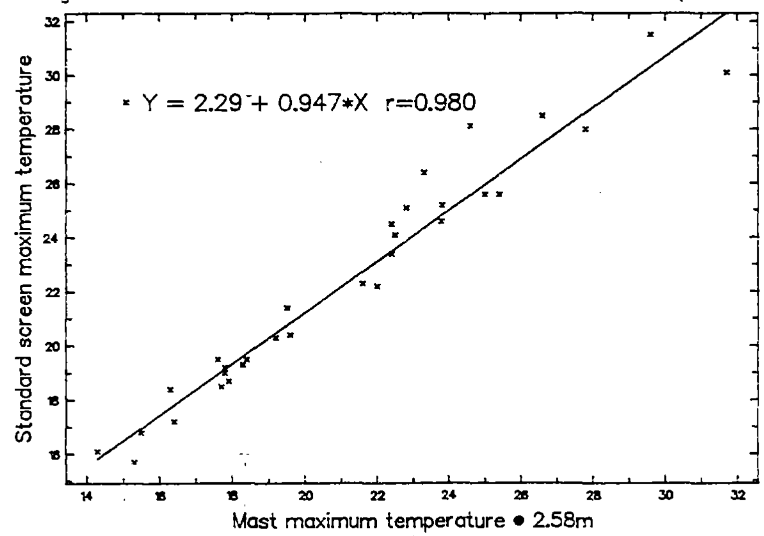


Fig. 9.2.14 Broadfield: calibration of mast ● 0.56m vs std screen (min temp)

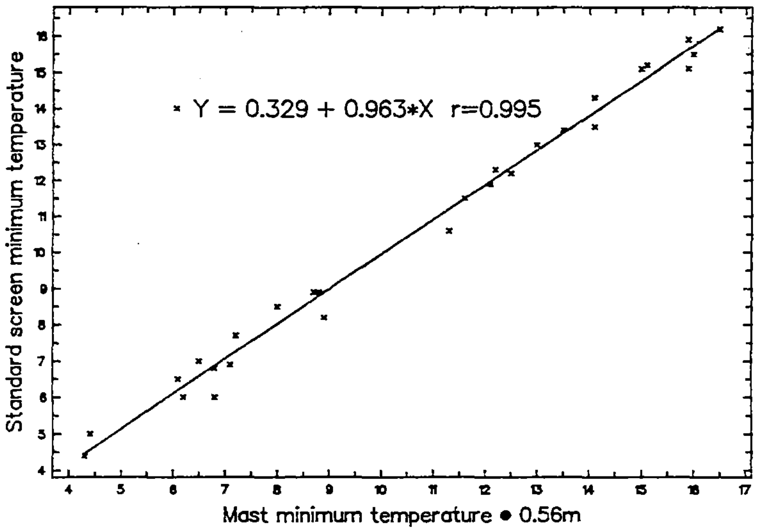


Fig. 9.2.16 Broadfield: calibration of mast vs met station (6m wind speed)

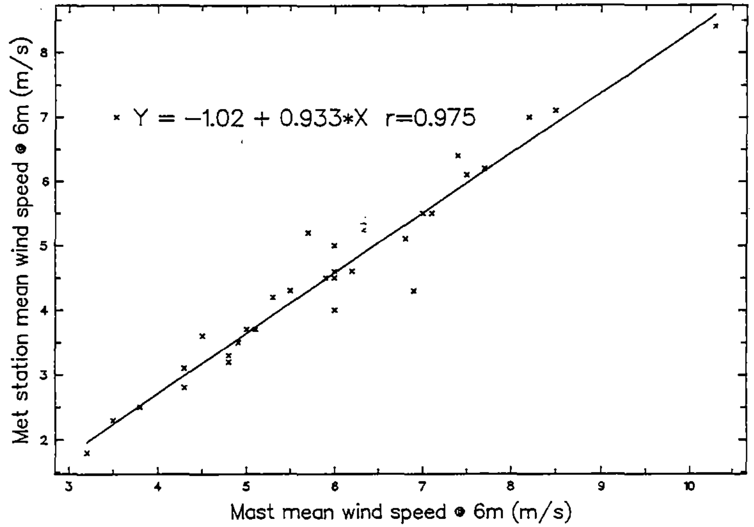


Fig. 9.2.15 Broadfield: calibration of mast ● 2.58m vs std screen (min temp)

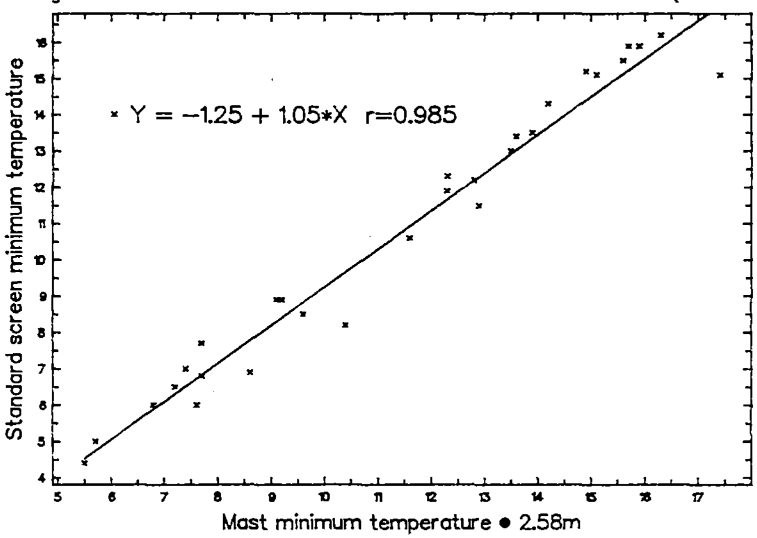
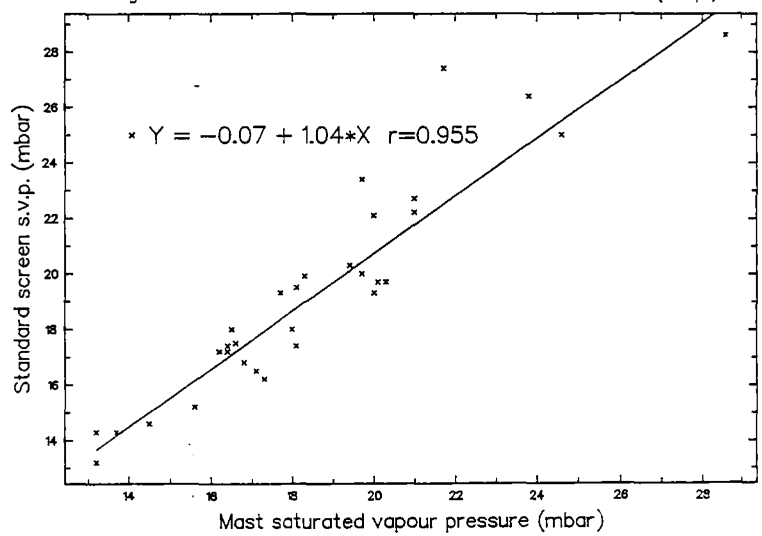


Fig. 9.2.17 Broadfield: calibration of mast vs std screen (s.v.p.)



However the mast values were consistently about 1 ms^{-1} higher than the Broadfield values, which was a significant elevation from the 1:1 line (p>0.01). As shown in Appendix E, the mast anemometers frequently underwent calibration checks. This suggests that the station anemometer may have been consistently reading low. For the purposes of this study the good correlation between the two provided a solid basis for making site comparisons of 6 m wind speeds.

Vapour pressure

Relationships for saturated vapour pressure, vapour pressure and vapour pressure deficit are presented in Figs. 9.2.17-9.2.19. The mast and screen values showed significant correlations in all cases. However several outliers were apparent in the regression of actual vapour pressure. The methods of calculating vapour pressure from mast and screen data were the least similar of all the variables. The screen values are routinely calculated from dry and wet bulb temperatures and the mast values from relative humidity as recorded by the probes. On three occasions rapidly changing temperature and humidity conditions led to big differences in the mast averages as compared with the instantaneously recorded screen values. The other outliers corresponded to high humidity conditions and again differences arising from the nature of measurement. Overall mast derived data for vapour pressure, saturated vapour pressure and vapour pressure deficit proved to be satisfactory predictors of screen values.

Evapotranspiration

Both Penman and Priestley-Taylor estimates of evapotranspiration correlated well, with the mast derived values proving to be good predictors of screen values. Results are presented in Figs. 9.2.20-9.2.21. An empirical check on the constant for the Priestley-Taylor equation was carried out for this site. As stated earlier, the original assumption was that a value of 1.26 was satisfactory for all but strongly advective conditions. All site comparisons were made on this basis, but it was considered worthwhile, as a matter of observation, to check the consistency of results between the two methods of estimation. As stated in section 8.5.4 Penman estimates were assumed to give the best approximation of potential evapotranspiration, given the available data. Using data from all days over the calibration period an $\alpha = 1.74$ was obtained, with a significant correlation $r = 0.811$, p>0.01. Table 9.2.1 shows that there was a high frequency of drying northwest winds over the calibration period. The four highest evapotranspiration values, all corresponding to conditions of strong advection, were removed. Subsequently an $\alpha = 1.34$, $r = 0.863$, was obtained, Fig. 9.2.22. It would seem, therefore that a value of 1.26 underestimated evapotranspiration at this site over the period of measurement, which was characterised by a higher than normal frequency of drying northwest winds. This result should be treated cautiously because of the empirical nature of the method used.

Fig. 9.2.18 Broadfield: calibration of mast vs std screen (vapour press)

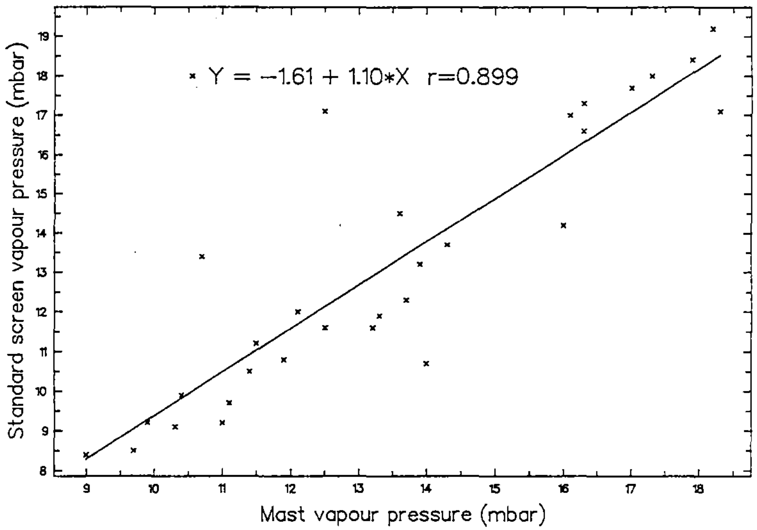


Fig. 9.2.19 Broadfield: calibration of mast vs std screen (v.p.d.)

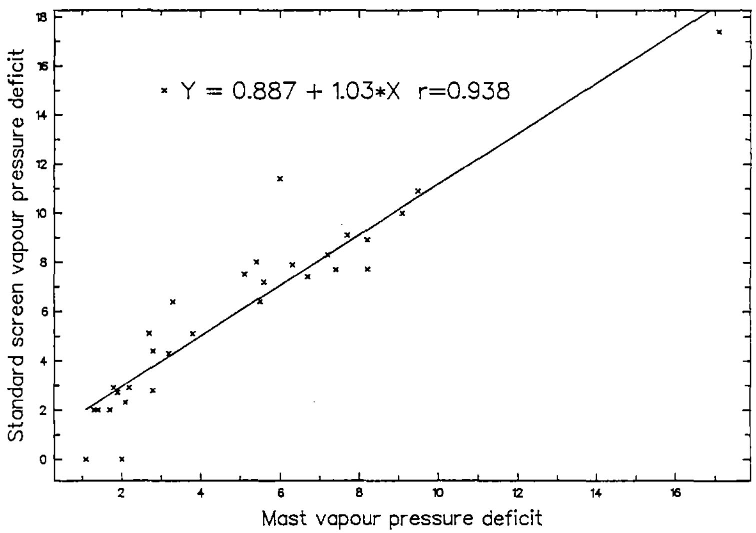


Fig. 9.2.20 Broadfield: calibration of mast vs met station (Penman ET)

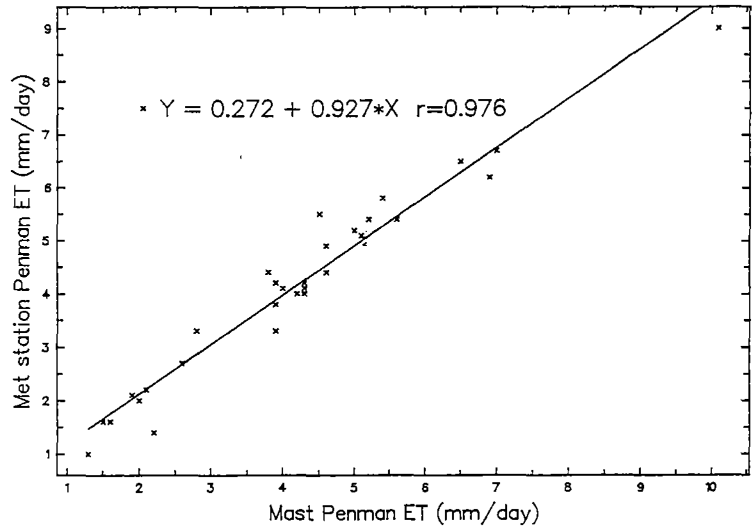
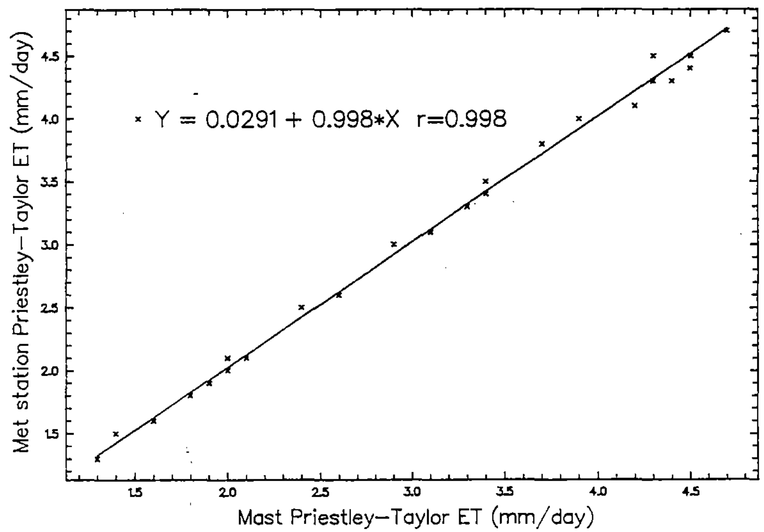


Fig. 9.2.21 Broadfield: calib. of mast vs met station (Priestley–Taylor ET)



9.3 The Plant Science site

9.3.1 Site description

The Plant Science research block is located directly to the south of the Lincoln College campus and covers a total area of approximately 10 ha. A complete 360° view of the site environs is given in Fig. 9.3.1. As can be seen the Lincoln campus is several hundred metres to the north, the nearest building being part of the Field Service Centre complex, located about 100 m away. To the northeast are some houses and beyond is the Lincoln Agriculture and Science complex and Lincoln village. Banks Peninsula is clearly visible to the east. To the northwest is the well sheltered Horticultural Research Area about 500 m away. The immediate south is noticeably more exposed as are the southeast and southwest sectors. However clusters of trees are apparent in the landscape with a cluster of buildings and trees obvious to the southwest. Several kilometres to the south is the Selwyn river and its associated riparian environment. To the southeast is Lake Ellesmere. This site appears to be less exposed than Broadfield.

The recording period at this site was from 14/10/1987 to 11/11/1987. This was shorter than other measurement periods. Being the first measurement site teething problems were experienced with the mast and instrumentation giving a shorter time series of data.

Both October and November 1987 were mild and cloudy. October rainfall was above average, with most of it falling over a three day period immediately before the start of measurement. With rising temperatures evapotranspiration exceeded rainfall in both months and deficit days were above average. This marked the very early stages of the record drought period.

9.3.2 Site roughness

Wind profile data for the Plant Science site are presented graphically in Figs. 9.3.2-9.3.9. Wind frequencies and z_0 values for each wind sector and overall are tabulated in Table 9.3.1.

Table 9.3.1

Site roughness and frequency of wind from each sector

Wind sector	Frequency	Site roughness (z_0) Upper profile	Lower profile
N	0.34	0.11	0.002
NE	0.28	0.08	0.002
NW	0.07	0.04	0.006
S	0.17	0.03	0.005
SE	0.03	0.02	0.011
SW	0.07	0.24	0.001
W	0.04	0.03	0.003
Overall		0.06	0.003

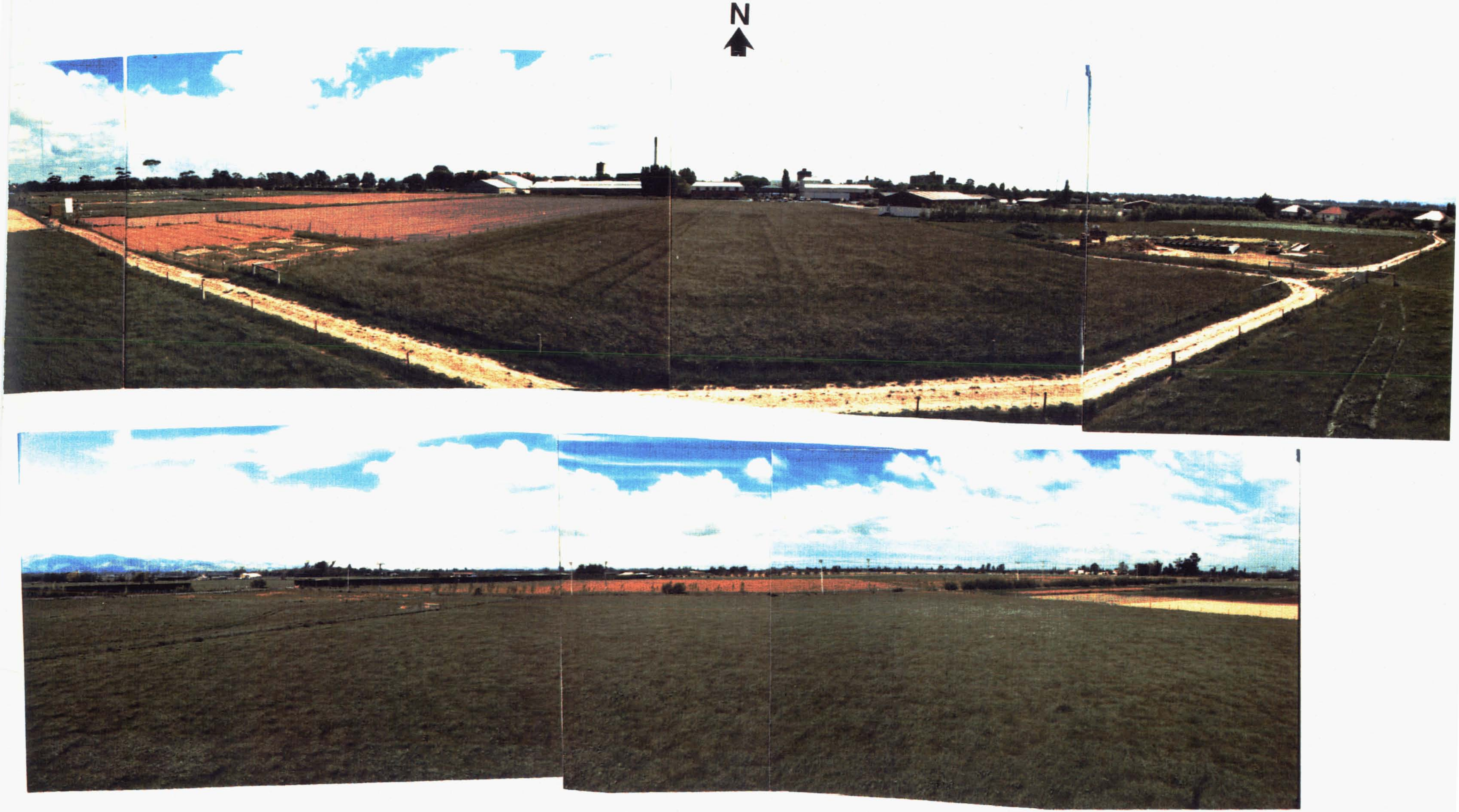


Fig. 9.3.1 360° view of the Plant Science site environs

Fig. 9.3.2 Plant Science: wind profile for Northerly sector

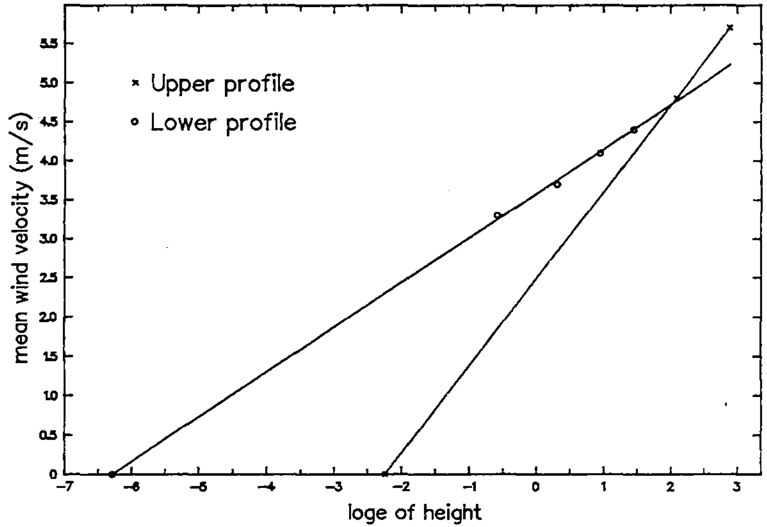


Fig. 9.3.3 Plant Science: wind profile for Northeast sector

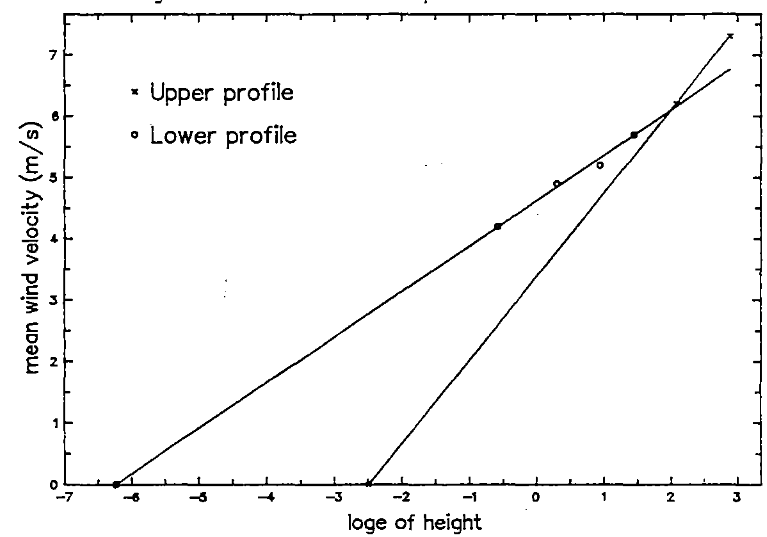


Fig. 9.3.4 Plant Science: wind profile for Northwest sector

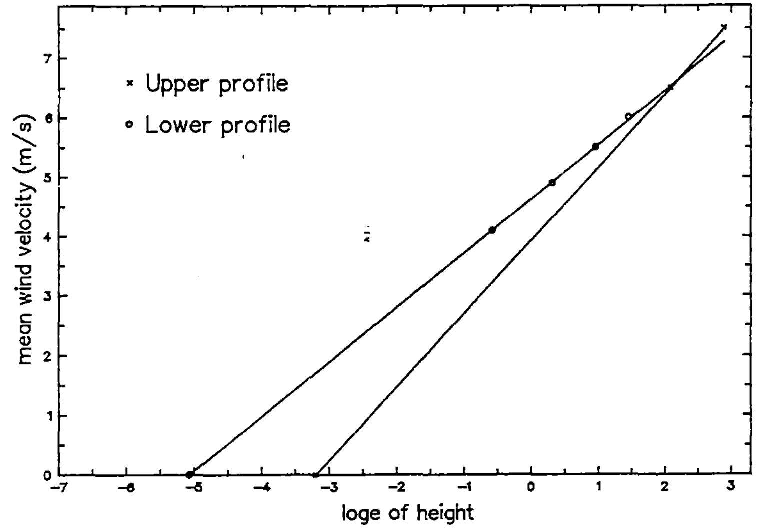


Fig. 9.3.5 Plant Science: wind profile for Southerly sector

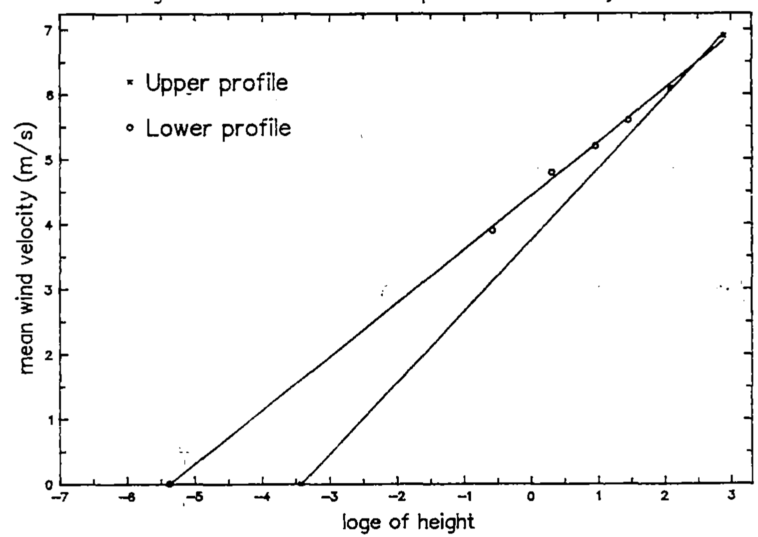


Fig. 9.3.6 Plant Science: wind profile for Southeast sector

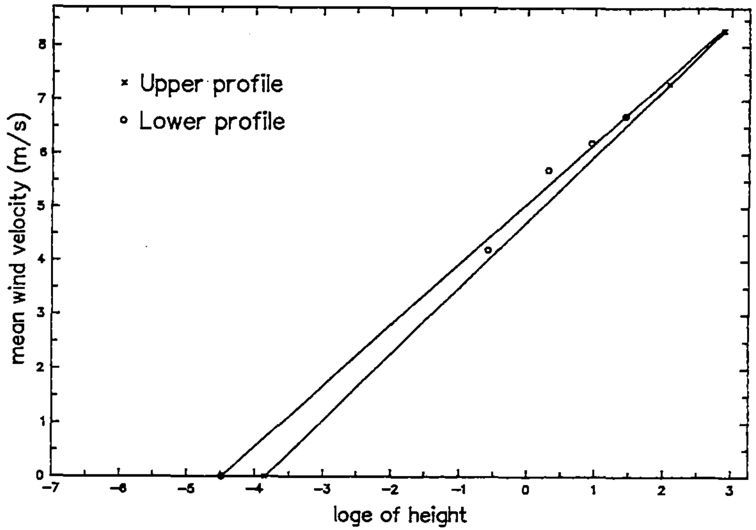


Fig. 9.3.7 Plant Science: wind profile for Southwest sector

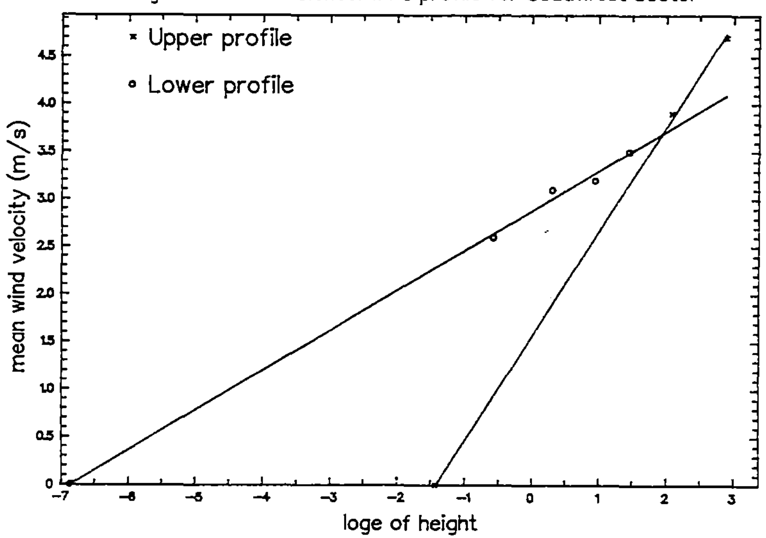


Fig. 9.3.8 Plant Science: wind profile for Westerly sector

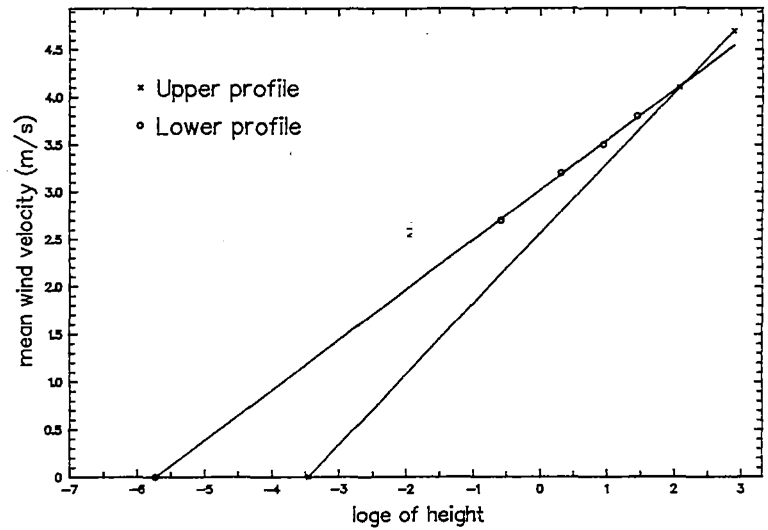
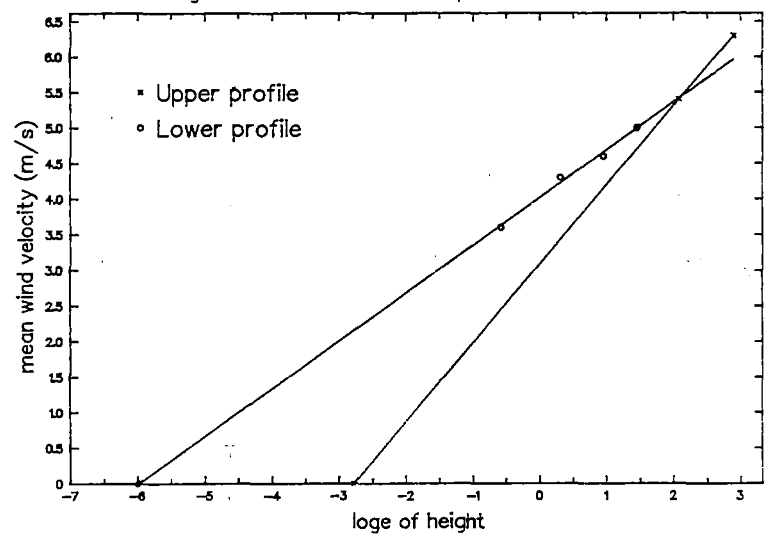


Fig. 9.3.9 Plant Science: wind profile over all sectors



Over all sectors the top two anemometers appeared to be affected more by regional roughness characteristics. They reflect the transition from the regional to the more local environment. The lower, or site profile was characterised by the bottom four anemometers. The transition height is higher than for the more exposed Broadfield site, being approximately 8 m. This reflects a generally more sheltered situation and is in good agreement with Guyot and Seguin's (1975) transition height of about 7 m for a large field.

Data from the southern sectors should be treated with caution because of the siting of the trailer to the southeast. At this site the mast was incorrectly positioned with the anemometers pointing to the east and thus more open to interference from the trailer. At all other subsequent sites the mast was positioned so the anemometers were pointing to the northwest sector, furthest away from the trailer.

The site photos suggest greater exposure to the south and this is generally reflected in the upper profile results. The one exception is the southwest, which is an order of magnitude higher than all values except for the north and northeast, but is still at least double these values. There was a low frequency of winds from the southwest which may partly explain the anomaly. The other possibility is the presence of obstacles not visible from the immediacy of the site. The cluster of buildings and trees may have had some effect, but they are quite localised. The anomaly is quite possibly a combination of a low number of observations and a rougher landscape than immediately apparent. The environment to the north is moderately rough, as would be expected with the campus to the north and the fairly built up area to the northeast. Apart from the southwest the remaining sectors are fairly exposed. However the Hort. Research area to the northwest has less effect than might be expected. Winds from this sector are likely to come around the northern end of the sheltered area so some funnelling may occur. This may also be a reflection of the low observation number and the tendency for stronger winds from this sector which would tend to have more of a smoothing effect.

Lower profile data is, on average, two orders of magnitude greater than that for Broadfield. This is a reflection of a more sheltered local environment giving a sharper wind speed reduction. The high soil moisture content at the start of this spring period, combined with fairly mild conditions was very conducive to pasture growth. This was certainly evident in the locale of the mast with rapid growth of pasture occurring. This roughening of the ground surface would also have contributed to a sharper reduction of wind speed in the lower profile.

Although a large field situation, this area is considerably more sheltered than Broadfield over all sectors. The low number of observations from some sectors makes comparisons less certain. Lower profile comparisons are compounded by the differences in pasture height between the sites.

9.3.3 Site Microclimate

Regression between estimated Plant Science data and actual Broadfield data are presented graphically in Figs 9.3.10-9.3.18. The t values for the slope and elevation of the fitted lines and their significance are given in Table 9.3.2.

Table 9.3.2

Plant Science vs Broadfield
Significance of differences in slope and elevation of fitted lines from 1:1 lines

Variable	t(slope)	t(elevation)
Mean temp.	-5.68**	1.89
Max. temp.	-2.27*	9.18**
Min. temp.	-1.49	1.91
Wind speed	-5.96**	-8.26**
S. vap. press.	-0.90	7.00**
Vapour press.	1.19	2.54*
Vap press def	-1.62	5.54**
Penman ET	-1.61	1.23
Priestley-Taylor ET	0.0	-0.61

Note: ** = 1% significant
* = 5% significant

Temperature

Results for temperature comparisons are given in Figs. 9.3.10-9.3.12. Four outliers were excluded from the analysis of mean temperature differences. Two of these appeared to be biased by the effects of averaging at lower temperatures. The mast probes, particularly the lower one, appeared to be insensitive to recorded screen frosts on both of these days. Uncertainty over this was seen as sufficient reason for removal of these values as their positioning would have had a high leverage effect. On the other two occasions, a sharp transition from northwest to southerly conditions gave a high maximum and low minimum. The average of these two was greater than the 24 hr average which was weighted down by the mostly cooler conditions that prevailed.

Although the slope of the fitted line is significantly different from a slope of 1, the scatter of the data suggests that on most days the sites were similar. This is confirmed by the elevation of the fitted line which was not significantly different. If the slope is true, then there exists the potential for significant differences in mean temperature, most particularly at the extremes.

Fig. 9.3.10 Mean screen temperature: estimated Plant Science vs Broadfield

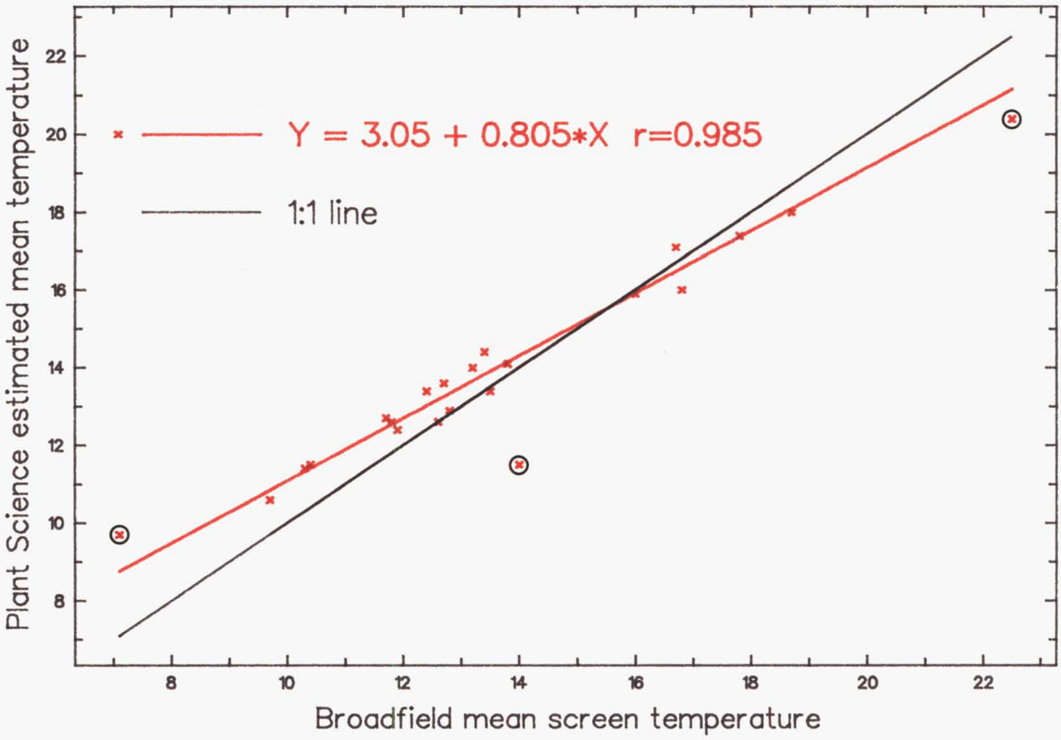
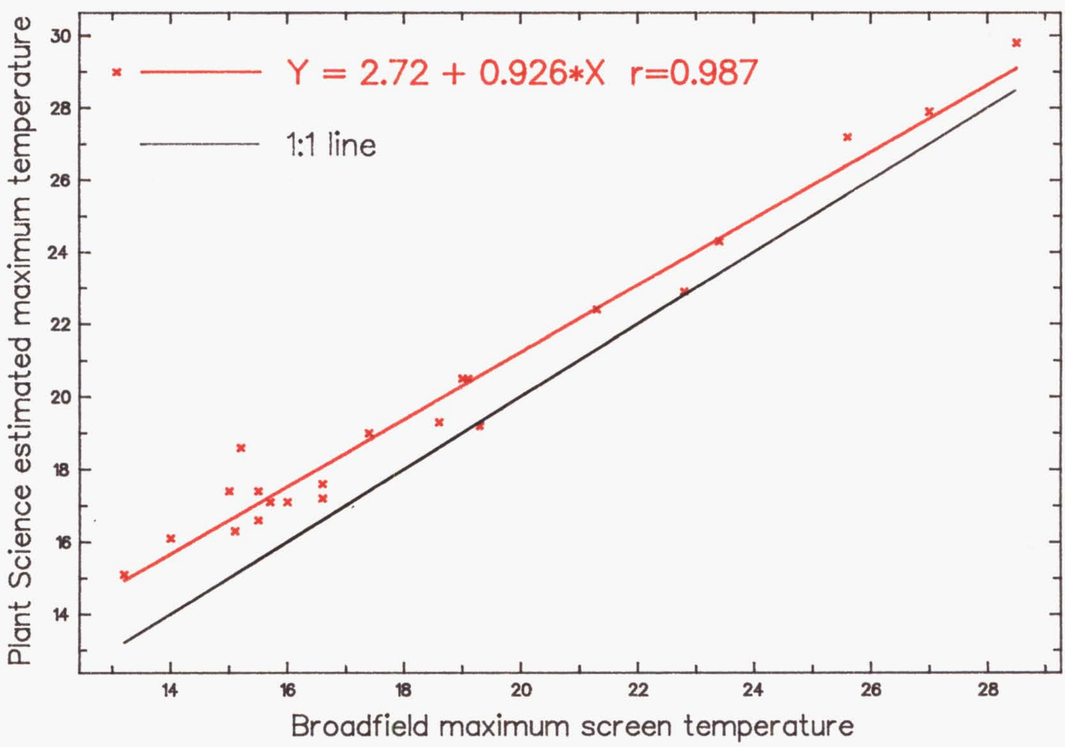


Fig. 9.3.11 Maximum screen temperature: estimated Plant Science vs Broadfield



○ = Outlier

Fig. 9.3.12 Minimum screen temperature: estimated Plant Science vs Broadfield

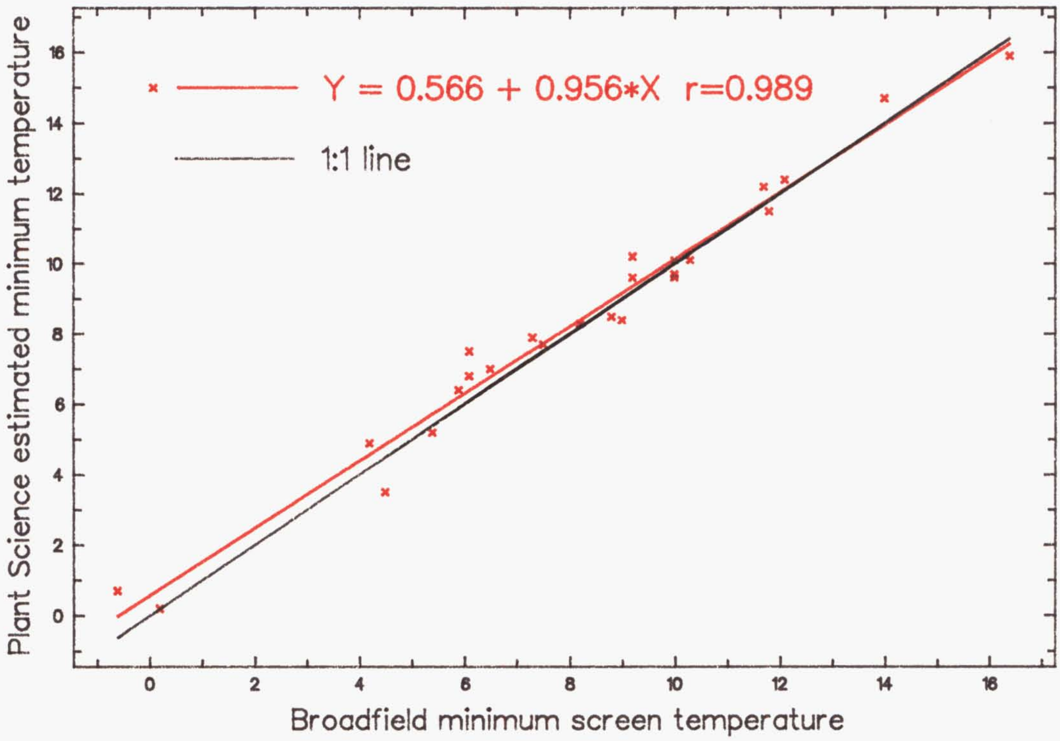
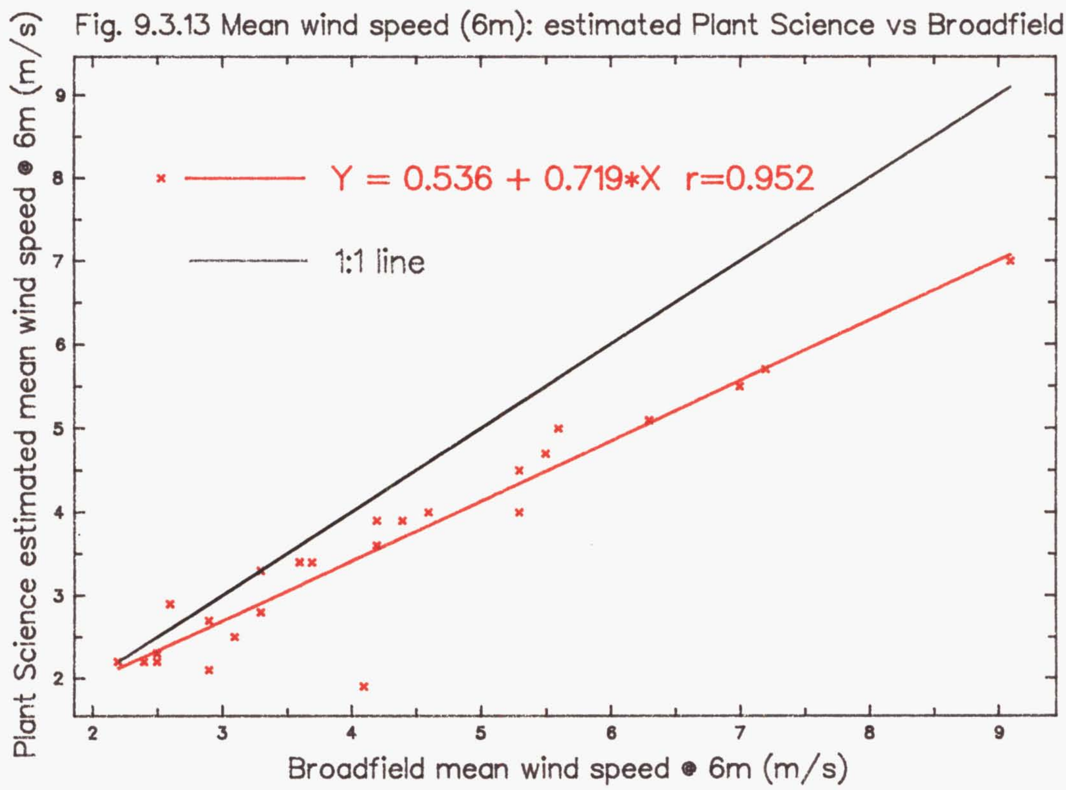


Fig. 9.3.13 Mean wind speed (6m): estimated Plant Science vs Broadfield



There were no strong outliers with either maximum or minimum temperatures, confirming that the mean temperature outliers were largely a result of averaging bias. The slope of the fitted regression line for maximum temperatures was significantly different and ,importantly, the mean was significantly elevated away from the 1:1 line. Estimated Plant Science values were higher on virtually all days, suggesting warmer daytime conditions at this site. The slope suggests that daytime temperature differences are greater on cooler days. No significant differences in slope or elevation occurred with minimum temperatures suggesting that night-time conditions were similar at both sites.

Wind speed

It is apparent from Fig 9.3.13 that the Plant Science area is significantly more sheltered than the climate station, as already indicated by the site roughness data. Both the slope and the elevation of the fitted line are significantly different. The obvious trend is for lower 6 m wind speeds at this site, particularly under windier conditions. Although there are two apparent outliers these were included because of the high potential for local modification of wind.

Vapour pressure

Results are presented graphically in Figs. 9.3.14-9.4.16. Three outliers were apparent with saturated vapour pressure, Fig. 9.3.14, all directly resulting from mean temperature outliers. Their removal led to a significant change in the nature of the relationship. Although the slope was not significantly different with or without the outliers, their removal resulted in a significant elevation of the fitted line where previously there had been no significant difference. This result suggest a higher saturated vapour pressure at the Plant Science area over the measurement period. This is directly attributable to the tendency for warmer daytime conditions at this site.

With actual vapour pressure there were two outliers that exerted a significant downward leverage on the fitted line. One was related to the different methods of estimating vapour pressure, the mast relative humidity value being much lower than the screen derived value. The other related to anomalous differences in temperature. Their removal significantly altered the slope of the fitted line. With the outliers present it was significantly lower, with them removed there was no significant difference in slope. Elevation of the fitted line was significantly higher after their removal. This result should be treated conservatively.

As expected vapour pressure deficit followed the pattern set by the variables from which it is derived. Four outliers were removed, all resulting from bias introduced with temperature anomalies. There was no significant difference in slope, but vapour pressure deficit appeared to be higher at this site, suggesting a greater potential for evapotranspiration.

Fig. 9.3.14 Saturated vapour pressure: estimated Plant Science vs Broadfield

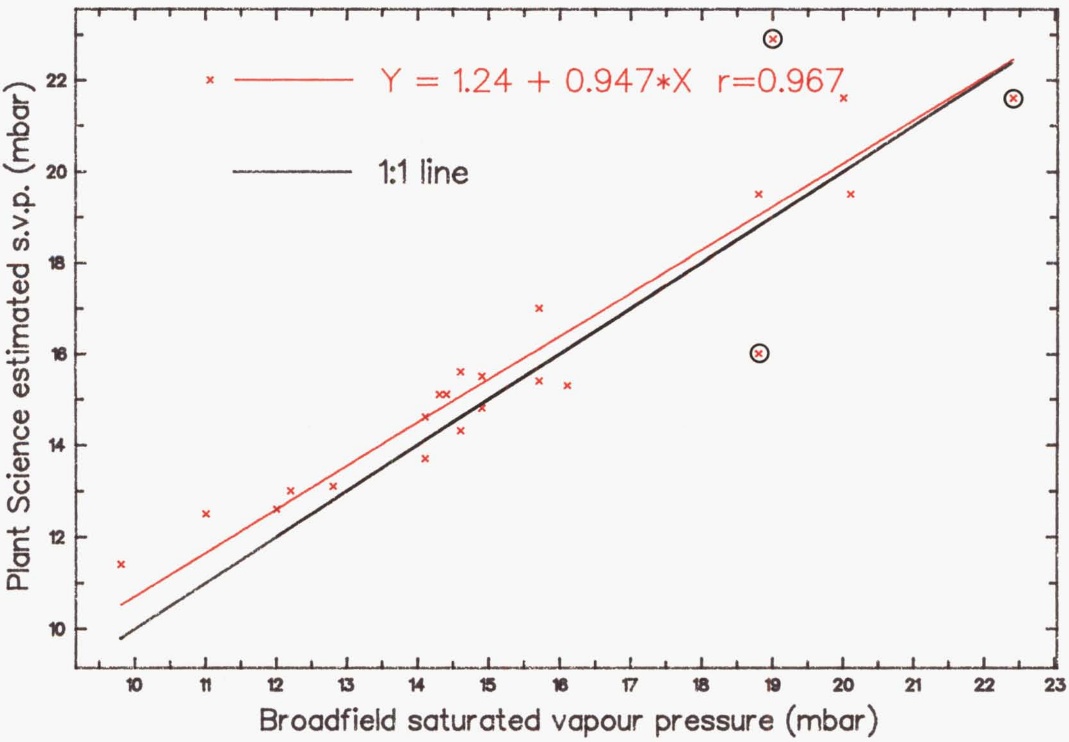
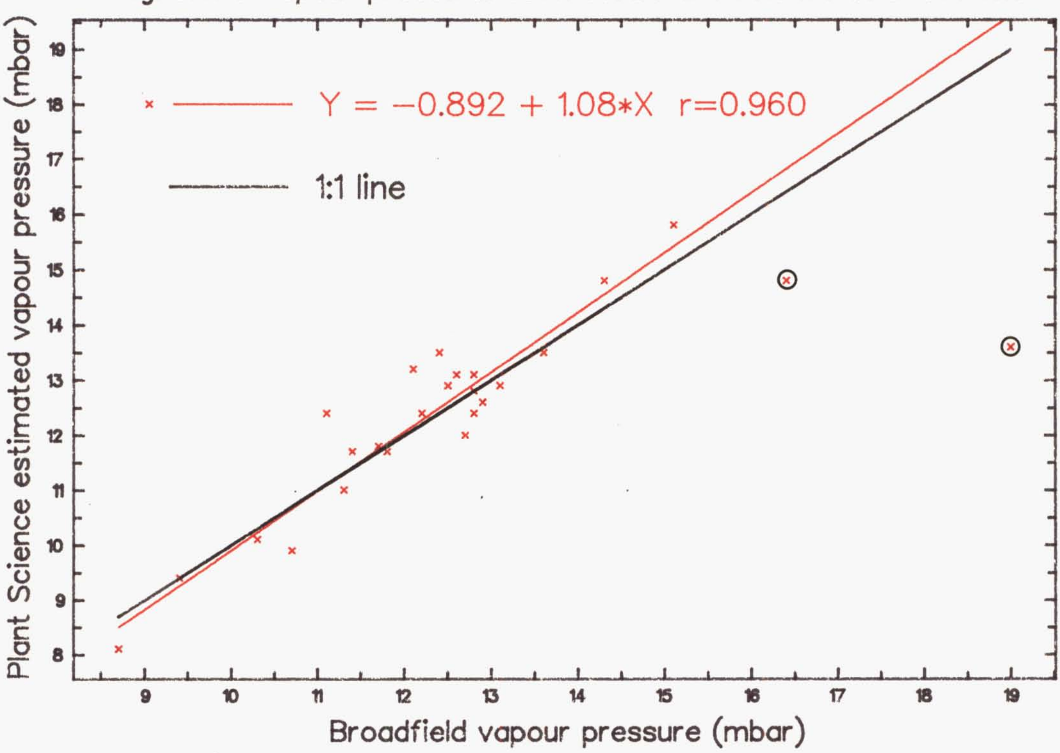


Fig. 9.3.15 Vapour pressure: estimated Plant Science vs Broadfield



○ = Outlier

Fig. 9.3.16 Vapour pressure deficit: estimated Plant Science vs Broadfield

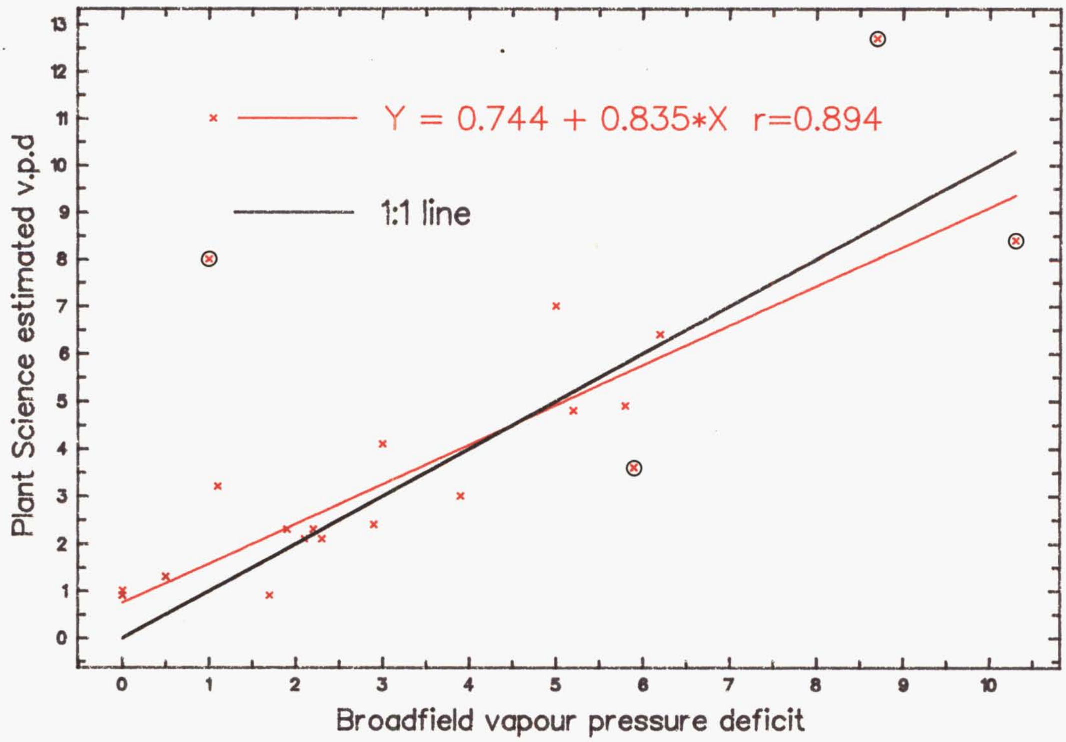
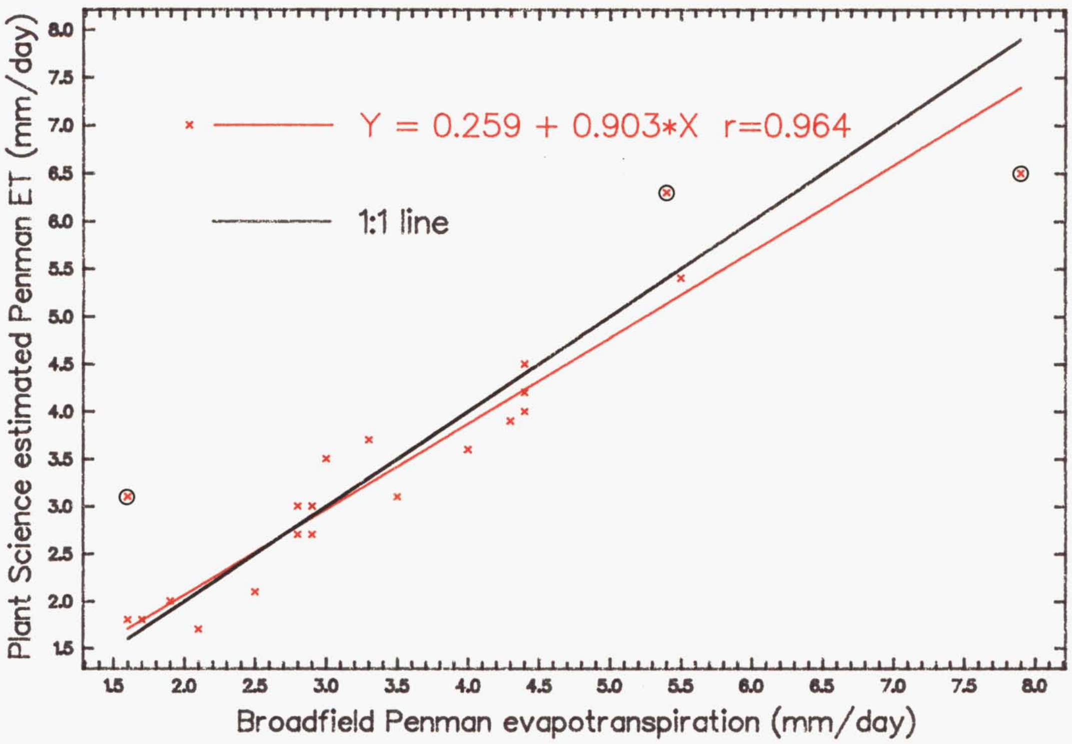


Fig. 9.3.17 Penman evapotranspiration: estimated Plant Science vs Broadfield



O = Outlier

Fig. 9.3.18 Priestley–Taylor ET: estimated Plant Science vs Broadfield

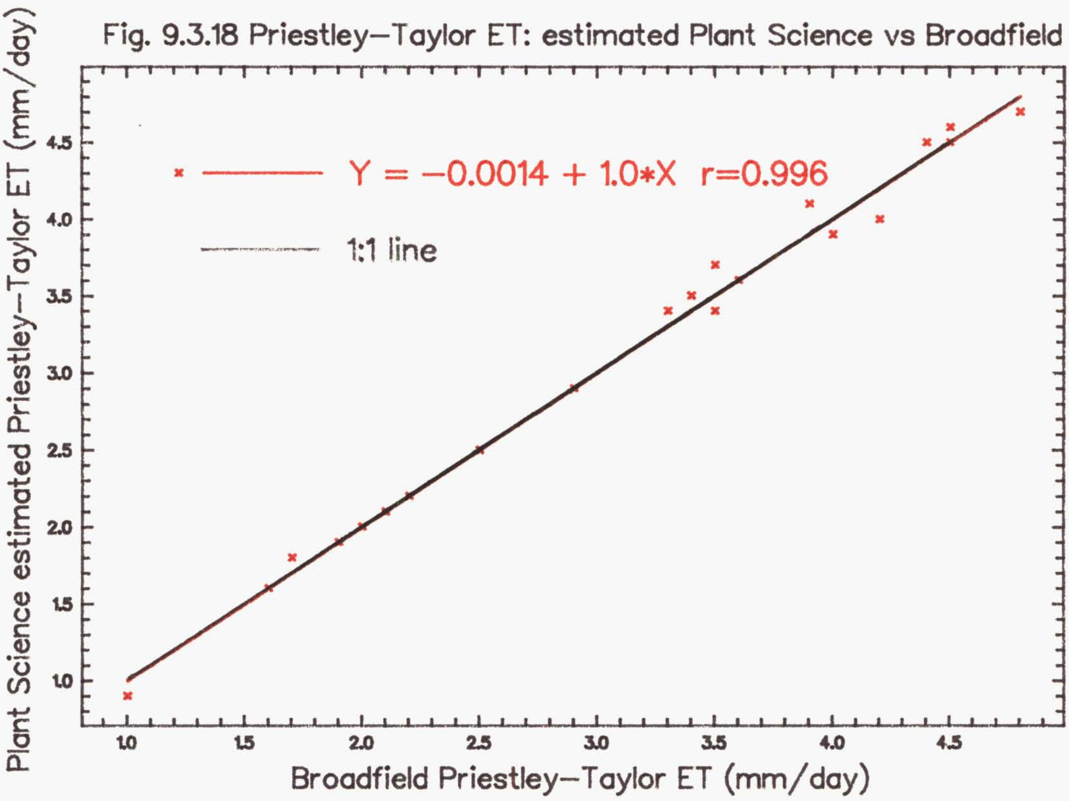
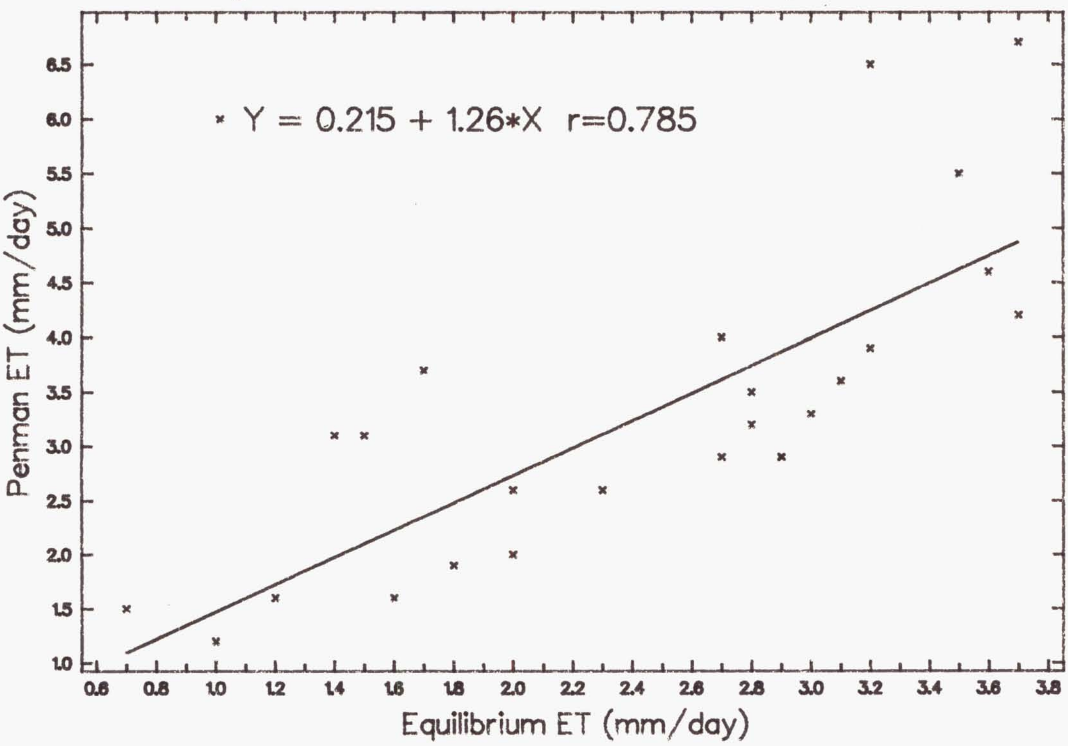


Fig. 9.3.19 Plant Science: Penman ET vs Equilibrium ET



Evapotranspiration

Regression of Penman and Priestley-Taylor evapotranspiration are presented in Figs. 9.3.17-9.3.18. Four outliers were removed from the Penman evapotranspiration regression, all resulting from temperature anomalies previously highlighted. There was no significant change to the result. Despite the apparently higher potential for evapotranspiration given the higher vapour pressure deficit, there was no significant difference in Penman ET between the sites. This can perhaps be attributed to the lower wind speeds at the Plant Science site and thus the greater resistance to the movement of water vapour away from the site. The Priestley-Taylor values appear to be more conservative but the overall result is the same.

The consistency of the Priestley-Taylor estimates were empirically checked by a regression between Penman ET and equilibrium ET as previously described. The result is presented in Fig. 9.3.19. The correlation was significant, $r = 0.785$, $p>0.01$, and gave an $\alpha = 1.26$. This illustrates that there was good consistency between the two methods of estimation at this site. This is a reflection of both the lower exposure of this site and the lower frequency of drying northwest winds over the period of measurement as compared with Broadfield.

9.4 The Horticultural Research Area site

9.4.1 Site description

The Hort. Research Area and approximate site location is indicated on the Lincoln area map, Fig. 9.1.1. It is located to the west side of the Lincoln campus. To the north and west of the H.R.A. are some of the College research farms. To the south is more farmland. It is the most sheltered piece of land within the Lincoln area, with the exception perhaps of parts of the built up area. The location of the mast within the H.R.A. was limited to grassed blocks, so as not to interfere with orchard management and to be consistent with the other sites. It had several advantages, being centrally located in the Research Area, one of the largest grassed areas and also close to a power supply. The mast was located at a fairly equal distance between the north and south ends of the block. The narrowness of the grassed area restricted location in the east to west direction so that the mast was sited only about 20 m east of a roughly north to south oriented shelterbelt. The top of the mast just cleared this shelterbelt, which is around 15 m in height. Most shelterbelts within the H.R.A. are of a similar height. To the immediate west of the mast were fruit trees. These site features are clearly seen in the 360° photo that is Fig. 9.4.1.

The period of measurement at this site was from 18/12/1987 to 26/1/1988. Mild, cloudy weather dominated in December, as with the previous two months. A series of depressions brought some light rain and persistent periods of cloud, but rainfall for the month was well below average. This weather sequence was interspersed with occasional hot, sunny days.

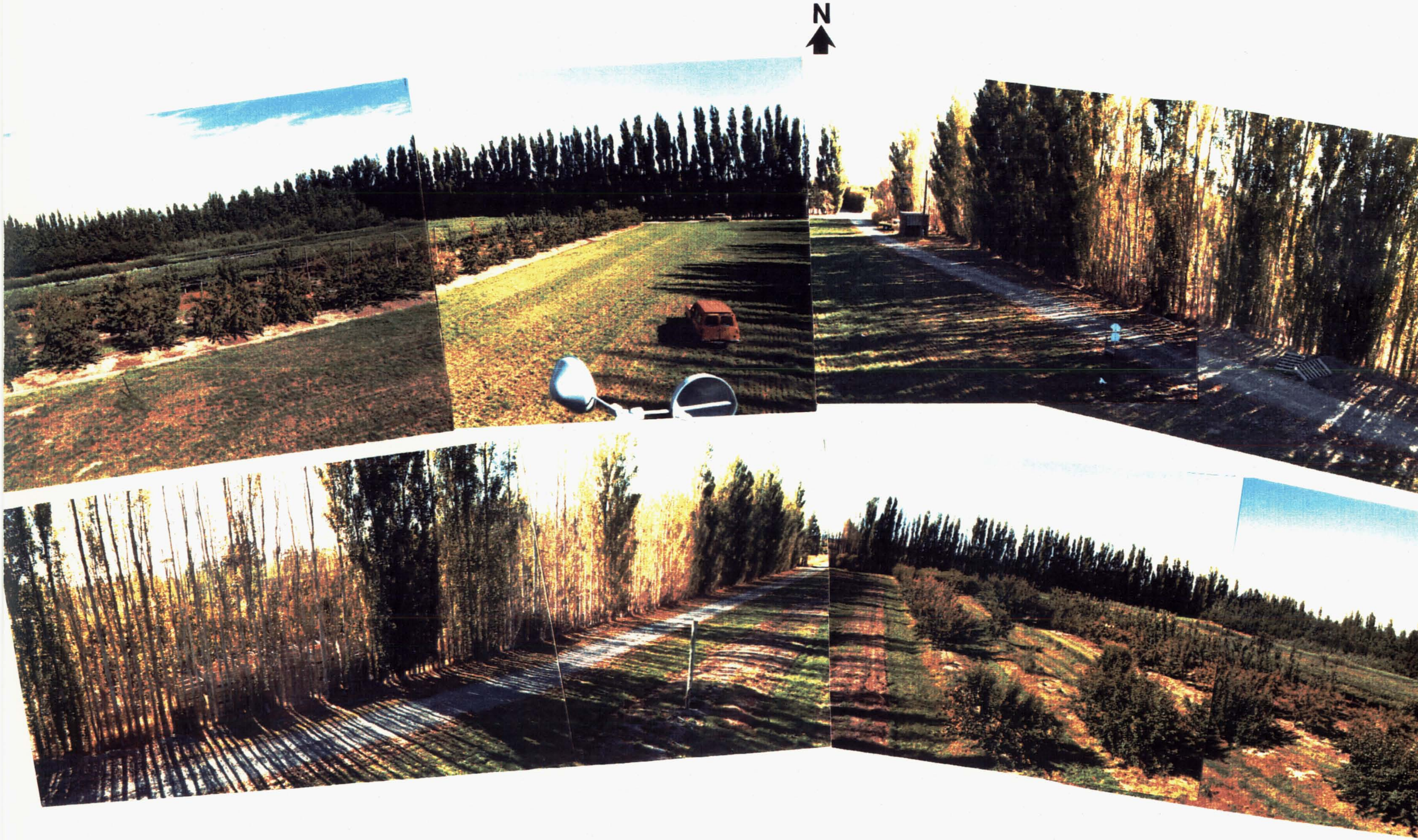


Fig. 9.4.1 360° view of the Horticultural Research Area site environs

The dry weather persisted into January, with a period of more settled, sunny weather characterised by generally higher atmospheric pressures over New Zealand. Deficit days for these two months totalled 44, well above the average of 36.

9.4.2 Site roughness

Results are presented graphically in Figs. 9.4.3-9.4.10 with frequency of observation and z_0 values from each sector in Table 9.4.1.

Table 9.4.1

Site roughness and frequency of wind from each sector

Wind sector	Frequency	Site roughness (z_0) Upper profile	Lower profile
N	0.14	3.33	0.003
NE	0.48	4.60	0.0000005
NW	0.10	1.99	0.005
S	0.11	1.28	0.01
SE	0.01	2.14	-
SW	0.10	1.11	0.008
W	0.07	1.25	0.002
Overall		3.16	0.0007

Because of the greater sheltering effect a high frequency of calms was recorded at this site. All observations corresponding to a calm at either of the bottom two anemometers were excluded from the analysis.

The top anemometer was the only one to clear the top of the shelterbelts. The upper profile is representative of a sharp transition from the regional to the local environment and suggests a high degree of decoupling of the sheltered area from the surrounding environment. There is uncertainty about the actual transition height because only one anemometer cleared the shelterbelt, with the next one being well contained within the sheltered environment. The result also reflects the proximity of the mast to the H.R.A. shelterbelts, particularly to the east. As would be expected the greatest drop in wind speed is experienced with the northeast sector, representing the lee effect on the 8 m anemometer. The values to the north and southeast sectors are also probably partly influenced by this shelterbelt, although the latter result should be treated with some caution because of the low number of observations from the southeast. The exposure is greater for all other sectors, the results indicating the magnitude of the exposure. To the north and south there is possibly still some lee effect on wind speeds at 8 m. To the west and northwest 8 m wind speeds are probably affected by the roughening effect of the fruit trees.

Fig. 9.4.2 Hort. Research Area: wind profile for Northerly sector

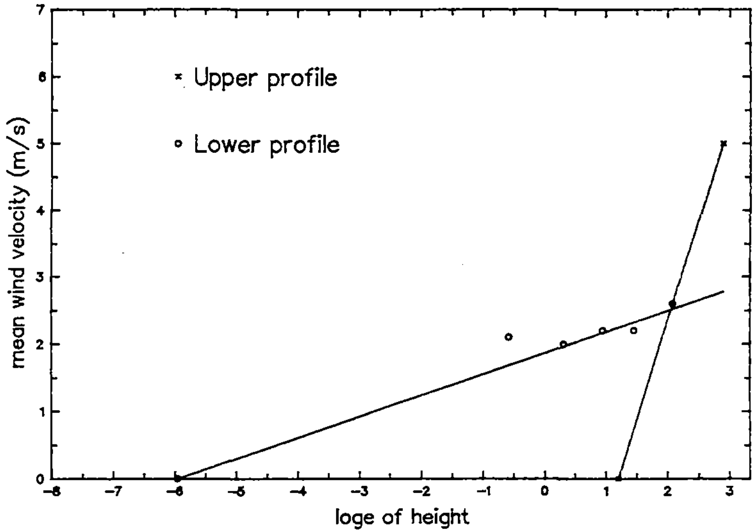


Fig. 9.4.3 Hort. Research Area: wind profile for Northeast sector

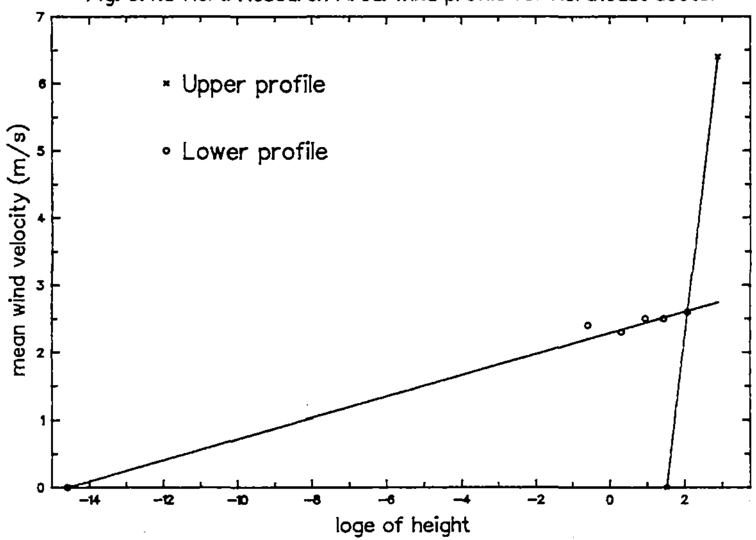


Fig. 9.4.4 Hort. Research Area: wind profile for Northwest sector

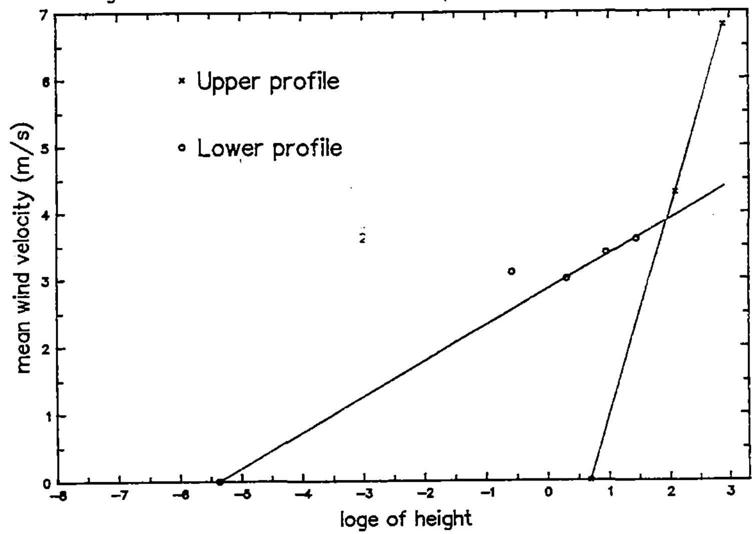


Fig. 9.4.5 Hort. Research Area: wind profile for Southerly sector

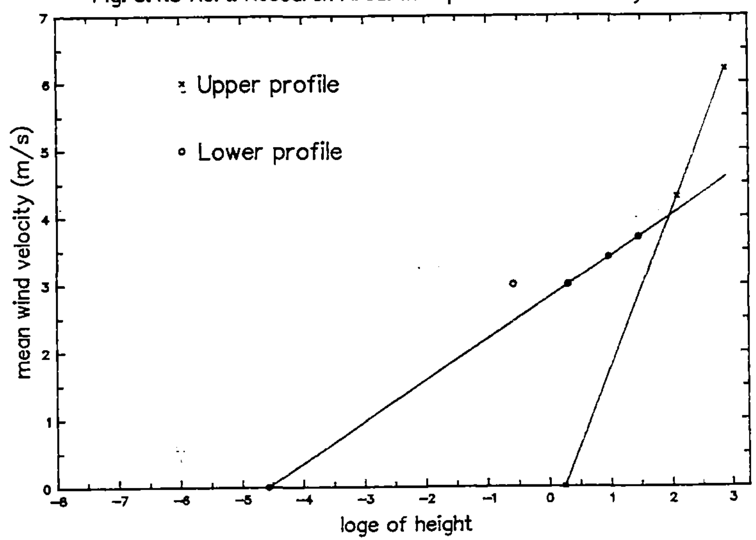


Fig. 9.4.6 Hort. Research Area: wind profile for Southeast sector

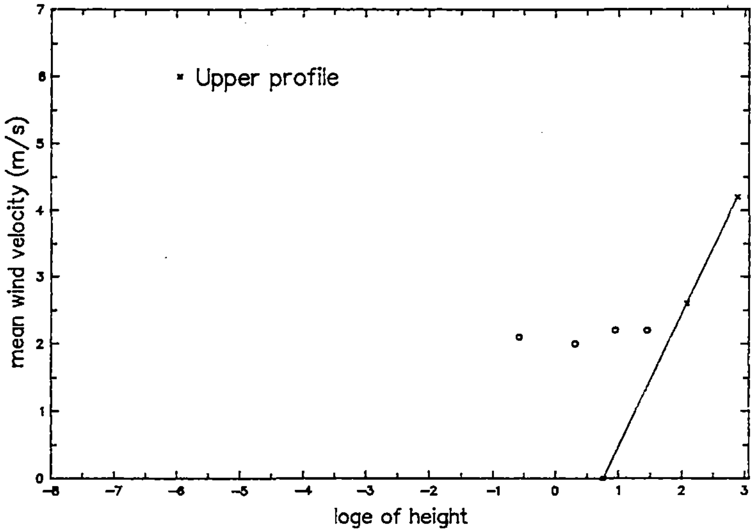


Fig. 9.4.7 Hort. Research Area: wind profile for Southwest sector

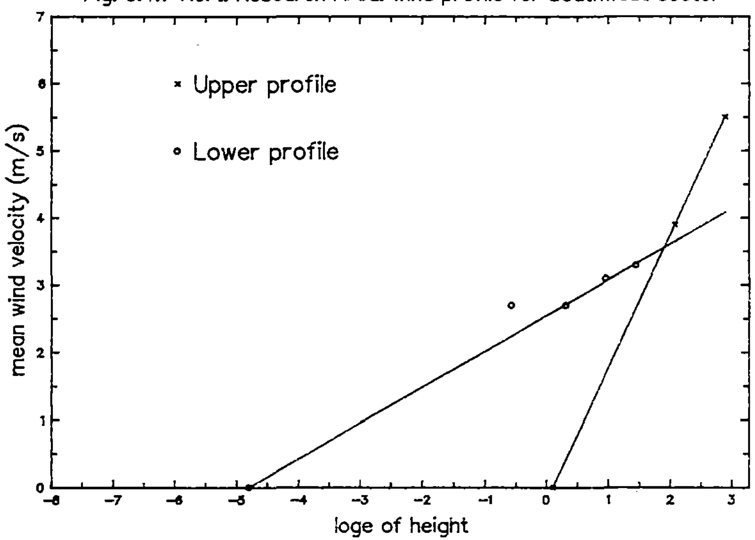


Fig. 9.4.8 Hort. Research Area: wind profile for Westerly sector

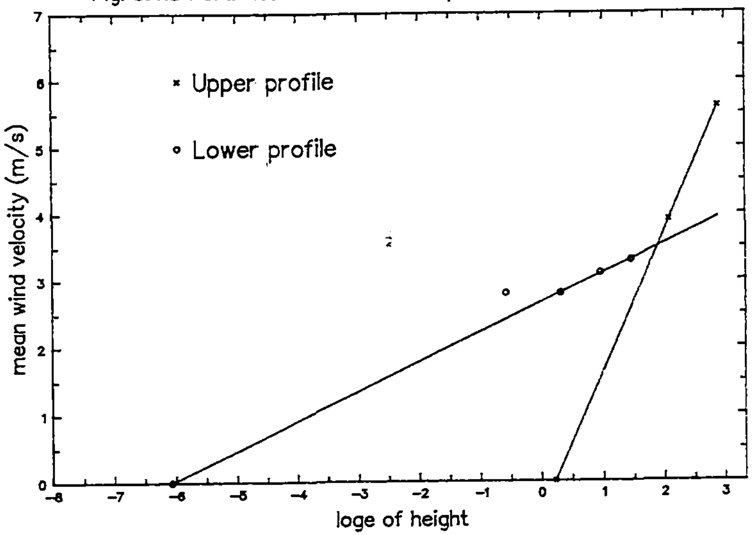
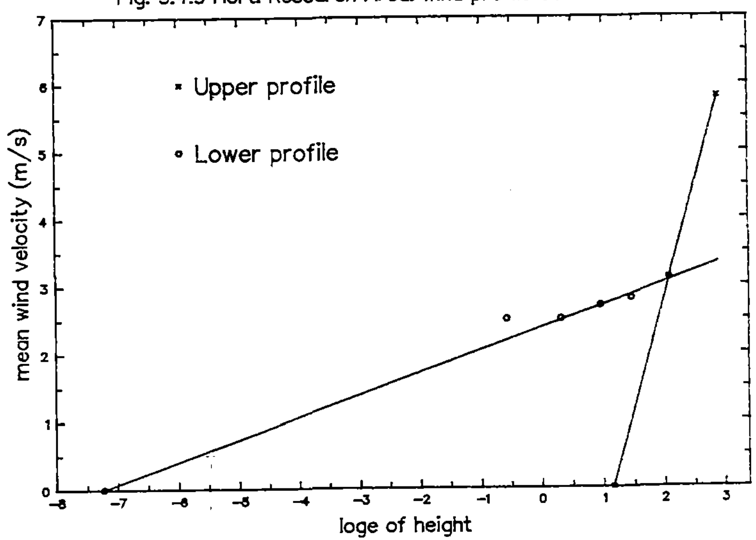


Fig. 9.4.9 Hort. Research Area: wind profile over all sectors



Lower profile values are obviously low because of the sheltering effect, both of the shelterbelts and the fruit trees. The effect is particularly strong with the northeast sector reflecting the proximity of the mast to the shelterbelt in this direction. The bottom two anemometers were the most strongly affected, with a high frequency of calms. As can be seen in the graphs, the lowest anemometer gave consistently higher wind speeds than the next highest one. A possible explanation is the effect of air passing through gaps in the shelter and fruit trees near the ground. Data from this anemometer was excluded from the regression. Lower profile data for the H.R.A. should be treated cautiously because of the difficulty of calibrating the anemometers at low wind speeds and the high frequency of such winds (<3.0 ms^{-1}) in the lower profile.

9.4.3 Site microclimate

Regressions between estimated H.R.A. data and data for the reference site are presented in Figs. 9.4.10-9.4.18. The t values for the slope and elevation of the fitted lines and their significance are given in Table 9.4.2.

Table 9.4.2

Hort. Research Area vs Broadfield
Significance of differences in slope and elevation
of fitted lines from 1:1 lines

Variable	t(slope)	t(elevation)
Mean temp.	-2.20*	7.79**
Max. temp.	-1.78	2.96**
Min. temp.	-3.76**	6.19**
Wind speed	-11.40**	-38.38**
S. vap. press	-1.44	4.78**
Vapour press	3.31**	1.18
Vap press def	-0.78	5.04**
Penman ET	-6.26**	9.93**
Priestley-Taylor ET	1.38	0.14

Note: ** = 1% significant
* = 5% significant

Temperature

Three outliers were excluded from the comparison of mean temperatures. The first was removed because of its high leverage effect and a slight anomaly as a result of the averaging procedures. The other two were both strongly biased by the different averaging methods.

Fig. 9.4.10 Mean screen temperature: estimated Hort. Res. Area vs Broadfield

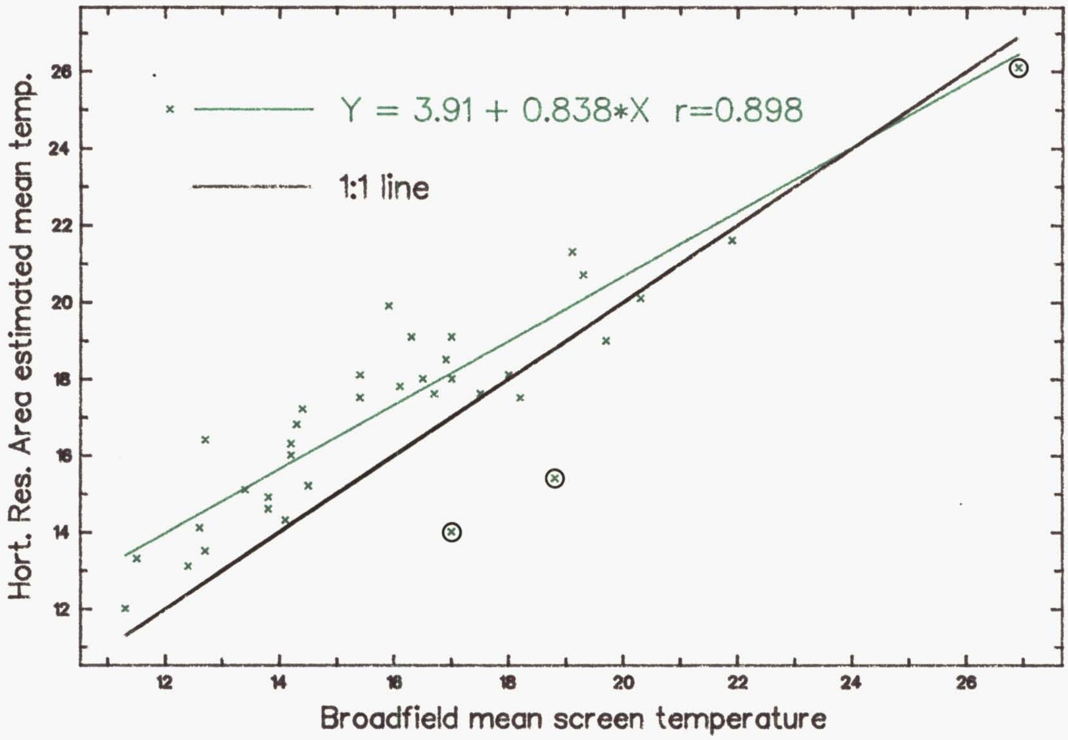
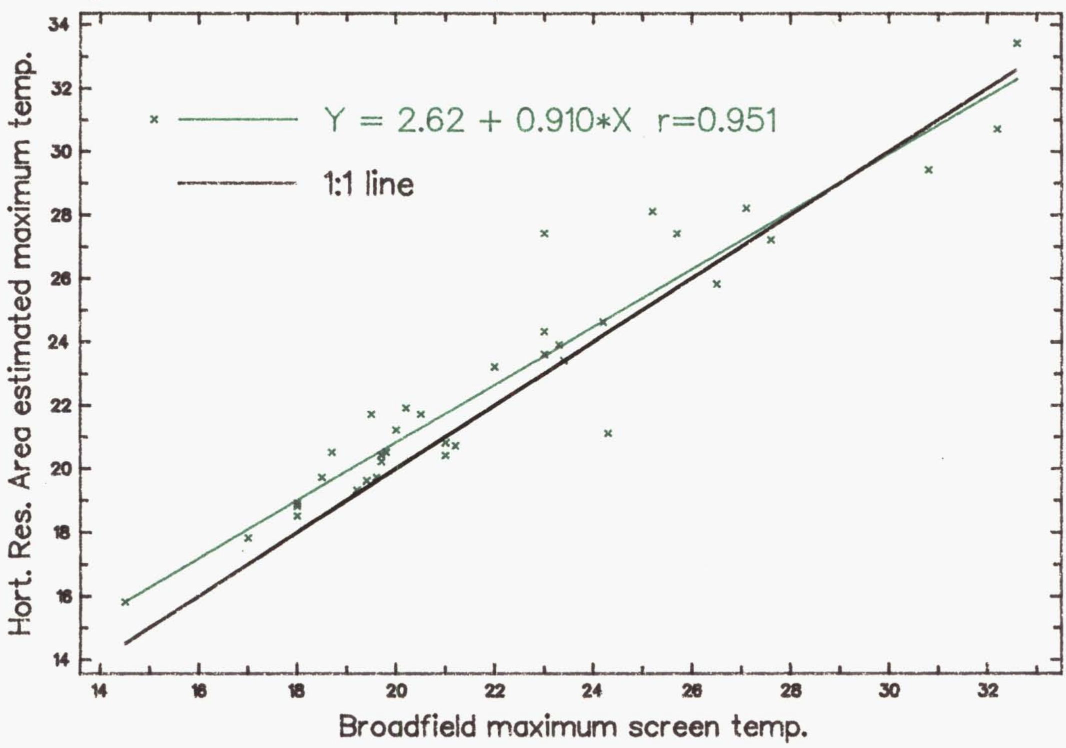


Fig. 9.4.11 Maximum screen temp.: estimated Hort. Res. Area vs Broadfield



O = Outlier

Fig. 9.4.12 Minimum screen temp.: estimated Hort. Res. Area vs Broadfield

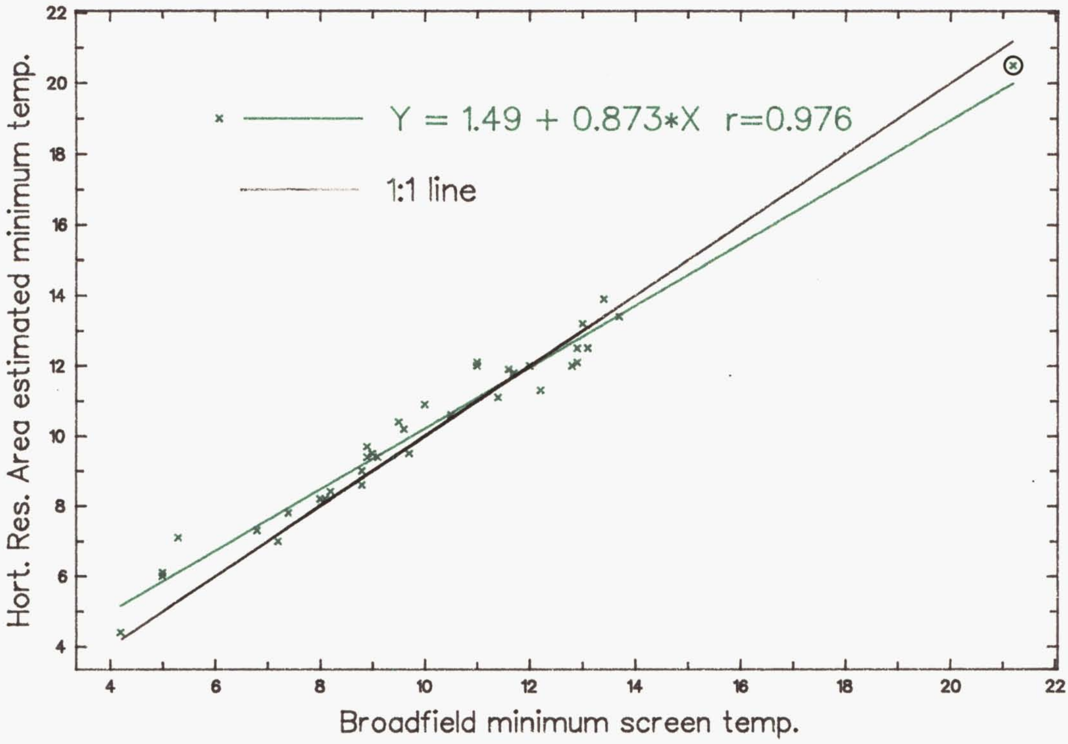
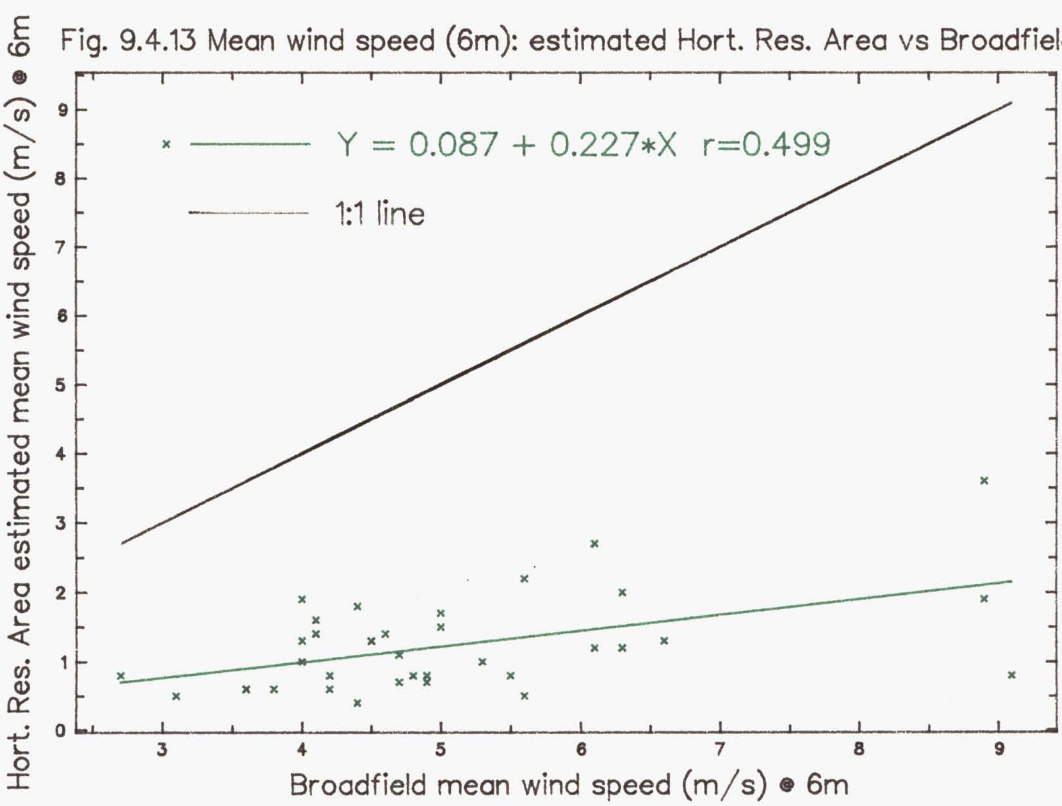


Fig. 9.4.13 Mean wind speed (6m): estimated Hort. Res. Area vs Broadfield



O = Outlier

These latter two both occurred on days that began with warm, northwesterly conditions and then turned southerly close to midday with a corresponding rapid temperature drop. The generally cooler conditions that prevailed were not fully reflected in the 2-point means. A fourth outlier was examined for bias, but was found to be a real sheltering effect, occurring on a warm night when the shelter apparently became a trap for warm air. Removal of biased outliers led to an increase in significance of the elevation of the fitted line above the 1:1 line. With a significantly lower slope the fitted line tended to approach the 1:1 line at higher temperatures.

Maximum temperatures estimated from data from each of the two mast heights individually gave a more significant result than when regressing estimates from the combined equation. There was no significant difference in slope, however maximum temperatures in the H.R.A were consistently higher than Broadfield with a significant elevation. At higher temperatures the difference was less, as reflected in the mean temperature relationship. This is consistent with the result from the Plant Science block.

Minimum temperatures showed a significant difference in slope, which was reduced but still significant when an outlier exerting high leverage was removed. Minimum temperatures were significantly higher in the H.R.A., as indicated of a significant elevation of the fitted line away from the 1:1 line. Although minimum temperatures were consistently higher the difference was again less under warmer conditions as shown by the scatter of the data. As measurements were made in mid summer this result is not surprising. With low soil moisture conditions and a strong sheltering effect there would be low potential for evaporative cooling and the sheltered area would tend to become a sink for sensible heat at night time.

Wind speed

Understandably mean wind speeds at 6 m were significantly lower in the H.R.A., the wind undergoing considerable modification with the presence of the shelterbelts. The important result is the highly significant elevation of the regression line, being well below the 1:1 relationship.

Vapour pressure

Two of the outliers from the mean temperature analysis, again had a significant effect on the site comparisons of saturated vapour pressure. Their removal from the analysis significantly altered the result. Although there was no significant difference in slope of the fitted line it was significantly elevated above the 1:1 line. A higher saturated vapour pressure in the H.R.A is consistent with the higher temperatures at this site.

Fig. 9.4.14 Saturated vapour pressure: estimated Hort. Res. Area vs Broadfield

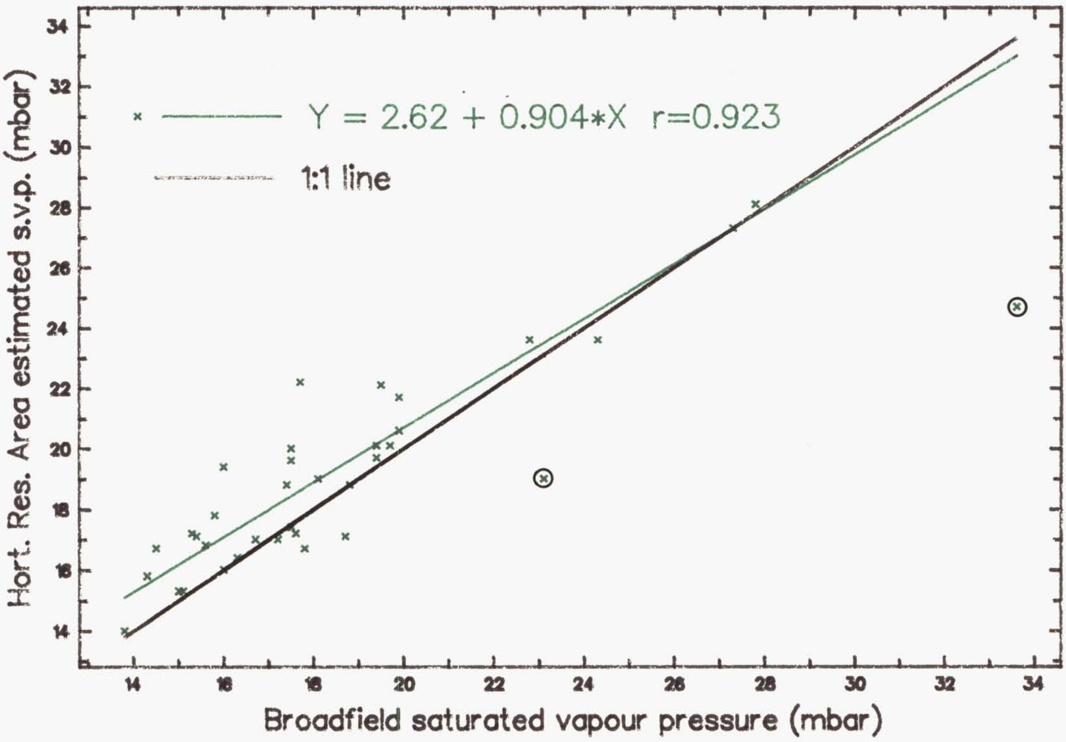
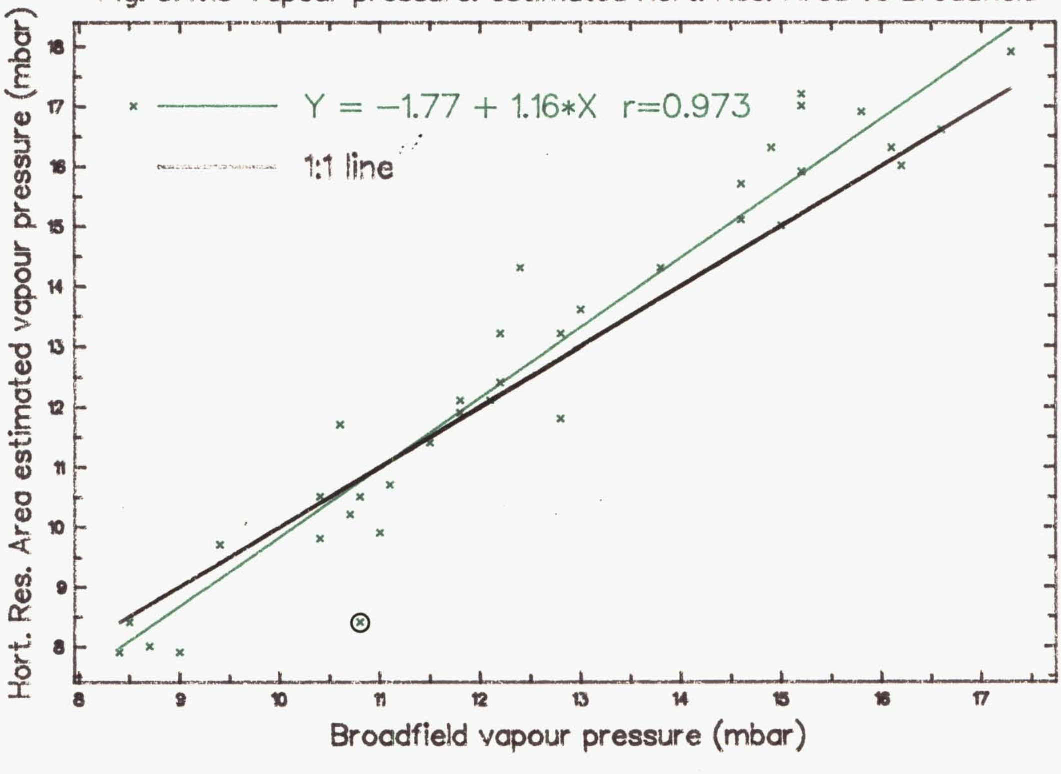


Fig. 9.4.15 Vapour pressure: estimated Hort. Res. Area vs Broadfield



○ = Outlier

Fig. 9.4.16 Vapour pressure deficit: estimated Hort. Res. Area vs Broadfield

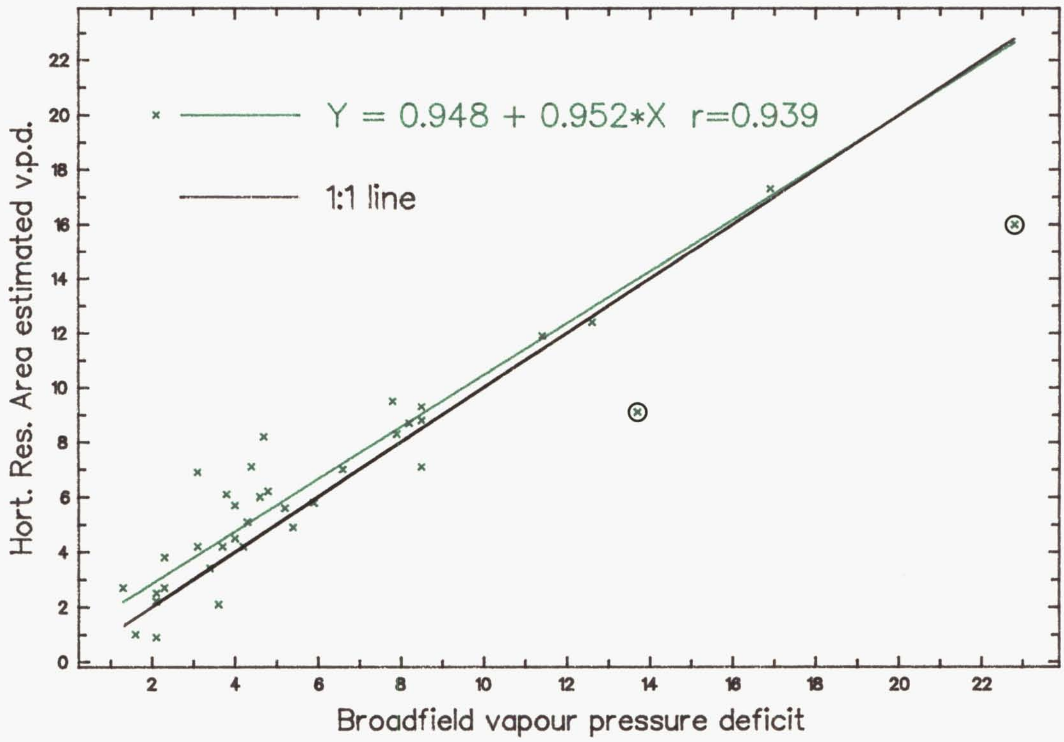
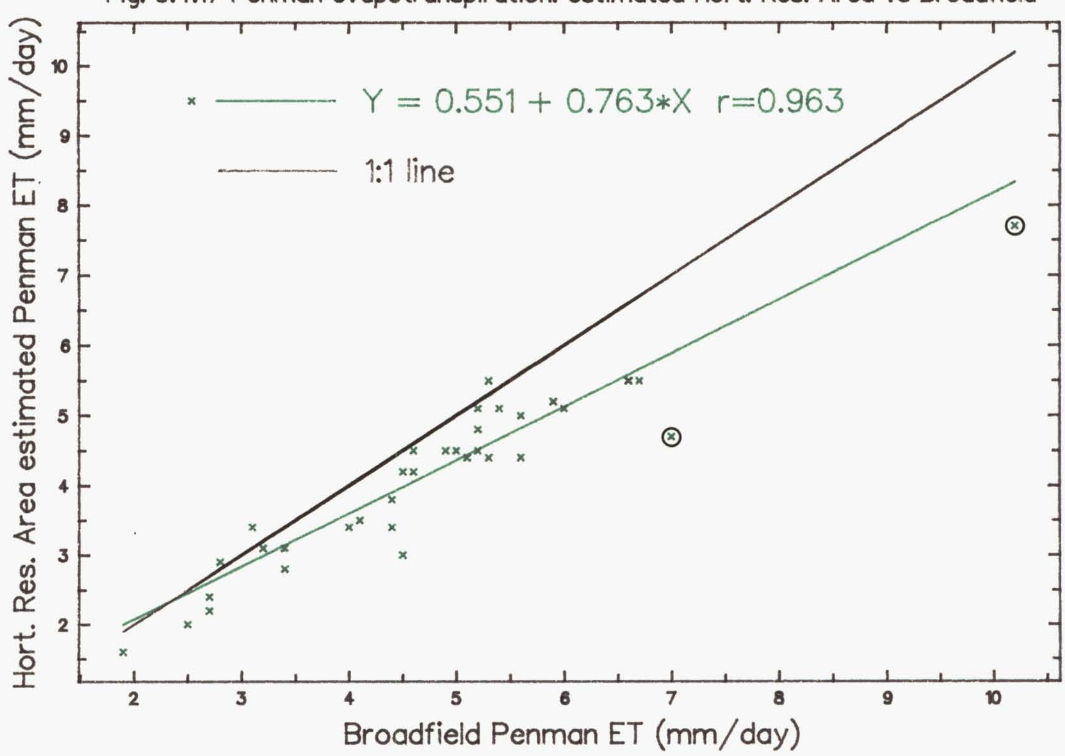


Fig. 9.4.17 Penman evapotranspiration: estimated Hort. Res. Area vs Broadfield



○ = Outlier

Fig. 9.4.18 Priestley–Taylor ET: estimated Hort. Res. Area vs Broadfield

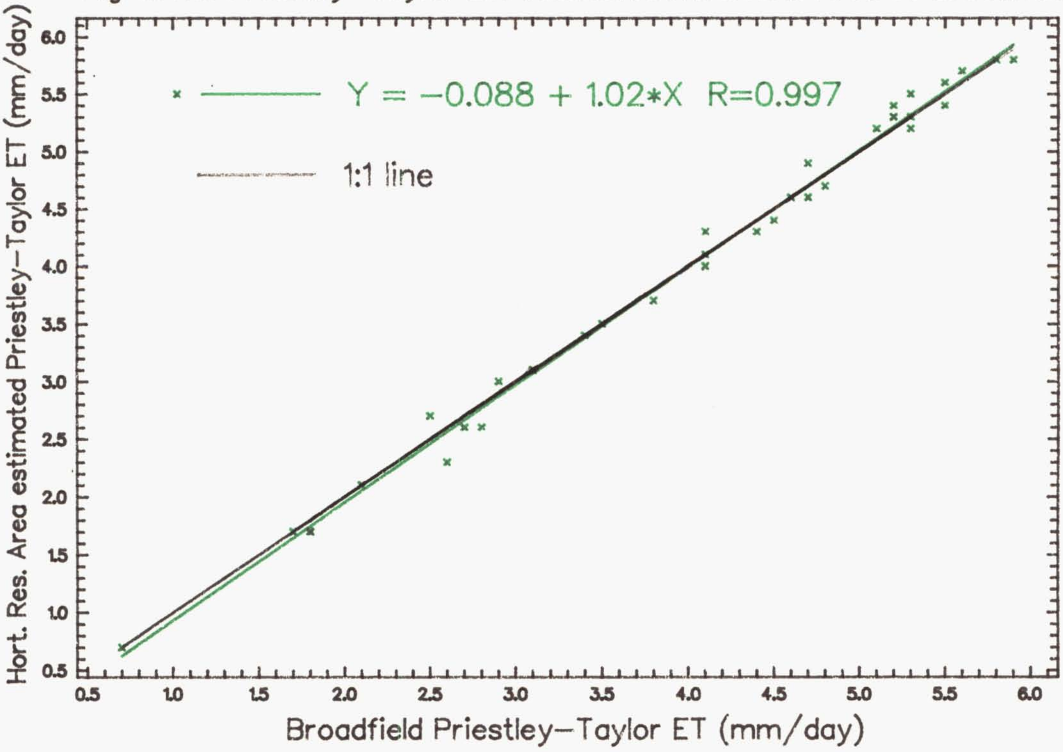
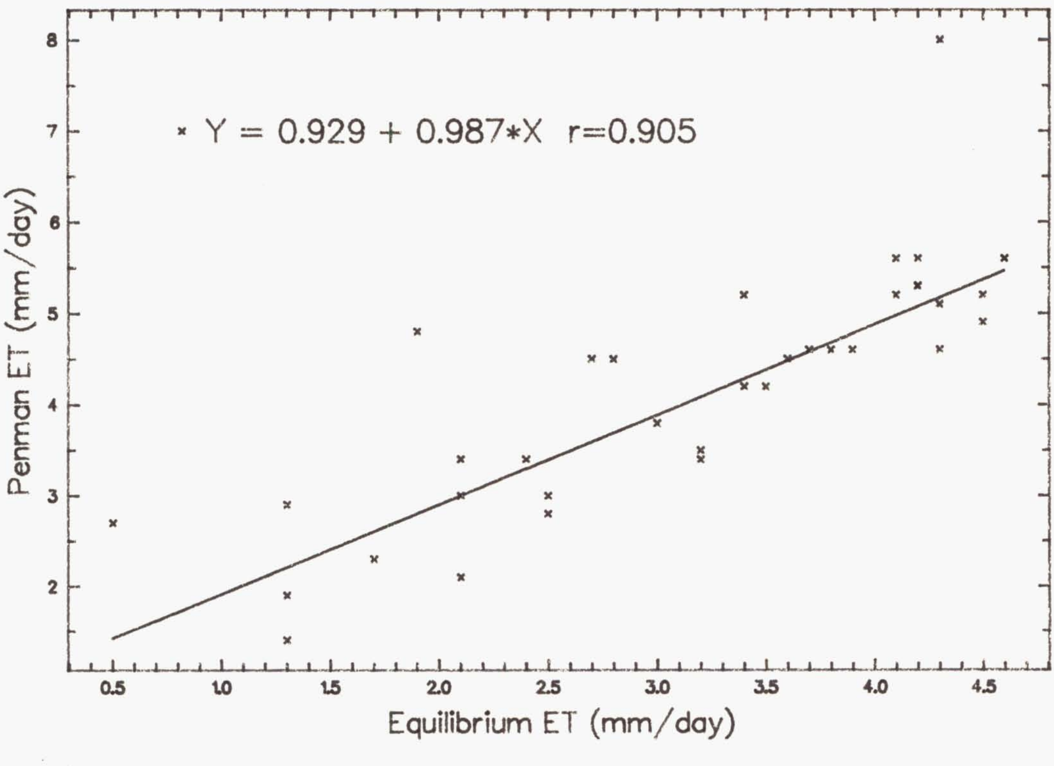


Fig. 9.4.19 Hort. Res. Area: Penman ET vs Equilibrium ET



There was no significant difference in elevation of vapour pressure, although a significant difference in slope suggests the potential for higher vapour pressure in the H.R.A under warmer conditions. The conservative nature of the measurement should be considered when making site comparisons.

The combined effect of higher saturated vapour pressure and no significant difference in vapour pressure is reflected in a significant elevation of vapour pressure deficit about the means. This effect tends to be reduced at higher temperatures, reflecting the upward trend in vapour pressure under such conditions at the H.R.A.

Evapotranspiration

Penman evapotranspiration showed both a significantly lower slope and elevation in relation to the 1:1 line. Removal of the two outliers that resulted from earlier mentioned temperature anomalies did not alter the significance of the result. The largest difference between this and the reference site was with the mean wind speeds. This significant reduction in turbulent mixing even under northwest conditions had a marked effect on this estimate of evapotranspiration.

The Priestley-Taylor equation showed no significant differences between the sites. It appears that an $\alpha = 1.26$ is inappropriate for this site, given the high degree of decoupling from the regional environment. Again an empirical check was carried out using the Penman and equilibrium evapotranspiration data. Initially the analysis was carried out with two outliers, both corresponding to northwest conditions, included. The result was an $\alpha = 0.97$, with a significant correlation $r = 0.827$ ($p>0.01$). Removal of the outliers did not substantially alter the result. The result of this latter regression is given in Fig. 9.4.19. This time an $\alpha = 0.987$ was obtained with a slightly improved correlation. This suggests that the Priestley-Taylor method gave more conservative estimates than the Penman method for this site. The result is consistent with results achieved by Judd and McAneney (1984) in Northland, in a sheltered orchard.

9.5 The Lincoln Springs site

9.5.1 Site description

The Lincoln Springs orchard is situated 5 km north of the Lincoln campus. The village of Prebbleton is 2-3 km to the north with the dominant geographic feature again being the Banks Peninsula. The site was purchased by Lincoln College in 1982 and has been developed since that time. The photos giving the 360° perspective, Fig. 9.5.1 give an indication of the state of development of the site. Much of the shelter comprises deciduous poplar and willow species with the boundary shelter double planted with poplars and evergreen Eucalyptus trees. They are obviously less mature than the shelter trees in the H.R.A. It should be noted that the photos were taken during the Autumn transition, at the end of the measurement period.

Fig. 9.5.1 360° view of the Lincoln Springs Orchard site environs

The mast was sited at the eastern end of the orchard, being the only available grassed area. As can be seen the site is most sheltered to the north and around to the west. The exposure is generally greater to the northeast and the southerly quarter.

The period of measurement at this site was from 23/3/1988 to 4/5/1988. Measurements began in a period of mild, sunny and dry conditions. The dry sunny weather persisted until the end of measurement, in early May. As with March this period was characterised by high atmospheric pressures over New Zealand. Temperatures were cooler on average in April and May. As with the other sites deficit days were above average over the period of measurement.

9.5.2 Site roughness

Results are presented graphically in Figs. 9.5.2-9.5.9, with wind frequency and z_0 values from each sector in Table 9.5.1.

Table 9.5.1

Site roughness and frequency of wind from each sector

		Site roughness (z_0)	
Wind sector	Frequency	Upper profile	Lower profile
N	0.04	0.94	0.074
NE	0.56	0.57	0.005
NW	0.03	1.10	0.100
S	0.10	0.31	0.026
SE	0.02	0.09	0.023
SW	0.18	0.50	0.096
W	0.06	0.64	0.081
Overall		0.39	0.045

Over the period of measurement at the Lincoln Springs site, the wind vane did not always read true. This was verified by checking Christchurch airport data against the mast data and identifying days of a known weather pattern. The wind vane was still functional, but the movement of the potentiometer appears to have been restricted. The most likely explanation is that the mounting clamps were tightened too hard thus restricting movement. There were markings on the arm that suggested that it had been used as a perch but this hardly explains the failure of the vane to register a southerly change. When the mast data matched the general pattern at the airport it was left unchanged. Easterly winds were assigned as northeast because of the effect of the Peninsula. It was mostly northwest, westerly, southwesterly and southerly conditions that were not accurately recorded. Previous comparisons had shown other sites to be fairly consistent with the airport with winds from these sectors and so it was considered reasonable to use airport data for this site.

Fig. 9.5.2 Lincoln Springs: wind profile for Northerly sector

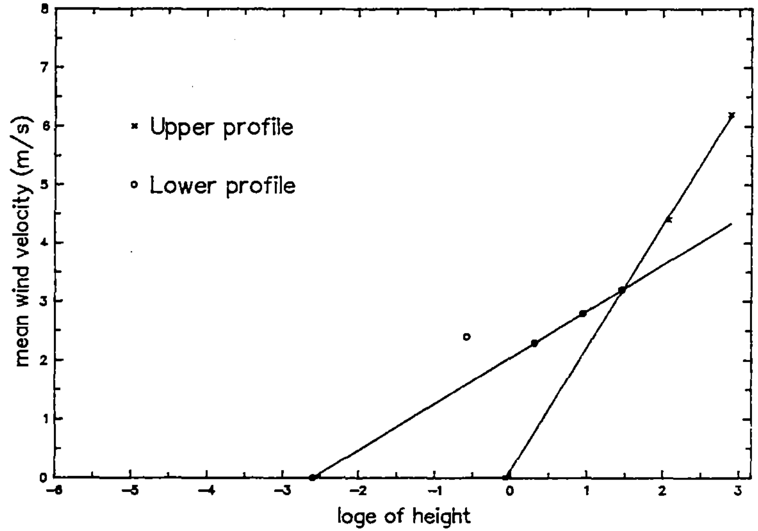


Fig. 9.5.3 Lincoln Springs: wind profile for Northeast sector

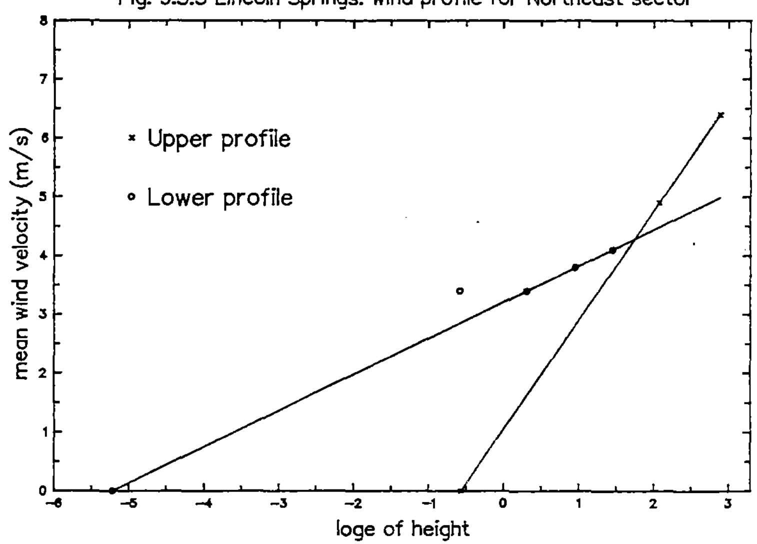


Fig. 9.5.4 Lincoln Springs: wind profile for Northwest sector

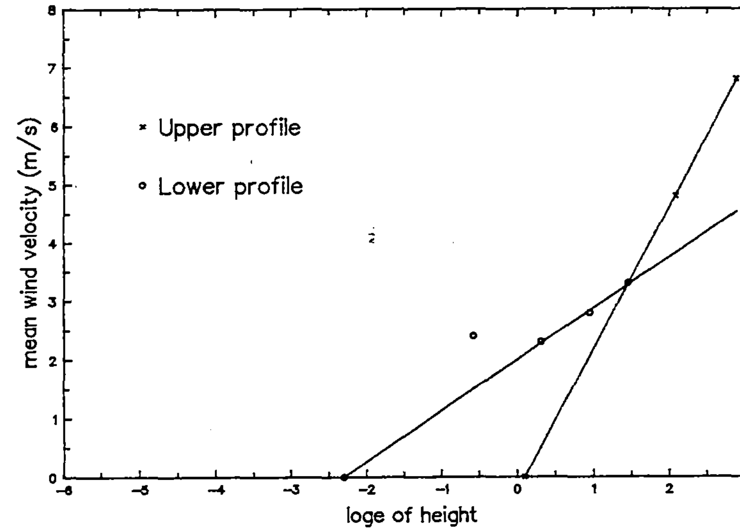


Fig. 9.5.5 Lincoln Springs: wind profile for Southerly sector

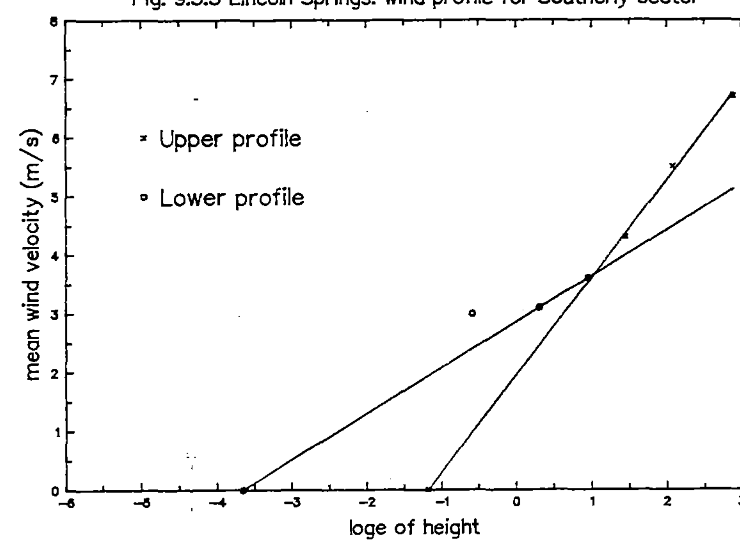


Fig. 9.5.6 Lincoln Springs: wind profile for Southeast sector

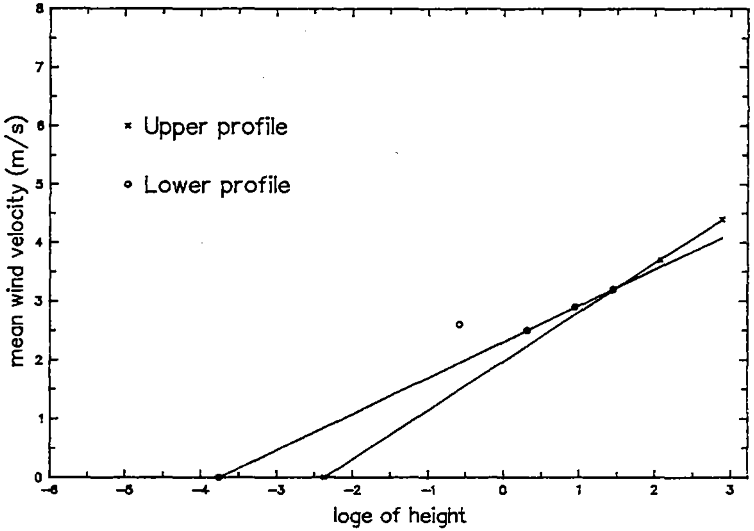


Fig. 9.5.7 Lincoln Springs: wind profile for Southwest sector

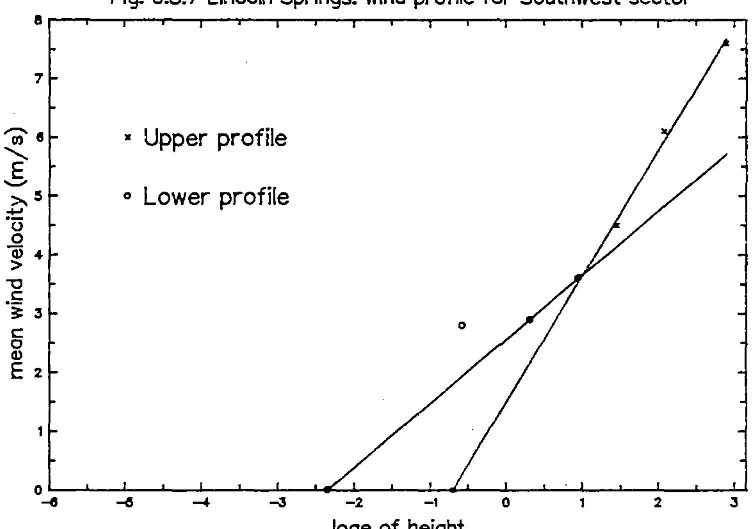


Fig. 9.5.8 Lincoln Springs: wind profile for Westerly sector

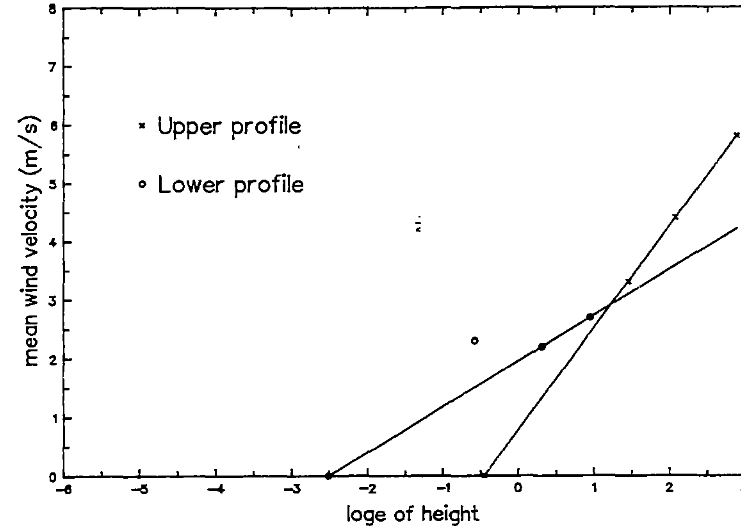
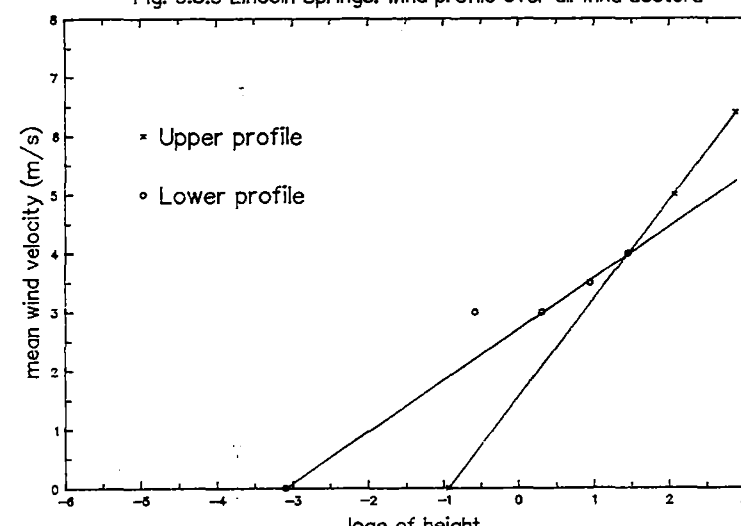


Fig. 9.5.9 Lincoln Springs: wind profile over all wind sectors



The results for the different profiles do seem to be sensible but should be treated with a degree of caution.

Because this site is more strongly coupled with the regional environment than the H.R.A. the upper profile was covered by three and sometimes four anemometers depending on the exposure of a particular sector. There was however still a strong sheltering effect on the result, as indicated by the upper profile results. Data from the northwest and southeast sectors should be treated with more caution because of the low frequency of observations. They do, however, follow the general pattern. The northern sectors and the westerly sectors all show a greater upper profile z_0, with the southern sectors showing greater exposure. The northeastern sector is the most exposed of the northern sectors, facing to the entranceway, with an open field situation beyond. Certainly the exposure is nothing of the magnitude of the Broadfield site.

The lower profile values are all affected by within site roughness effects. The most exposed sector is to the northeast, which is characteristic of a smoother fetch, as indicated by the open grassed area. Again the anomaly with the lowest anemometers was experienced, reinforcing the belief that the cause was near surface air movement. As before these data were removed from the profile characterisation.

9.5.3 Site microclimate

Regressions between estimated Lincoln Springs data and reference site data are presented in Figs. 9.5.10-9.6.18. The t values for the slope and elevation of the fitted regression lines and their significance are given in Table 9.5.2.

Table 9.5.2

Lincoln Springs vs Broadfield
Significance of differences in slope and elevation
of fitted lines from 1:1 lines

Variable	t(slope)	t(elevation)
Mean temp.	-4.22**	2.71*
Max. temp.	-5.01**	15.95**
Min. temp.	0.44	1.56
Wind speed	-9.55**	-22.71**
S. vap. press.	-4.02**	3.95**
Vapour press	0.64	8.08**
Vap press def	-3.09**	-0.69
Penman ET	-5.04**	-4.00**
Priestley-Taylor ET-0.86	-1.75	

Note: ** = 1% significant
* = 5% significant

Temperature

On two days rapidly changing northwest to southerly conditions led to temperature anomalies. Removal of these values from the analysis led to no significant change in the slope of the regression line with the slope being significantly different from a 1:1 relationship. Their presence however had a downward effect on the elevation so that with their removal the result was a significant elevation of the fitted line above the 1:1 line. With the differences in slope the trend was toward less differences between sites with warmer conditions. This is consistent with results from both the Plant Science block and the Horticultural Research Area.

Differences in mean temperatures were obviously strongly influenced by differences in maximum temperatures. Two outliers were removed. Both occurred under rapidly changing temperature conditions. Broadfield data, Christchurch airport data were all checked for the relevant period. The indication was that actual time of recording would have been critical and that differences in timing may have led to the apparent anomalies. As it was their removal did not alter the result. Maximum temperatures from the mast showed a significantly different slope and elevation. Although tending towards the 1:1 line at higher temperatures the Lincoln Springs site had consistently higher temperatures. There was no significant difference in minimum temperatures suggesting that the differences between this and the reference site are greatest in the daytime. This is in contrast to the H.R.A and is perhaps a reflection of the cooler autumn conditions that prevailed at this time.

Mean wind speed

Although this site is less sheltered than the H.R.A. The sheltering effect was still significant. The regression line was well below the 1:1 line with a significant difference in elevation. The sheltering effect was apparently greater under windier conditions with a significantly lower slope.

Vapour pressure

The two mean temperature anomalies that were earlier highlighted again had a downward levering effect on saturated vapour pressure. The pattern was generally the same as with mean temperatures with significant differences in slope and elevation. The downward slope showed a trend towards the 1:1 line and at higher temperatures Lincoln Springs saturated vapour pressure was generally lower than that for the reference site

Two obvious outliers were apparent with vapour pressure both resulting from temperature anomalies. Their removal did not alter the result although their effect had been to pull the estimated Lincoln Springs mean down toward the 1:1 line.

Fig. 9.5.10 Mean screen temperature: estimated Lincoln Springs vs Broadfield

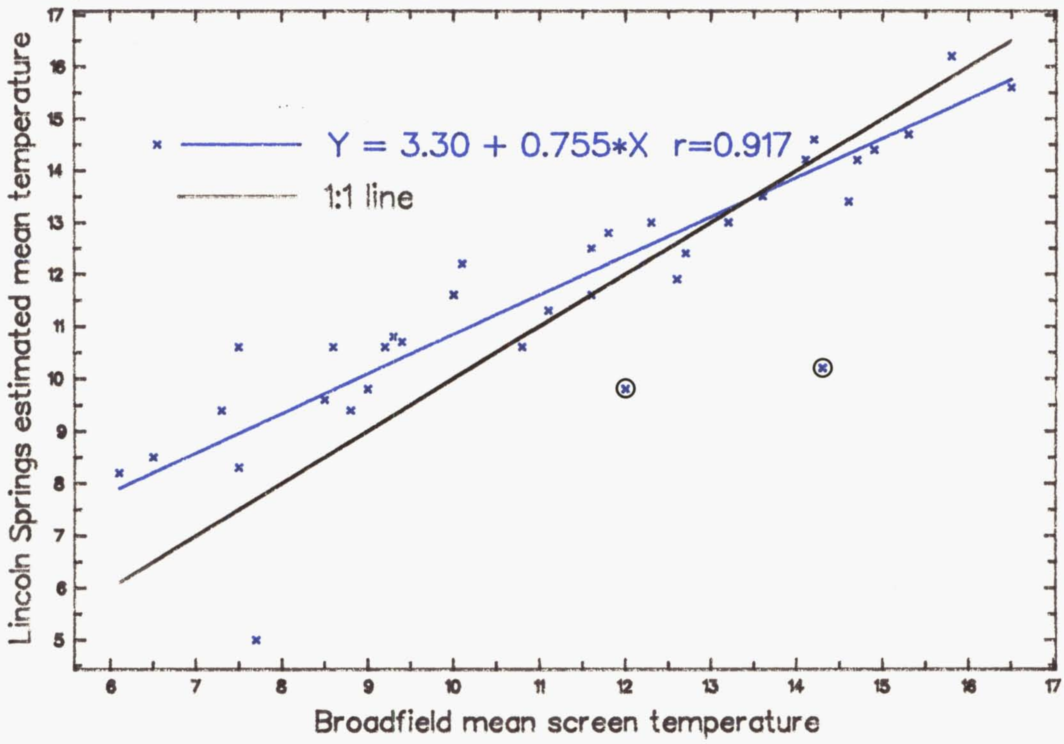
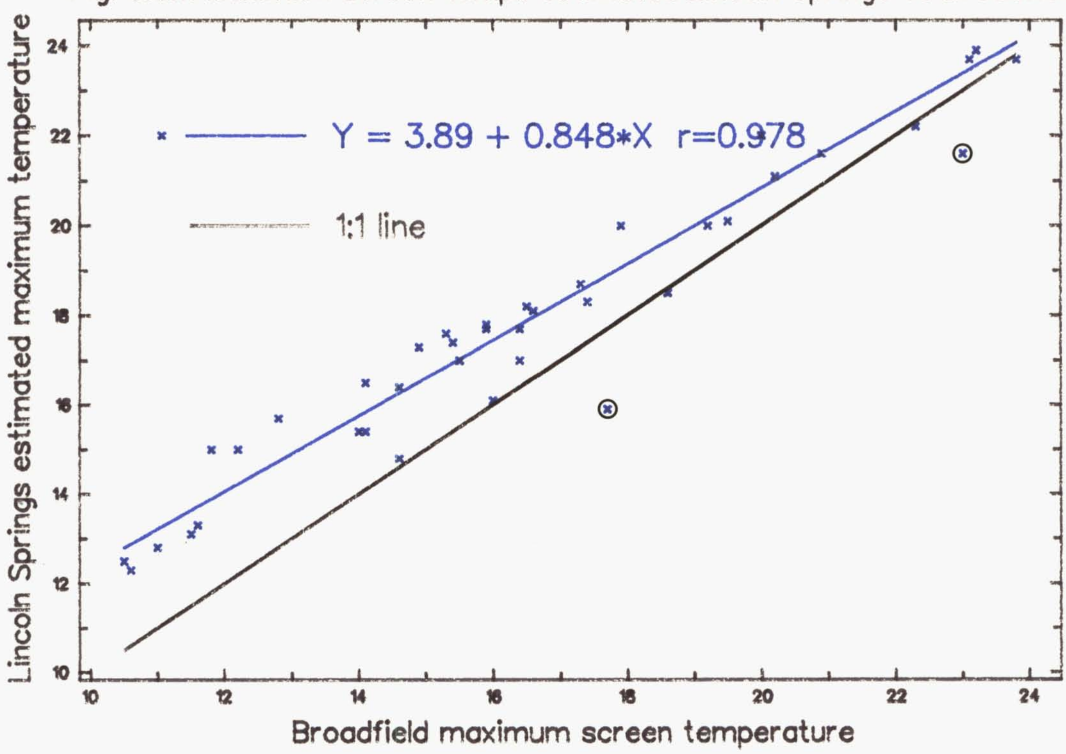


Fig. 9.5.11 Maximum screen temp.: estimated Lincoln Springs vs Broadfield



○ = Outlier

Fig. 9.5.12 Minimum screen temp.: estimated Lincoln Springs vs Broadfield

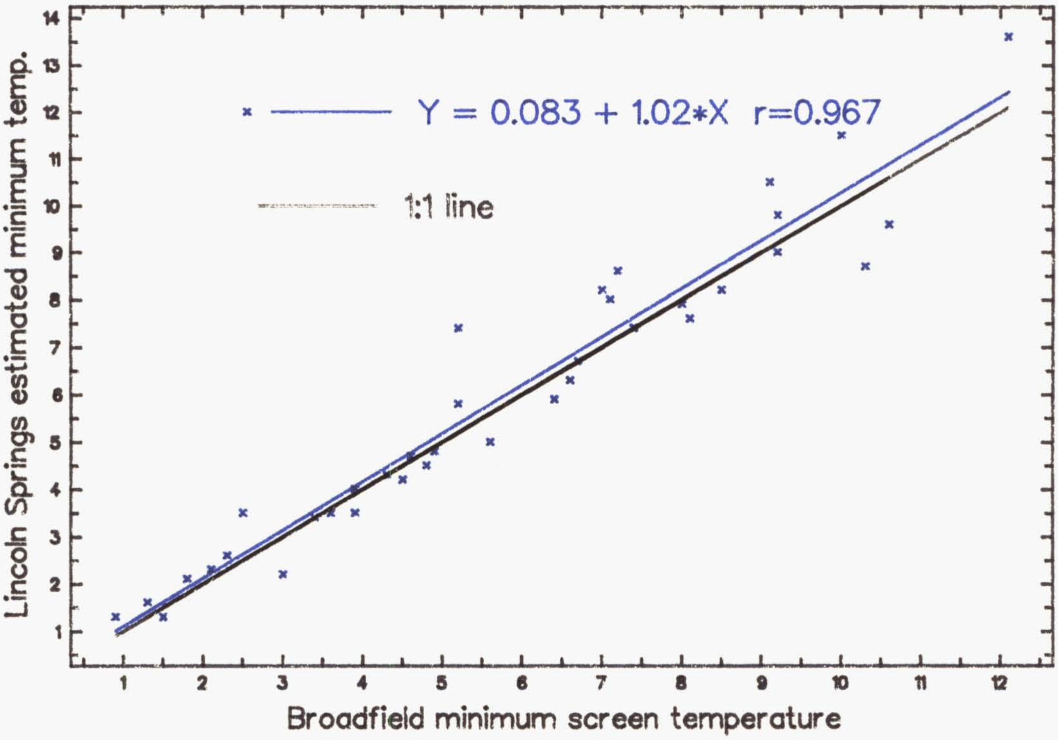


Fig. 9.5.13 Mean wind speed (6m): estimated Lincoln Springs vs Broadfield

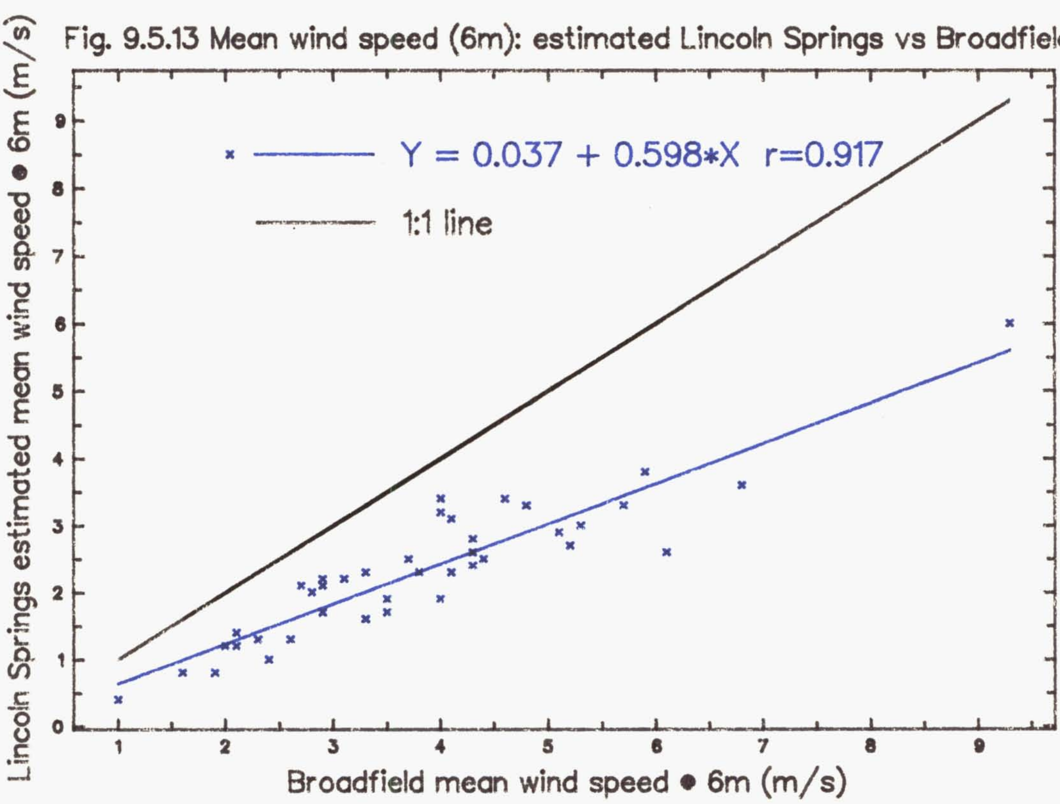


Fig. 9.5.14 Saturated vapour pressure: estimated Lincoln Springs vs Broadfield

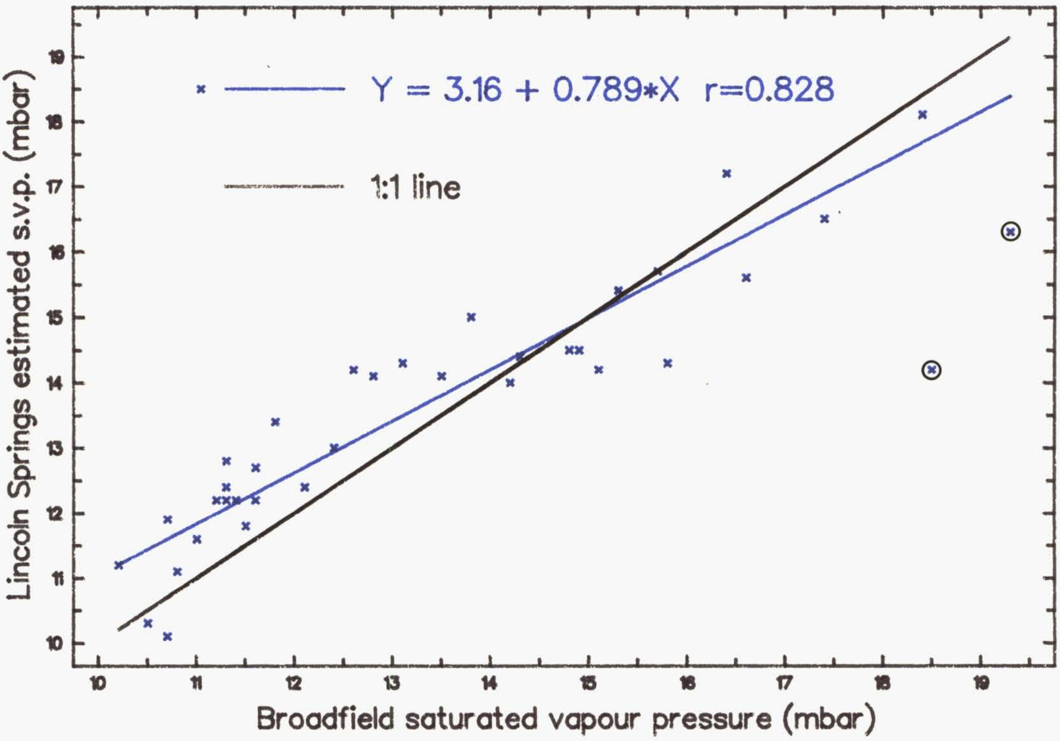
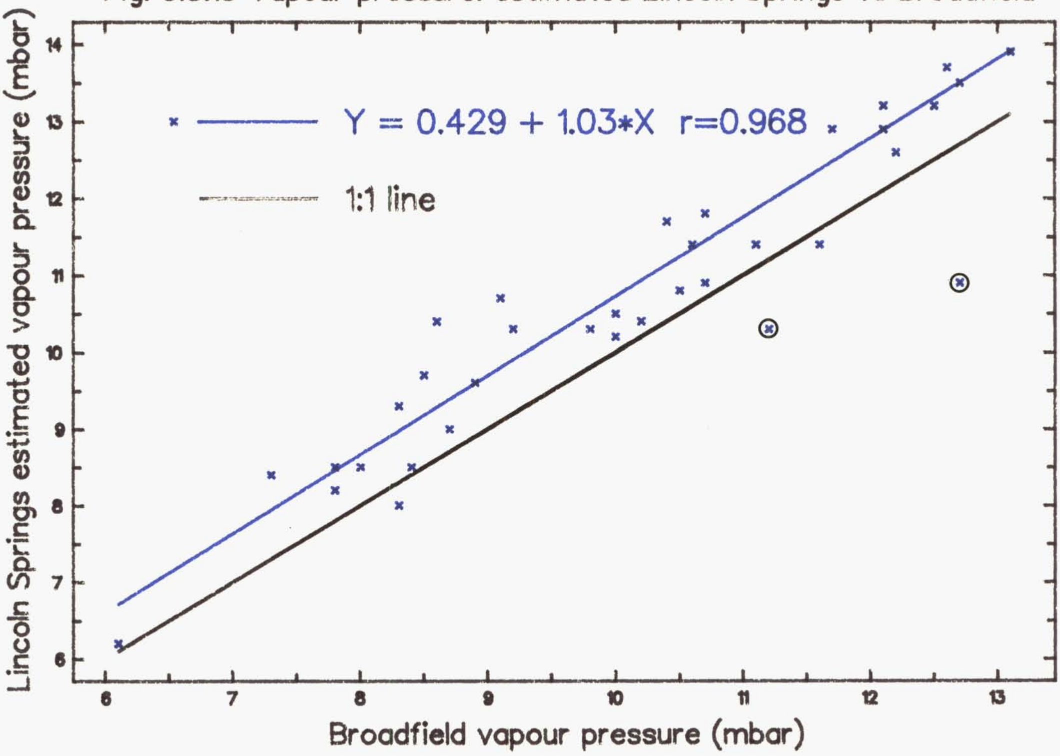


Fig. 9.5.15 Vapour pressure: estimated Lincoln Springs vs Broadfield



O = Outlier

Fig. 9.5.16 Vapour pressure deficit: estimated Lincoln Springs vs Broadfield

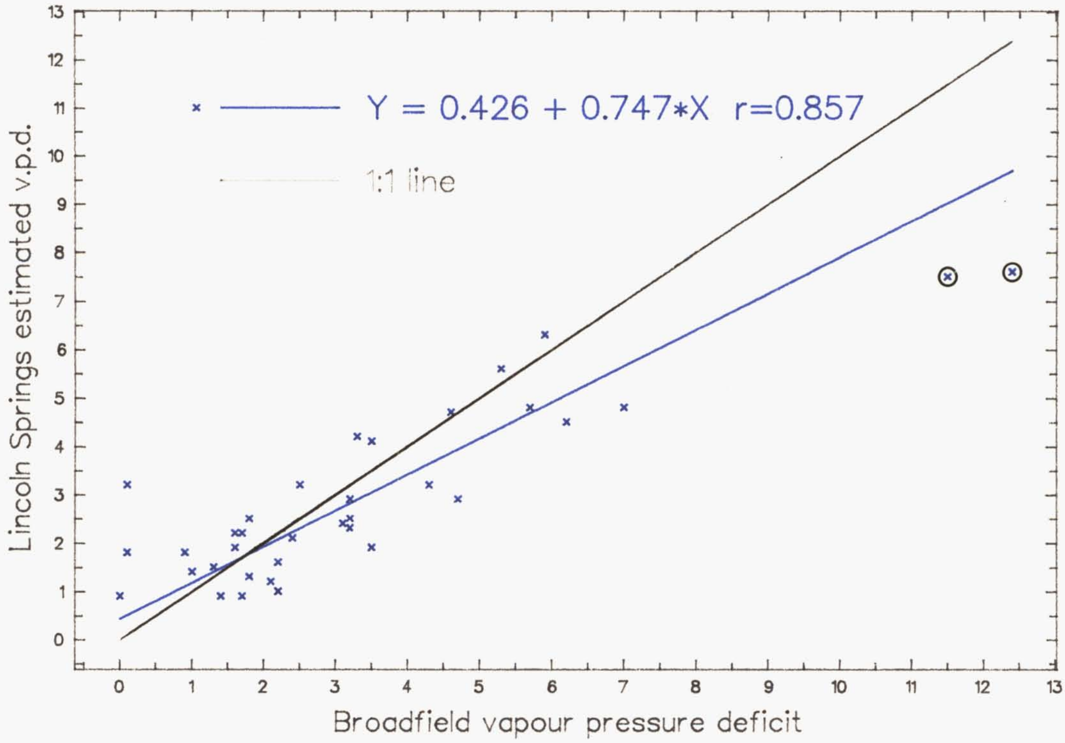
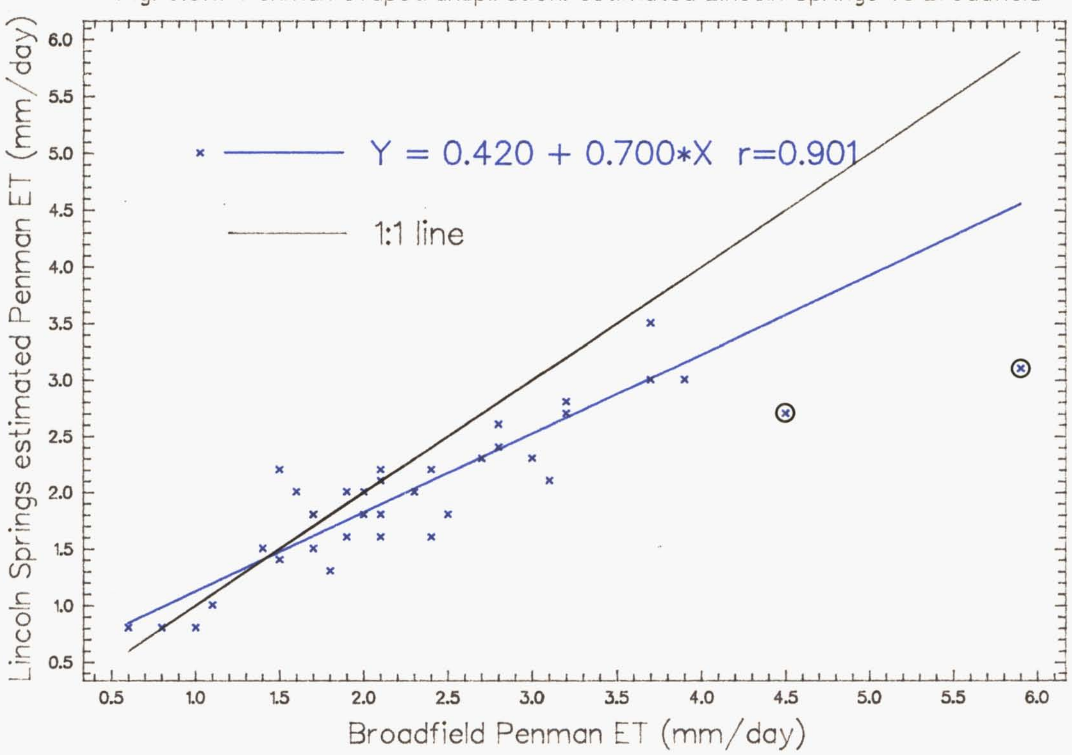


Fig. 9.5.17 Penman evapotranspiration: estimated Lincoln Springs vs Broadfield



O = Outlier

Fig. 9.5.18 Priestley–Taylor ET: estimated Lincoln Springs vs Broadfield

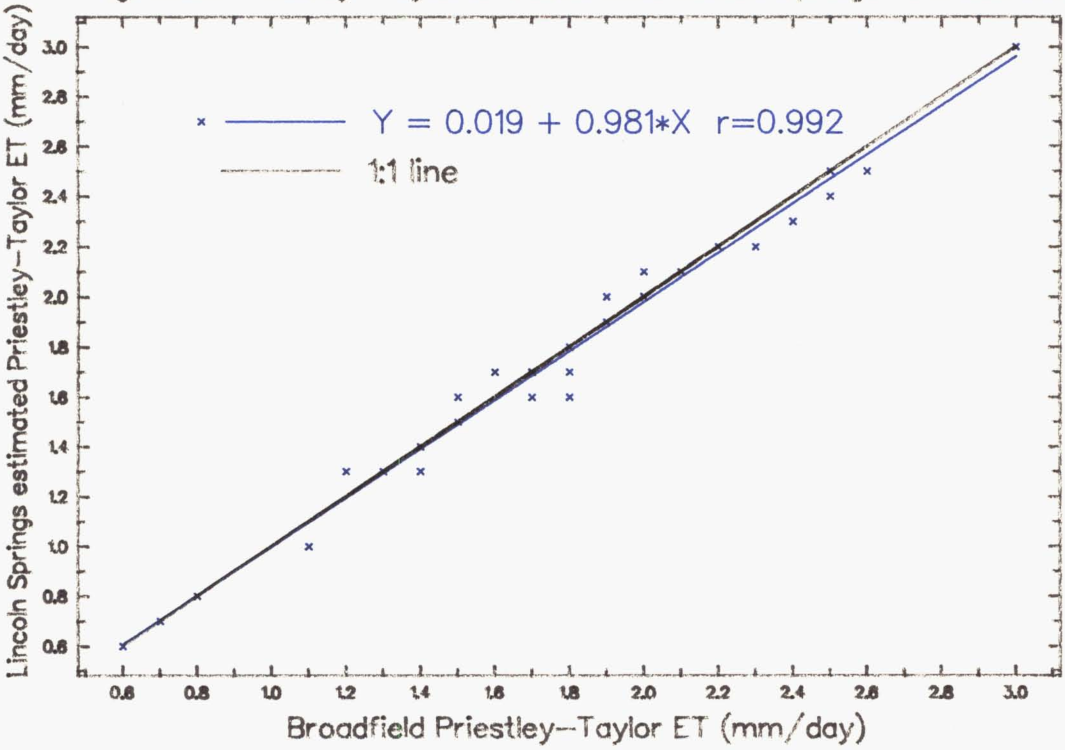
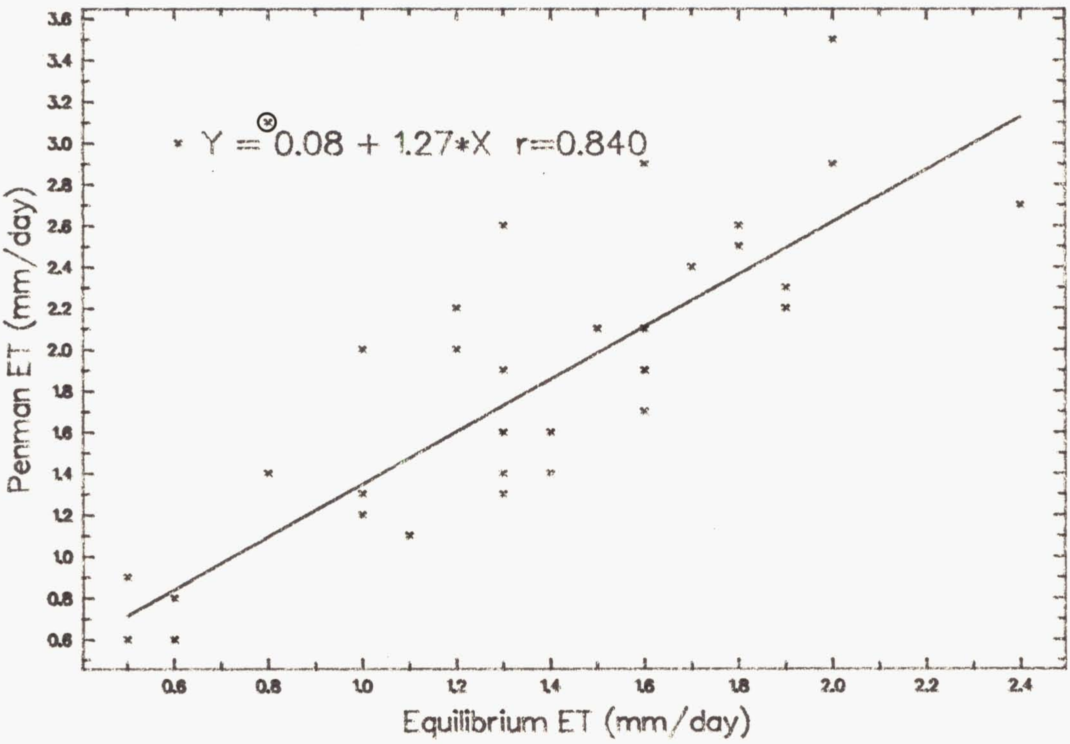


Fig. 9.5.19 Lincoln Springs: Equilibrium ET vs Penman ET



With no significant difference in slope and a significantly higher elevation vapour pressure tended to be higher in the orchard under most conditions covered by the period of measurement.

Vapour pressure deficit was affected by patterns with both the previous two variables as expected. Four outliers were removed, arising from temperature anomalies. A significant difference in slope reflected the trend with saturated vapour pressure, however there was no significant difference in elevation of the mean. The trend was toward lower vapour pressure deficit conditions in the orchard area at higher temperatures, but not reflected in the means.

Evapotranspiration

Again two outliers were removed from the regression of Penman evapotranspiration, corresponding to the mean temperatures anomalies. As with the H.R.A., Penman evapotranspiration was significantly lower in the orchard than at the reference site with a significant difference in elevation. This tendency appeared to be greater under warmer and windier conditions with a significantly lower slope.

As previously, Priestley-Taylor evapotranspiration proved conservative, with no significant difference. Regression of Penman against equilibrium evapotranspiration gave an $\alpha = 1.14$ with a correlation of 0.734 ($p>0.01$). However removal of an obvious outlier, which corresponded to a northwest to southerly change and above average wind speeds, gave an $\alpha = 1.27$. At this site there is an obvious difference between the results with the two methods of estimation. This result may be a reflection of the intermediate status of this site, between the Plant Science site and the H.R.A., in terms of the degree of coupling with the surrounding environment.

9.6 Summary

The four sites examined can be classified hierarchically in terms of their roughness, as characterised by z_0. Broadfields (z_0=0.008) is an ideal reference site with good exposure to all sectors. It is well representative of open plains conditions and is strongly coupled to the regional climate. The Plant Science block (z_0=0.06), although not formally sheltered is located in a generally more sheltered environment. The results with Lincoln Springs (z_0=0.39) and the Horticultural Research Area (z_0=3.16) suggest a progressive decoupling from the surrounding environment as a site becomes more sheltered. The transition height is not fixed being dependent on the roughness elements for each wind sector. The presence of a regional to local transition is consistent with the work of Guyot and Seguin (1975) and the measurements of Cherry and Smyth (1984). Results reinforce the earlier suggestion that the measurements of McAneney et al (1989, in press) at a fixed height were subject to local roughness features from the beginning of measurement and that vertical profile measurements would have shown a progressive decoupling as the shelter grew.

Microclimatic differences are consistent with site roughness features. Absence of simultaneous measurement at all four sites precludes hierarchical classification. Temperature responses are consistent with the literature. All measurements were made over the spring to autumn period, and all sheltered sites showed higher than average temperatures than the exposed site. A direct effect of wind speed reduction is a decrease in turbulent mixing and reduced transfer of sensible heat. This is most noticeable with daily maximum temperatures. The tendency towards reduced differences in maximum and minimum temperatures, at higher values, between the two orchard sites and Broadfields is an interesting result. It suggests that the effect of shelter on day time temperatures is greatest under non-advective conditions. The elevation of minimum temperatures in a highly sheltered situation, in mid summer was attributed to reduced evaporative cooling under high soil moisture deficit conditions and reduced transfer of sensible heat under calmer conditions. Spring and autumn measurements at the two lesser sheltered sites showed no significant differences in minimum temperatures. On the basis of the literature it would be expected that intensification of night-time inversions would occur over the winter months.

Vapour pressure measurements proved to be fairly conservative, which again tends to be consistent with the literature. Higher saturated vapour pressures in sheltered areas can be directly attributed to warmer temperatures.

At the Plant Science and H.R.A. sites this led to significantly higher vapour pressure deficit conditions which gave a greater potential for evapotranspiration. Significantly lower evapotranspiration was recorded in the two orchard sites based on Penman estimations. This was directly attributable to the reduction in wind speed. Evapotranspiration tended to be lower, but not significantly so, in the Plant Science block.

The empirical checks on the Priestley-Taylor constant gave some interesting results which appeared to be consistent with site exposure. While the α values obtained have a good deal of intuitive appeal it is reiterated that they were the result of an empirical check on the internal consistency between the two methods for estimating evapotranspiration. Locally calibrated values of α would require measurement of actual evapotranspiration, and comparison with equilibrium values, as done by Green et al (1984).

CHAPTER 10

A greener Canterbury ?

10.1 Background

Drought is an important phenomenon in Canterbury, as it is in other districts in New Zealand. Spatial analysis of deficit days showed a similar response to rainfall and other variables. It was also shown that drought in Canterbury is a persistent and recurrent phenomenon. Results from analysis of national and district crop-climate interactions had shown the significant effects on crop yields of low rainfall, often coupled with warmer than average temperatures. This suggested relationships between low yields and high moisture deficit conditions at critical developmental stages. Correlation analysis of Canterbury grain and pipfruit data with deficit day data confirmed these relationships.

10.2 A possible framework for integrated analysis

The experiences from the past, including the most recent Canterbury drought, raise questions about response options in the face of probable future droughts. Some of the possibilities were briefly discussed in Chapter 2. Three broad possibilities are identified for Canterbury. These are:-

1. Do nothing (i.e. business as usual).

2. Introduce more drought hardy species and varieties (i.e. adapt to the probability of dry years)

3. Further investigate the potential of trees for shelter, and the potential for wider irrigation.

These possibilities require critical evaluation. The ecological theory of habitat diversity and stability, developed for natural ecosystems, has been widely applied in the field of agroecology. A critical review by van Emden and Williams (1974) concluded that well planned diversity could lead to greater stability in agricultural systems, in particular in the field of insect pest management. A similar hypothesis is proposed for diversifying production systems on a regional scale as a means of providing greater stability and therefore greater security against climatic variability. The systems approach of Odum (1971, 1983) could provide a useful framework for testing such a hypothesis, incorporating an analysis of the alternative options identified above. This involves modelling systems in terms of energy sources, sinks and flows, with energy efficiency being the desired goal. Such an analysis is beyond the scope of the present work. It is a particularly valid approach with increasing interest in and emphasis on energy efficiency and sustainability, particularly in the context of current energy inefficient systems which appear to have contributed significantly to possible global climatic change.

This thesis explored some of the components that could be incorporated into such an analysis. An assessment of possible crop yield responses under different scenarios would be a key component to such an analysis. In the next section the possible benefits of shelter to crops are discussed, drawing from the results of the field study, presented in Chapter 9.

10.3 The benefits of shelter to crops in Canterbury

10.3.1 Horticultural crops

Sheltering and irrigation are common practices with horticulture and the use of both in Canterbury has no doubt contributed to reduced impact of drought on horticultural crops. The results from the shelter study showed a high degree of decoupling of highly sheltered areas from the surrounding environs, with much higher z_0 values than exposed sites from upper profile measurements. Lower wind speeds lead to reduced physical damage of plants. The results from the field work, in Chapter 9, showed significantly warmer daytime temperatures in all sheltered sites, most noticeably under non-advective conditions in the two orchard sites. Warmer temperatures coupled with adequate moisture would also generally encourage fruit sizing and maturation. From reviewing the literature on stonefruit, in Chapter 6, it was clear that warmer conditions generally reduce the length of the season, and shorten the harvest period. Such conditions would encourage flowering, pollination and pollen tube growth in deciduous fruits. Potential evapotranspiration is lower in sheltered sites, as a direct result of reduced wind speeds. This was shown by comparison of Penman estimates between the exposed reference site and the two orchard sites. Priestley-Taylor estimates were more conservative, as discussed. With reduced turbulent mixing it might be expected that there is reduced direct evaporation from the surface. At the same time stomata would tend to be open more in sheltered areas. It has been suggested (Rosenberg et al, 1983) that the major pathway for water exchange in sheltered sites is through transpiration. Higher winds and a higher frequency of stomatal closure in exposed areas would tend to result in increased direct evaporation from the surface and reduced transpiration. This line of argument is also consistent with the general conclusion of Rosenberg et al (1983) that greater water use efficiency results with sheltering of crops, leading to higher yields.

Even given these benefits with horticultural crops there is still the potential for drought to be detrimental to yield. This has a socio-political dimension as exemplified by the water restrictions imposed in fruit growers in Loburn in the recent drought. It is apparent that for a viable horticultural industry in Canterbury a critical review of potential water demand, and critical demand periods is required. From the empirical analysis of pipfruit January was a critical water sensitive month. Future provision should be made for possible demand in this period, particularly in drought years.

10.3.2 Grain crops

Stringer (1984) commented that there is "unreasoned antagonism to shelter" in some quarters. This is particularly true with arable cropping. The sensitivity of arable crops to moisture deficit conditions at certain developmental stages was illustrated in the empirical yield models. Shelter has an obviously beneficial role to play, both in reducing erosion and improving water use efficiency. The results from the Plant Science block, which could be classified as a large field situation, suggest that there are potential benefits to cropping from a roughened, more sheltered landscape. Differences in evapotranspiration weren't significant. However there were significantly lower wind speeds and warmer temperatures. It is recalled that measurements at this site were taken in mid to late spring. This is a period of active growth for arable crops. It is suggested, as before, that lower wind speeds would reduce direct evaporation and encourage greater stomatal opening than in more atypical plains sites such as Broadfield. Coupled with warmer temperatures this would lead to greater transpiration and associated benefits in terms of plant growth. As the soil continues to dry into the summer months and with no significant rainfall soil moisture levels tend towards deficit conditions in both sheltered and unsheltered environments (Rosenberg et al, 1983). This can coincide with critical moisture sensitive stages for some crops, such as barley. Superior reserves from spring growth would benefit sheltered crops and is the usual explanation given for the greater yield response to shelter in dry years. The review of Sturrock (1984) suggests a synergistic effect from well timed irrigation, that would give an even greater yield response.

10.4 A wider perspective

There are other benefits from shelter aside from erosion control and improved yields. These include shelter for stock, which can be crucial at periods such as lambing, particularly when southerly storms occur. Well managed shelterbelts and woodlots can also be a source of timber, fence posts and firewood. Tane (1983) has advocated the planting of trees in the high country of the South Island as a source of timber and bee fodder amongst other uses. He provided an extensive list of tree species and cultural uses of each. Uses cover timber production, stockfodder, nectar, pollen, fruit and nuts, medicinal and ornamental. The sort of development advocated by Tane (1983) for the high country could equally be applied to the Canterbury Plains. Two other advocates of trees in Canterbury are Stringer (1984) and Lucas (1984). The former detailed planting arrangements for shelterbelts including a detailed list of suitable shelter species. The latter dealt with the aesthetics of woodlot and shelter design. It is well apparent from her presentation that a well planned and designed mosaic of trees in Canterbury could add considerably to the aesthetic appeal of the region, as well as the considerable physical and biological benefits.

10.5 Summary

There is ample evidence to suggest that shelter can lead to direct yield benefits with both horticultural and arable crops. While these benefits may not be so strong in average or above average rainfall years, it is generally very apparent in drought years. Such years are a sufficiently recurrent and persistent phenomenon in both Canterbury and other regions of New Zealand to warrant greater use of shelter. Planned on a regional scale a mosaic of shelter could impact significantly not only at the local scale but on the region as a whole. This has been the aim of the Catchment Boards in the past but has faced the antagonism identified by Stringer (1984) for the various reasons outlined in Chapter 8.

A lot of basic research has been carried out with shelterbelts, and there is considerable scope for more as identified in the National Shelter Working Party report, Sturrock (1984). The impact of both Cyclone Bola in the North Island and the drought in Canterbury have again highlighted the need for greater watershed protection and wind and water erosion control for the conservation of water and protection of scarce arable and horticultural land. Integrated planning is needed on a regional scale to satisfy these goals. The prospect of climatic change has added impetus to the need for an integrated regional approach.

CHAPTER 11

Greenhouse scenarios: agricultural impact

11.1 Introduction

There is strong current interest in the possible effects of increasing levels of CO_2 and other greenhouse gases on global climate. The greenhouse effect has been well documented with some excellent reviews such as that by Bolin et al (1986). It is a logical progression from the preceding analyses of crop-climate interactions to give some tentative assessment of possible impacts of a warmer climate on New Zealand food production.

Salinger and Hick (1989) noted that, while there is a high level of confidence about projections for a global warming, regional scenarios are more speculative. Coupling empirical crop-climate models with regional climate scenarios must be treated with a good degree of caution. Such an approach is essentially a qualitative assessment, and would require verification from other approaches.

The methodology used here was based on that used by Lough et al (1983), which is discussed in more detail in Palutikof et al (1984). They constructed scenarios based on the instrumental record and used climate data from analogue years in combination with empirical crop-yield models. The analysis involved the selection of warm and cold ensembles and comparison of differences in yield response between the two periods.

11.2 Scenarios

Tentative greenhouse scenarios for Australia and New Zealand were developed by Pittock and Salinger (1982). They used four different approaches, which gave a good degree of consistency. Of the methods used the most direct approach is numerical modelling. However such methods at present lack regional detail (Wigley et al, 1980; Lough et al, 1983). The other main approach is the use of past warm periods as analogues. Pittock and Salinger (1982) evaluated a scenario based on the Hypsithermal, a maximum warming period from the Holocene, some 8000 to 10000 years BP. Another analogue approach used by Pittock and Salinger (1982) was to evaluate the instrumental record and compare extreme warm and cold year ensembles. The fourth method used was to develop an empirical discussion based on knowledge of atmospheric dynamics.

The scenarios for New Zealand were further evaluated by Salinger (1982). They showed warmer temperatures over the whole of the country. Increased precipitation was indicated in the east of the North Island and in the northeast of both islands, with reduced precipitation in the south of New Zealand. More detailed regional scenarios for New Zealand have been developed by Salinger and Hicks (1989) for the New Zealand Climate Change Impacts Working Group.

Scenario 1, based on the Hypsithermal, gives an average temperature warming of 1.5° C. Rainfall is projected to be higher, by up to a maximum of 15%, in regions west of the axial ranges. Regions east of the axial ranges show decreased rainfall, mostly by 5% but up to 10% in South Otago and part of Southland. Scenario 2 is based on the upper limit of a greenhouse warming in the New Zealand area, equating to a 3° C temperature rise. This is associated with a more positive mode of the Southern Oscillation. Rainfall is increased, up to a maximum of 15%, in all regions except for the south of the North Island and the west and south of the South Island, which show decreases of 5%.

For use with empirical crop-climate models analogues based on the instrumental record offer the most practicable option. This allows for input of actual climate data and evaluation of yield responses. In developing their instrumental analogue in the Southern Hemisphere Pittock and Salinger (1982) followed the methods of Wigley et al (1980). Following the rationale that the Greenhouse warming will be strongest in high latitudes Wigley et al (1980) selected warm and cold years from 50 years of data for the latitudes 65-80°N. Pittock and Salinger (1982) selected from a similar latitude range, south from about 65°S from a time series of only 23 years. The years chosen for the Southern Hemisphere were not fully consistent with those chosen for the North. Altogether there were seven 'cool' years which were: 1958, 1959, 1963, 1964, 1965, 1969, 1976; and nine 'warm' years: 1957, 1961, 1968, 1970, 1971, 1973, 1974, 1975, 1977. Scenarios for Australia and New Zealand were developed by evaluating the regional differences between these warm and cold years, as mentioned previously.

Differences in mean temperatures and precipitation were statistically significant over New Zealand (Pittock and Salinger, 1982). Lough et al (1983) believed that statistically significant differences "justifies the use of warm and cold groups as analogues of separate populations, even though both are drawn from a single population". There was some criticism of the use of single years (Pittock and Salinger, 1982; Lough et al, 1983) for constructing the analogues. In particular it was commented that ocean and cryosphere boundary conditions lag behind changes in the atmosphere. Groups of consecutive years, it was argued, would allow for a higher degree of equilibrium between the atmosphere and underlying boundary conditions and therefore be more suitable for constructing analogues. Lough et al (1983) therefore developed a second scenario from a gridded Northern Hemisphere temperature set. They chose warm and cold 20 year periods from this data set.

The scenario used here, in conjunction with the empirical-statistical crop-climate models discussed in Chapters 5 and 6, was the intrumental analogue scenario developed by Pittock and Salinger (1982). Because the yield data sets did not cover exactly the same periods as the analogue scenario, not all of the 'warm' and 'cold' years could be used.

A second analogue scenario, using extended warm and cold periods, after the work of Lough et.al.(1983), was considered and rejected because the period for which yield data was available had little contrast between the warm and cold periods. Instead of this the scenarios developed by Salinger and Hicks (1989) were used for the purposes of discussion. They provided some basis for evaluating the sensibility of the results derived from the empirical analysis.

11.3 Agricultural impacts

The crop-climate models used for tentative assessment of impacts on agriculture of a greenhouse warming are those presented and discussed in Chapters 5 and 6. The fruit crop models should be treated with more caution because of the lack of model verification with the stonefruit and generally poor verification with pipfruit. For grain crops the weighted national, and district, multiple regression models were used. For fruit crops weighted national models were used, in the case of pipfruit assessment was made with the models developed for the 1941-1981 and 1963-1981 periods. Results are presented in Table 11.3.1, and show the yield change (difference between warm and cold years) and the percentage variance explained by the models used. Although the numerical values are presented they should only be treated as indicators of possible direction and magnitude of change. Lough et al (1983) suggested that to do more than present the results in qualitative terms would be to impart a false sense of precision. However, to contradict this statement, their results were presented quantitatively in the related paper by Palutikof et al (1984). It was considered appropriate to include the numerical results here, with the qualification that they should be treated in a more qualitative manner.

11.3.1 Wheat

Wheat shows a moderate yield reduction on a national scale. This is largely attributable to increased winter rainfall in the warm years. Only a slight warming in spring temperatures was apparent. The dominant wheat area, Canterbury, shows only a slight yield reduction. For this growing district there was little difference in winter rainfall between warm and cold years. Otago shows a similarly slight yield reduction which is attributable to a rise in summer temperature. No analysis was carried out for Southland because of the low amount of variance accounted for by the model. However a negative relationship with spring temperature in this district would lead to lower yields under warmer conditions.

Scenario 1 from the Impacts Working Group shows warmer temperatures and lower rainfall in eastern districts and Southland, covering the main wheat growing districts. Temperature warmings have been shown to be greatest in winter months (Wigley et al, 1980). This might be an advantage to autumn sown wheat in Canterbury and North Otago. Any increase in winter rainfall will be detrimental to yield of autumn sown wheat. Previous analyses showed the sensitivity of wheat to spring and summer temperatures and agricultural drought.

Table 11.3.1

Yield changes indicated by CO_2 warmed scenarios

Crop	Yield change	% variance explained by model
Wheat (N.Z)	-0.20	31
Wheat (Canterbury)	-0.07	39
Wheat (Otago)	-0.07	20
Oats (N.Z.)	-0.02	34
Oats (Canterbury)	-0.11	58
Oats (Otago)	-0.04	16
Oats (Southland	-0.05	13
Barley (N.Z.)	-0.28	51
Barley (Hawkes Bay)	-0.13	19
Barley (Wellington)	-0.21	31
Barley (Marl.)	-0.01	29
Barley (Canterbury)	-0.17	49
Barley (Otago)	-0.05	49
Apples (1941-81)	0.61	31
Apples (1963-81)	-1.15	65
Pears (1941-81)	2.53	29
Pears (1963-81)	-0.21	75
Apricots	-0.77	35
Cherries	-0.18	58
Nectarines	-1.03	48 (2 pred. model)
Nectarines	-1.77	68 (4 pred. model)
Peaches	1.94	70
Plums	0.74	22 (1 pred. model)
Plums	0.13	79 (6 pred. model)

Increases in spring temperatures coupled with less rainfall in the east and south of the South Island would therefore be detrimental to yield. Higher temperatures and rainfall in the Manawatu and an associated decrease in deficit days could generally be beneficial to spring sown wheat in this region, although higher rainfall could delay sowing and lead to lower yields.

The number of deficit days would increase in Canterbury under Scenario 2 as a result of increased temperatures and only slightly increased rainfall. This would generally have a detrimental effect, particularly if coinciding with moisture sensitive developmental stages. This scenario suggests a large increase in deficit days in South Otago and Southland which may prove detrimental to spring sown wheat. The main wheat growing region of the North Island, centred around the Manawatu, shows reduced rainfall under this warmer scenario and a substantial increase in deficit days which may make this region more marginal for wheat.

Overall there might be an increasing dominance of South Otago and Southland as wheat growing districts, which has been a trend over recent decades.

11.3.2 Oats

On a national scale oats show only a very slight yield reduction, attributable to a slightly warmer late spring and early summer period. Canterbury yields show the greatest reduction, but still not very great. This yield reduction is generally a result of slightly warmer spring and early summer conditions and increased early spring rainfall. Otago and Southland show slight yield reductions which are again related to warmer late spring and summer temperatures.

Warmer temperatures combined with lower rainfall in eastern regions, as suggested by Scenario 1, would generally be undesirable for oats. There would be an increase in the number of deficit days and therefore greater potential for extended dry periods.

The higher temperatures of Scenario 2 offset the slight increase in rainfall indicated for mid Canterbury. The remainder of the oat growing region, south to Southland shows either no change or a slight decrease in rainfall. As with Scenario 1 this will generally be detrimental to oat yields, particularly if it leads to a greater frequency of deficit days in spring and summer.

As with wheat the overall effect of a climate warming may be a southward shift in oats, with increasing dominance of Southland as an oat producing district.

11.3.3 Barley

From the warm and cold ensembles barley shows moderate to slight reductions in yield as a result of a climate warming. The yield reduction appears greatest with national yields and with Wellington and Canterbury. Only a very slight reduction is shown for Marlborough and also a slight reduction in Otago. In Hawkes Bay the yield reduction results from an increase in January rainfall and an increase in late spring to early summer temperatures. The moderate reduction in Wellington yields results from a significant reduction in December rainfall and a strong warming effect in November. Marlborough shows reduced rainfall in November and a warming in late spring to early summer, however not of sufficient magnitude to make much difference to barley yields. The yield reduction in Canterbury results from warmer and wetter early spring conditions. The slight reduction in Otago is largely a result of slightly warmer January temperatures.

Under Scenario 1 it could be expected that the potential for an increased frequency of agricultural drought in spring and summer could lead to net yield reductions in eastern districts. Warmer temperatures in Southland might lead to an increase in importance of this growing district for barley. From the crop-climate analysis it appeared that higher rainfall in spring, coupled with warmer temperatures appeared to have a positive impact on barley yield in the western North Island. These districts might increase in importance for barley under Scenario 1.

Possibilities are less clear under Scenario 2. No change in deficit days in Hawkes Bay may see little change in relative importance of this district for barley. An increase in deficit days in the western North Island may see a relative decline in importance of this region. In the east and south of the South island the pattern appears similar to Scenario 1.

Overall there is uncertainty about scenarios for the North Island. For the South Island it appears that Southland may become a more attractive area for barley. Currently Southland temperatures are sub-optimal for this crop in relation to available moisture. Even a 10% reduction in Southland rainfall would give it a higher annual total than Canterbury. Combined with warmer temperatures conditions could become more optimal for barley in Southland than currently prevail in Canterbury.

11.3.4 Apricots

Apricots show a moderate yield reduction, using the analogue data. This results from warmer August temperatures. With the crop grown predominantly in Central Otago it was suggested that this may relate to the susceptibility of apricots to spring frost.

Both scenarios developed for the Impacts Working Group suggest a significant increase in the frost free season in Central Otago. Scenario 1 suggests no change in the temperature range, but an increase is suggested by Scenario 2. The same, or increased continentality associated with an extension of the frost free season could generally be seen as beneficial to apricots. Warmer and drier summers would also be of benefit, and possibly advance the average harvest date and shorten the harvest period. Apricot growing is already extending to the Waitaki valley. Extended frost free periods would be of benefit to this area. Parts of the McKenzie basin and Canterbury Plains may also become increasingly attractive for apricots, with warmer summers and longer frost free periods.

11.3.5 Cherries

A slight yield reduction is indicated for cherries and results from increased October rainfall. This crop shows a high sensitivity to rainfall at blossom and harvest time, so the timing and intensity of rainfall will be more critical than annual totals. Marlborough and Central Otago are currently the main growing districts for cherries, with the former increasingly dominant over the last twenty years.

Scenario 1 and 2 both indicate increases in rainfall in Marlborough. This suggests a greater potential for damaging rainfall events. Reduced rainfall and increased continentality in Central Otago and inland basins may make these regions increasingly attractive for cherries. Rainfall in Canterbury may be relatively unchanged which may see a revival in interest in this area for cherry production, particularly if the climate in Marlborough becomes less suitable.

11.3.6 Nectarines and Peaches

Interestingly nectarines and peaches show different yield responses using the analogue data. This can be attributed to different distributional patterns and consequent differences in significant predictors. Decreased nectarine yields largely result from increased spring rainfall, which would be detrimental to blossom and fruit set. Increased peach yields result from warmer April temperatures suggesting yield benefits from enhanced autumn photosynthetic activity.

Warmer temperatures would generally be beneficial to peaches and nectarines in all districts where they are currently grown. Rainfall totals and seasonal distribution will largely determine future regional distribution of these crops. Higher rainfall in the Auckland area would tend to exacerbate disease problems and increase problems of waterlogging. There is uncertainty about rainfall scenarios for Hawkes Bay, the principal stonefruit district. A slight decrease under Scenario 1 would be beneficial, given adequate irrigation at critical stages. Increased rainfall in Hawkes Bay under Scenario 2 could be detrimental depending on seasonal patterns. Warmer conditions in Marlborough with slightly increased rainfall would generally be suitable for peaches and nectarines. Conditions in Canterbury will also generally become more suitable for these crops under both scenarios. Warmer winters and a longer frost free period in Central Otago would make this area increasingly suitable also.

11.3.7 Plums

There was some scepticism about the relationship between plum yields and May temperatures, with no immediately apparent explanation. This relationship shows a slight to moderate increase in yields. Using a six predictor model the combined effect of April and May temperatures gives a slight increase in yields in warmer years. Negative relationships with rainfall over the growing season offsets this warming effect.

It is recalled that Japanese plums have a lower winter chilling requirement than European plums. Warmer temperatures may generally be beneficial to plums in most districts. In Auckland, a major growing district, temperatures may potentially become too warm. Increased rainfall in this area would be detrimental, making this a less suitable growing district. The differing rainfall scenarios for Hawkes Bay suggest that this region may or may not remain a dominant growing district. Increased rainfall under Scenario 2 will generally be detrimental. As with the other stonefruit the climate of the east coast of the South Island and Central Otago may become increasingly optimal for plums.

11.3.8 Apples

Differing predictors resulted in different yield responses with the two apple models. The differences in predictors are at least partly due to changing distributional patterns and hence different climate weighting factors for the years 1941-1965 in the longer time series. The result from the 1963-1981 period is used with more confidence because the weighting factors were held constant for this model and because of the similar results obtained from the yield per hectare and yield per tree data.

The yield increase shown for the longer time series reflects lower December rainfall and warmer March temperatures, which were negatively and positively related to yield. These offset the effect of warmer July temperatures. With the 1963-1981 model July temperatures have a more dominant effect leading to a negative yield response.

The district models developed for the 1941-1965 period showed excess rainfall to be a major limiting factor to apple production in Auckland. Both Scenario 1 and 2 show increased rainfall in this region. Combined with warmer temperatures it could be expected that Auckland will become increasingly marginal for apples. Temperature will possibly become the main limiting factor in Hawkes Bay, particularly in winter, as previously discussed in relation to July temperatures. Reduced yields will generally result from such conditions and there may be a shift in the varietal mix. Increased rainfall in Nelson if associated with a summer increase would make summer drought less limiting to apple production and decrease dependence on irrigation over this period. Warmer temperatures may be beneficial in spring for pollen tube growth and early fruit development, and again in autumn for fruit maturation and photosynthetic activity. The greatest benefit would be attained in districts where temperatures are currently limiting at these times. The district models showed this to be true for Central Otago, which may develop a more suitable climate for apples. Irrigation would be crucial in this district. Canterbury may also become increasingly suitable for apples, although again irrigation would be a critical factor. Warmer temperatures in South Otago and Southland may make this region increasingly suitable for apples also, with adequate rainfall to sustain the crop.

11.3.9 Pears

Pears show a large yield increase with the 1941-1981 model. This is largely a result of warmer October temperatures, which were the dominant predictor. The obvious benefits of warmer October temperatures would be to flowering, pollination and pollen tube growth, particularly in presently marginal areas. As with apples there were different distributional patterns over this longer time series. The 1963-1981 model shows only a slight yield reduction which relates to increased September rainfall, which would be detrimental at blossom time.

The July temperature response wasn't explicit in any of the district models for pears. However it did come through as a weaker predictor in the 1941-1981 model. It might be expected that the temperature response could be similar to that with apples, possibly making conditions in Hawkes Bay less optimal. As with apples increased rainfall in Nelson may reduce dependence on irrigation, given a summer increase. Increased frequency of deficit days in eastern districts would possibly necessitate greater use of irrigation. A southward shift in the optimum climatic zone for pears may occur, as described for apples, with increased plantings in Canterbury and possibly Otago and Southland.

11.4 The uncertainties

Some important points were raised in Lough et al (1983) and Palutikof et al (1984). Perhaps the most important is that the crop-climate models do not account for possible changes in climate variability. This is particularly important where there may be an increase in variability leading to possibly greater frequency and intensity of extremes. Other factors not taken into account in the models include the effects of possible future technological change, direct influence of CO_2 on crop photosynthesis and possible future changes in pest and disease complexes.

While the effects of CO_2 enrichment are not certain, higher CO_2 levels may lead to greater water use efficiency (Rosenberg, 1982). Warwick et al (1986) presented a comprehensive review of CO_2 enrichment data, mainly from growth chambers. This suggested a yield increase for most crops with increased CO_2, the amount depending on the crop and the prevailing growing conditions. Given these probable yield increases, it is conceivable that some of the steady increase in CO_2 over the last century has contributed to the upward trend in the yield of many crops. However, as Palutikof et al (1984) pointed out, such effects may have been obscured by the impact of technological improvements.

The present geographic distribution of both naturally occurring and cultivated plants will also be affected, depending on the degree to which conditions change. This was discussed briefly for each of the crops used in the empirical analyses for New Zealand. Parallel with this may be changes in climatic factors limiting to production of crops. It is important to be aware, as much as possible, of the limits to which crops are likely to be able to adapt to changed conditions, as this will assist in the exploration of response options. Such considerations would ideally be incorporated into a systems analysis, as previously suggested for Canterbury.

The possibility of future changes to the boundary conditions of the global climate system raises questions about the value of constructing scenarios based on past analogues. Little confidence is placed in instrumental analogue scenarios by Palutikof et al (1984) beyond the early decades of the 21st century after which changes in atmospheric boundary conditions will reduce "the realism with which past climatic change can be used as an analogue for the future". This conclusion would also apply to Southern Hemisphere scenarios. However this need not preclude updating the scenarios, as earlier suggested, particularly as a form of verification. This would be particularly desirable for the Southern Hemisphere given the relatively limited data base that Pittock and Salinger (1982) had to work with. At least in the short term as much use as possible should be made of available data.

11.5 Summary

Climate data from warm and cold ensemble years were fed into a number of crop-climate models for New Zealand. This provided a tentative assessment of the possible impacts of a warmer world on these crops. A lack of extreme warm and cold periods from the 1930s to late 1970s precluded development of a second analogue scenario. A period of warmer climate in the 1980s could provide a good opportunity for re-evaluating instrumental analogue scenarios for a warmer Southern Hemisphere. The empirical crop-climate models would also need to be updated to incorporate more recent data. Without a second instrumental analogue scenario possible magnitude and direction of change can't be verified in the same way as done by Lough et al (1983) and Palutikof et al (1984). However empirical discussion based on scenarios developed for the New Zealand Climate Change Impacts Working Group by Salinger and Hicks (1989) does provide some form of verification.

Generally the direction of change with the three grain crops; wheat, oats and barley, is consistent between the analogue result and that deduced from the Working Group scenarios. It appears that there will be an increased potential for agricultural drought in the major grain growing districts which would generally be detrimental to yield. This may lead to an increasing dominance of Southland as a temperate grain growing district. The response in Canterbury may be toward more drought tolerant varieties, a move to more drought tolerant crops, or increased use of shelter and irrigation.

The magnitude of the yield reduction is uncertain, although it could be reasoned that it might be greater in Canterbury and lesser further south. Results from the crop-climate models tends to support this.

Results with the fruit crops were not entirely consistent with what could be reasoned from the Working Group scenarios. Lack of analysis at the district level is a strong limitation, as it is apparent that there will be quite different responses around the country. The limitations of these crop-climate models are made apparent, as for example with apricots. While the model suggests a general yield reduction a lengthening of the frost free season in Central Otago as suggested by the Working Group scenarios would tend to reduce frost risk. Generally it appears that the east of the South Island and Central Otago will become more climatically favourable for both stonefruit and pipfruit. This may lead to a shift in the centre of production away from Hawkes Bay, possibly towards Canterbury.

Both the direction and magnitude of yield change with fruit crops is unclear. Lack of analysis at the district level makes any discussion of possible district impacts more speculative.

There are many uncertainties associated with the probability of changes in the global climate. These were briefly discussed. While the uncertainties are acknowledged it is also argued that maximum use should be made of existing data. It is suggested that in the medium term data bases should be strengthened, particularly in relation to the monitoring of crop responses to climate.

CHAPTER 12

Conclusions and recommendations

12.1 Introduction

The primary objective of this thesis was to assess the impact of natural climate variability on crops in New Zealand and to evaluate the potential of well planned modification of the local and regional environment to mitigate the effects of this variability. There were two major components to the thesis. The first was an empirical-statistical analysis of crop-climate interactions in New Zealand. The second was an evaluation of the agroclimate resource in Canterbury and an assessment of the potential of shelterbelts to modify the physical and biological environment. A secondary objective was to make a tentative assessment of possible impacts of regional greenhouse scenarios on crop yields in New Zealand.

12.2 The context

A global perspective on climate variability and food security was considered a necessary preliminary. The subject is multi-dimensional in nature. It has a historical dimension, gaining increased importance to humans as they shifted from being hunter-gatherers to settled farmers. Although often associated with poorer countries, as illustrated by the Sahel drought and famine in the early 1970s, climate variability and food security is a subject of importance to all countries in the world. It therefore has a spatial dimension. The Sahel case study further illustrated the multi-disciplinary nature of the subject area, covering a range of social, biological and physical sciences.

Many countries are aware of the importance of understanding more clearly crop-climate interactions as a source of information for improving food security systems. Others are becoming increasingly aware in the face of possible climate change. Concurrent with this is a growing awareness of the important links between trees and the environment, and their potential to contribute to the food security of a country. This provided a very appropriate context for analysis of crop-climate interactions in New Zealand, and an assessment of the possible role of shelterbelts in improving food security in the Canterbury region. New Zealand has a variable climate, both temporally and spatially. Different regions are subject to non-periodic extreme climatic events, as demonstrated most recently by Cyclone Bola and the Canterbury drought. This thesis has contributed substantially to a clearer understanding of crop-climate interactions in New Zealand, as well as identify limitations to the existing data base. Considerably more work needs to be done, including more detailed examination of possible response options.

12.3 Crop-climate analyses

The aim of this part of the thesis was to give an overview of crop-climate interactions in New Zealand, with the hope of some insight into regional differences in yield response to climate. The methods used were not new. However, their application to New Zealand data, particularly the fruit crops, was new. The comparative use of the different approaches of P.C.A. multiple regression, weighted multiple regression and straight-forward multiple regression analysis in the same body of work gave a greater opportunity for detecting spurious results and identifying regional differences. The retention of data for verification, where there were sufficiently long-time series, answered a major criticism made of many crop-climate analyses. This gave greater validity to the results with temperate grain crops. The shorter time series of data for fruit crops made the results of these analyses more speculative, particularly given the general lack of verification. Despite the speculative nature of the results with fruit crops, there were some interesting and encouraging results. It is unfortunate that data collection for many of these fruit crops was discontinued in the 1980s as greater value could have been gained from extended time series.

12.3.1 Grain crops

The most interesting feature to arise from the application of P.C.A. combined with multiple regression analysis of district yield data was the variable success experienced. In the case of oats the spatial variation in response appeared to be too great to give good results. Wheat gave a more encouraging result, but the model verified poorly for Canterbury, the principal growing district. The wider adaptability of barley reflected in a good result for this crop. Barley proved to be more spatially responsive to climate than wheat and oats. These results raise a note of caution for future application of the P.C.A. approach. The spatial responsiveness of a crop, combined with the spatial variability of climate over the area being examined, will determine the degree of success obtained. Perhaps the best safeguard is to combine several approaches as done in this thesis. These results showed that the application of several different approaches to analysis proved complimentary in terms of the insights gained.

An overall impression gained with the grain crops was the sensitivity to periods of moisture deficit. These occur with sufficient frequency in the principal New Zealand growing districts to cause a significant limiting factor to yield from year to year. Such conditions can be aggravated by warmer temperatures and higher evapotranspiration rates. These general conclusions provided an important introduction to the remainder of the thesis. In particular they set the scene for a more detailed agroclimate evaluation of Canterbury..

12.3.2 Fruit crops

Given the small number of documented crop-climate analyses of fruit crops, this section constitutes a significant contribution of this thesis. More such studies should be encouraged, despite the obviously greater complexity in dealing with perennial crops. As a generally exploratory study the results achieved were encouraging.

The strength of the result with cherries, which demonstrated a clear negative influence of rainfall at both blossom and harvest, suggested this to be a feature of the two principal growing districts of Marlborough and Central Otago. Apart from this result, all other results with stonefruit suggested quite distinct regional response characteristics. The unavailability of district yield data was a clear limitation in further exploring relationships. Therefore the conclusions remain somewhat speculative. It would be of value to carry out a P.C.A. approach to multiple regression to test the spatial responsiveness with these crops.

This opportunity did arise with pipfruit. A preliminary analysis using P.C.A. gave an unsatisfactory result, deterring further application. This was because the spatial variability in response was too great. Subsequent analyses of district yield data demonstrated a considerable variation in yield response to climate, particularly with apples. This generally wide spatial variability in response would account for the relatively poor model verification achieved with the forty year time series of national pipfruit yields.

Overall the results with the fruit crops suggest that there is value in applying empirical analyses to further understand crop-climate relationships. Such studies should be further encouraged. Given the climatic sensitivity of many fruit crops, the district level is considered the most appropriate scale for future analyses. The main problem is lack of continuous time series and the lack of available district data. This part of the thesis was valuable in itself as well as contributing to the remainder of the thesis.

12.3.3 Crop-Climate Model Conclusions

The stated aim of the crop-climate analysis was to provide an overview of crop-climate interactions in New Zealand, setting the context for a more detailed regional study. While the results were not all clear, a good impression of grain and fruit growing in New Zealand was given. The use of model verification where possible, the wide use of the literature, and the use of comparative approaches, is a significant contribution which adds to the credibility of the empirical-statistical approach to crop-climate analysis. The context within which it has been used is unique. The quite different spatial responses around the country highlighted the limitations of drawing from a national model to a local context, or from drawing relationships from one region and applying them to another. This appreciation of regional differences, and more particularly the understanding gained from crop-climate interactions in Canterbury within the New Zealand context, provided both the rationale and background for a more detailed agroclimate analysis for this growing district.

12.4 Canterbury agroclimate resource analysis

The crop-climate analyses showed that more detailed empirical assessments of the relationships are generally only possible at the regional scale. Such detail is necessary for impact assessment and evaluation of response options. The Canterbury agroclimate analysis provided an integrated perspective which has not previously been given for this region, though it drew from and built on earlier research. While it is not as comprehensive as it could potentially be, this study provided a clear impression of the spatial nature of the climate of Canterbury. It showed how this can impact on crop production, most specifically with wheat, and explored in more detail the great significance of drought as a limiting factor to yield.

A major theme was the general homogeneity in climate response over the Canterbury Plains. A secondary feature was the general north/south division. Of particular interest was the anomolous response of South Canterbury, both climatically and in the wheat yield-climate relationship. This is an important consideration for future analyses and for management. It would be of value to explore the spatial responsiveness of other crops, given available data. Another feature was the presence of local anomolies. These were mainly peripheral to the plains area itself.

An appreciation of the spatial response to climate over any region is an important step in evaluation of possible measures for mitigating the effects of climate variability. In confirming both the general homogeneity of the climate response in Canterbury, particularly with temperature and the frequent recurrence of agricultural drought, the foundation was established for a more localised study of shelter effects. These results suggested that the shelter study could be of relevance to the region as a whole, despite its local nature.

12.5 The contribution of shelter to regional food security

The principal effect of shelter is known, and shown here, to be the modification of the wind regime. With increased shelter there is increased decoupling of the site from the regional environment and a reduction in wind speed. This is important when considering the potentially damaging impacts of wind, particularly in drought conditions. Such conditions arise in Canterbury under extended periods of strong, hot, drying Nor'westerlies.

Modification of the wind regime because of increased surface roughness led to measureable microclimate differences. In particular, the resultant reduction in turbulent mixing led to a reduced transportation of sensible heat, especially under sunny skies, leading to higher daytime and mean temperatures. When warm, strongly advective conditions were brought by the Canterbury Nor'wester the temperature differences were less between the sheltered and exposed sites. Coupled with these wind speed and temperature differences was a calculated reduction in potential evapotranspiration in the sheltered sites. This appeared to be greater under more strongly advective conditions.

In evaluating shelter effects, both on microclimate and on crop yield, few studies have considered these effects in a wider context. The evaluation of wind profiles as reported in this thesis provided a regional connection. Observations from the Plant Science site demonstrated the compounding effects of the immediate vicinity to the site and roughness features further away. Data from all sites show higher daytime temperatures (correlating with faster crop growth rates) with similar or lower levels of evapotraspiration (using the Penman Method). This is consistent with the literature which strongly suggests that the modified environment in a sheltered area generally leads to increased crop yields along with an increase in water-use efficiency. The recorded increases are often highest during the drier than average years, helping to mitigate the effects of drought. The Canterbury Plains, being a drought-prone area, would therefore derive considerable benefit in terms of greater crop yields with similar or even lower water requirements, reducing the impact of extreme weather. Sheltering would also allow the planting of a greater diversity of crops because of the higher mean temperatures in sheltered areas compared with exposed areas. While the results of this thesis are consistent with the published literature in suggesting benefits from the strategic planting of trees, a more extensive study would be required to properly quantify and assess the full climatic and economic impact of extensive tree planting and sheltering of the Canterbury Plains.

12.6 Greenhouse warming

This part of the thesis was very much a tentative assessment because not a great deal of confidence can be placed in some aspects of the empirical crop-climate models. This is especially true for the fruit crops. Therefore the conclusions from considering a warmer climate must be viewed with caution.

While allowing for the caution, this study of the impact of warming scenarios yields some valuable insights and conclusions which are particularly relevant for New Zealand. This is not to ignore the important work of the Impacts Working Group. It was most encouraging to find that the results drawn from the grain models derived in this study were generally in line with the deductions made from the Working Group Scenarios. The fruit crop relationships, as concluded previously, require considerably more work.

Scenarios and results for Canterbury reinforce the significant effect of agricultural drought in this region. They make it very clear that a critical evaluation of possible regional responses be carried out. This evaluation would derive benefit from both the Canterbury agroclimate study and the shelter-effects study contained in this thesis.

12.7 Overview and Recommendations

12.7.1 Overview

The major contribution of this thesis is its attempt to integrate several major fields of enquiry over the range of spatial scales from the national to field level. Allowing for the resource limitations imposed on this study, the attempt was largely successful. If anything could be identified as particularly limiting the attainment of the objectives of the thesis, it would be the lack of regional and district yield data for some crops. This imposed limitations on the integration of the spatial scales of the crop-climate relationships and the shelter study.

In carrying out such an integrative study there is often a trade-off between the description of detail within a complex system, compared with the description of the system as a whole. In the first part of the thesis the larger scale of the crop/climate system is described on the global and national scale, creating a valuable context for the more detailed regional and field scale study which followed. What this thesis contributes, in relation to this trade-off, is the laying of a great deal of ground-work for future, more detailed analyses, which offer a lot of potential for further study.

12.7.2 Recommendations

With increased awareness of the probable global greenhouse warming there is a greater imperative for critical evaluation of New Zealand's agroclimate resource base. The New Zealand Meteorological Service has a well established climate station network, and a good historical data base. The value of crop yield data has not been so well recognised. Both the collection and recording of yields has been relatively poor. There is no clearly identifiable and accessible source of detailed yield data for New Zealand. It is suggested that there is a critical need for such a resource base, so that maximum value can be obtained from past, present and future data.

Grain crops may not require much further critical empirical evaluation in the short term. Relationships are generally clear and consistent. However it is improbable that relationships based on historical data will stay constant in the face of probable climate change. It is advised that the data bases for these crops be maintained, and improved. The uncertainties with the fruit crops are much greater. There is a need for more critical evaluation of these crops, particularly at the district level. This would require significant improvement on the existing data base.

The Canterbury agroclimate and shelter study showed the value of analyses at the regional scale. More detailed and critical evaluation of possible response options in the face of probable climate change is recommended. A systems analysis of the possible future benefits of shelter, and other response options, is suggested.

The thesis has provided a very useful foundation for the above recommendations. Analyses were predominantly empirical in nature. Interpretations were on occasion speculative. This highlights the considerable uncertainty that exists and reinforces the need for clearly identifiable and accessible data bases so that further critical evaluation can be carried out, both of crop-climate interactions and possible response options.

A final recommendation arises out of the difficulties encountered in carrying out this project. The project attempted to integrate information and research over a range of disciplines. Integration between disciplines makes an important contribution to the advancement of our understanding of the wider food/climate system. However the traditional separation of research into separate disciplines inhibits interdisciplinary studies. An extra effort is required to do it. Greater institutional understanding and support than presently exists is critical to the future success of interdisciplinary studies such as this.

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APPENDIX A

Climate data: site adjustments and missing value estimation

The climate stations from which climate data was used in the crop-climate analyses are indicated in Table A.1.

Table A.1

Climate stations selected for crop-climate analyses

(a) Grains, period=1933-1983

District (Stats. Dept.)	Rainfall station	Temperature station
North Auckland	Mangonui(hrs)	Waipoua forest
South Auckland	Ruakura	Ruakura
	Te Aroha	Te Aroha
Hawkes Bay	Napier(hrs)	Napier
Taranaki	New Plymouth(hrs)	New Plymouth
Wellington	Palmerston North	Palmerston North
	Masterton	Masterton
Marlborough	Blenheim	Blenheim
Nelson	Appleby	Appleby
Canterbury	Christchurch(hrs)	Christchurch
	Waimate	Waimate
Otago	Oamaru(hrs)	Waimate
	Alexandra	Alexandra
	Dunedin(hrs)	
Southland	Invercargill(hrs)	Gore

Note: (hrs)=homogenous rainfall series data

Also note that Waimate station was used as the source of temperature data in the weighted and district analyses. Although in South Canterbury it was the nearest site, with a sufficient time series, to North Otago where most of the temperate grains were grown.

(b) Fruits, period=1963-1981

District (M.A.F)	Rainfall Station	Temperature Station
Northland	Waipoua forest	Mangonui
Auckland	Albert Park	Albert Park
Waikato	Ruakura	Ruakura
Bay of Plenty	Tauranga	Tauranga
Manawatu/Taranaki	Palmerston North	Palmerston North
Wellington/ Wairarapa	Masterton	Masterton
Poverty Bay	Manutuke	Gisborne
Hawkes Bay	Napier	Napier
Nelson	Appleby	Appleby
Marlborough	Blenheim	Blenheim
Canterbury	Christchurch	Christchurch
South Canterbury	Waimate	Waimate
Oamaru/Dunedin	Oamaru	Dunedin
Central Otago	Alexandra	Alexandra

(c) Wheat in Canterbury, period=1945-1982

County (Stats. Dept.)	Rainfall station	Temperature station
Amuri		
Hurunui	Balmoral forest	Balmoral forest
Cheviot		
Rangiora	Ashley forest	Ashley forest
Eyrewell	Eyrewell forest	Eyrewell forest
Oxford		
Malvern	Darfield	Darfield
Paparua	Christchurch	Christchurch
		Christchurch airport
Ellesmere		Lincoln
Ashburton	Ashburton	Ashburton
Strathallan		Timaru airport
		Orari estate
Mackenzie		
Waimate	Waimate	Waimate

Note that not all climate stations are located in the counties with which they are associated, notably Christchurch and Christchurch airport which are in fact located in the city of Christchurch and Waimairi county respectively. Paparua was merely the nearest county for which there was yield data.

Rainfall data

Where possible rainfall data were used from the homogenous rainfall series (Thompson, 1984). This was supplemented by rainfall data from other, selected, stations. Salinger (1981) commented that since 1953 the quality control of the N.Z. Met. Service has been much superior than prior to this time. The homogenous rainfall series was therefore particularly valuable for use with the longer time series of yield for the grain crops. No detailed site comparisons were made for other rainfall stations used in the analysis of district and national yields, although Salinger's (1981) site descriptions were useful for selection of South Island stations. Principal components analysis gave sensible groupings therefore it was considered that these time series were of reasonable quality.

Detailed comparisons were possible with the Canterbury rainfall data. For the analysis of Canterbury wheat yields rainfall data for the 1945-1982 period were used and therefore site comparisons were confined to this time. Seasonal data sets were used. Site comparisons were made for all of the stations listed. Although some showed slight trends relative to neighbour stations most showed no significant differences before and after site changes.

There were obvious and significant discontinuities when comparing Ashburton with the neighbouring Winchmore station. This latter site has been consistently well exposed, with a clean record. For the period 1950 to 1980 these two sites showed very similar rainfall patterns. Salinger (1981) noted a poor record at Ashburton from 1947 to 1959. Analysis of rainfall ratios (1947-1950 vs 1951-1954) showed no significant difference. A strong discontinuity was apparent at Ashburton from 1980 on. Differences in rainfall ratios were significant in the winter and summer at the 1% level.

Adjustments to Ashburton rainfall data, 1981-1986

	ratio
Winter	1.24 **
Spring	1.11 n.s.
Summer	1.33 **

Note **=1% significant

For estimation of missing rainfall values Salinger (1981) recommended the use of rainfall ratios. Several Canterbury stations had some missing values. All had one or more neighbour stations in close proximity and showed similar totals in the months when a particular station had a missing value. Based on this missing values were estimated by adding the mean departures from the neighbour stations to the mean value for the month and station in question. This would not be recommended for less closely sited stations, but in this case gave satisfactory estimates.

The recommended approach of Salinger (1981) was used for estimating missing values for Oamaru district, a data set obtained from the homogenous rainfall series. There were 11 months in

1983 with missing values. Dunedin and Waimate were selected as the nearest neighbour stations. For the months in question the ratio between the monthly values and the long term means for those months were calculated for each of the neighbour stations. These ratios were averaged over the two stations and the long term means for the appropriate months at Oamaru were adjusted accordingly to give the estimates.

Oamaru district

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1983	56	33	77	77	59	53	52	22	73	47	19	77

Temperature data

There were no homogenous temperature data sets available, therefore all temperature data used in the crop-climate analyses were carefully checked. As with the rainfall data Salinger's (1981) site descriptions were used where possible in deciding whether or not site comparisons were necessary. Comparisons were made using seasonal data sets. Details of site change adjustment and missing value estimation for climate stations used in the national and district analyses is given. This is considered sufficient to exemplify the approach. Information is given sequentially, by station, from north to south.

1. Waipoua forest, A53651

No adjustment necessary

Estimated missing values for: winter 1929, 10.6; autumn 1973, 15.6; autumn 1978, 15.7; spring 1978, 12.3; spring 1979, 15.4.

2. Albert Park, Auckland, A64871

There was a change in screen type in 1950, which Salinger (1981) determined had a significant effect. Auckland was compared with four other stations before and after the site change (i.e. Waipoua forest, Te Aroha, Tauranga, Ruakura). In autumn and spring mean temperatures were 0.2°C cooler before the change of screen type. For the period 1928-1949 0.2°C was added to autumn and spring temperatures.

Estimated missing value for: summer 1984, 20.4.

3. Te Aroha, B75571

The site was changed on 22 November 1955. Salinger (1981) found the site change to be of no consequence, after comparison with Auckland and Tauranga. This was accepted, and no adjustment was made.

Estimated missing values for: winter 1932, 8.7; summer 1972, 18.9; autumn 1973, 16.0; winter 1974, 10.9; spring 1975, 14.7; spring 1976, 13.8; summer 1977, 19.7; spring 1979, 14.9; spring 1985, 14.4.

4. Tauranga, B76611

There was a site change at the end of June, 1940 to the present site. Site comparisons were made with Auckland, Waihi, Te Aroha and Whakarewarewa. The site change resulted in a significant increase in autumn and summer mean temperatures, by 0.5° and 0.3°C respectively. Data for the period 1928 to June 1940 was adjusted in these seasons.

Estimated missing values for: summer 1930, 17.0; winter 1981, 10.4.

5. Ruakura, C75731

Salinger (1981) suggested that the record was unreliable before 1939. Comparison of graphed annual temperatures with Auckland suggested a consistent pattern. There were two site changes in the 1928-1986 period. Site comparisons were made with Auckland, Waihi, Te Aroha, Tauranga before and after the site changes. Firstly the second site (13 May, 1936 to 17 October, 1939) was compared with the third. There was no significant difference in any season, so no adjustment was required. The first site was then compared with the second and third combined. The first site was significantly different from the other two, with a cooling in autumn and summer temperatures by -0.4°C. Adjustment was made to the first site, for the period 1928-1936, up until the site change.

Estimated missing value for: summer 1973, 19.0.

6. New Plymouth, C94003

There were two site changes between 1982 and 1973. These were on 1 July, 1938 and in July, 1942. The second of these changes proved to be insignificant. The first site was therefore compared with the other two. It was significantly warmer in all seasons. This site was adjusted to the other two by -0.4°,-0.3°,-0.5° and -0.5°C in autumn, winter, spring and summer. There was another site change in 1973. Comparisons were made before and after with Ruakura, Wellington, Wanganui and Palmerston North. Winter temperatures were 0.2 °C cooler, with spring temperatures 0.2 °C warmer. This site was adjusted to the 1928-1973 period.

Estimated missing values for: summer 1972, 16.4; spring 1972, 13.5; autumn 1973, 15.1; spring 1973, 13.4.

7. Palmerston North DSIR, E05363

No adjustment was required for this data set and there were no missing values.

8. Gisborne, D87692

No adjustment was required for this data set and there were no missing values.

9. Napier, D96591

The only site change between 1928 and 1986 occurred in November 1963. This station was compared with Gisborne and Masterton (adjusted) before and after the site change. Autumn and winter temperatures were significantly cooler, by -0.3° and -0.2°, after the site change. The earlier site was adjusted to the latter by these amounts for the appropriate seasons.

Estimated missing values for: summer 1976, 18.2; winter 1978, 9.5; summer 1979, 19.3; summer 1981, 19.7.

10. Waingawa, Masterton, D05964

There was a site change in September, 1942. Comparisons were made with Napier, Bagshot and Hastings. The first site was significantly cooler, by -0.6°, -0.7° and -0.4° in autumn, spring and summer. The record was adjusted to the present day site by these amounts.

Estimated missing values for: autumn 1977, 12.3; summer 1985, 18.1; autumn 1986, 13.2.

11. Appleby, G13211

Salinger (1981) comments that the record for this site is an excellent one, with no site changes since the record began in 1931. There were no missing values.

12. Blenheim, G13592

There were two site changes within a relatively short period, on 1 May 1942 and again at the end of December 1946. Comparisons were made with Appleby, Hanmer, Balmoral forest (adjusted) and Christchurch. The earlier sites were adjusted to the present site. For the period of May 1942 to Dec 1946, 0.4° and 0.8°C were added to the autumn and winter temperatures. For the period 1932 to the end of April 1942, 0.4°,-0.2°,-0.7°C were added to winter, spring and summer temperatures.

Estimated missing value for: autumn 1932, 12.8.

13. Balmoral forest, H22871

There was a site change on 31 Jan 1950. Comparisons, before and after, were made with Hanmer, Christchurch, Lincoln and Waimate. Data from Lincoln and Waimate were used over restricted periods, due to site changes at these stations, so only data from periods when no changes occurred were used. The analysis showed the only significant difference to occur in winter, with temperatures cooler after the site change. The 1950-1986 data were adjusted by 0.4° for winter.

Estimated missing values for: summer 1976, 15.4; spring 1977, 9.9; autumn 1980, 11.1.

14. Christchurch, H32561

No adjustment was made to this data set, with site changes being small and insignificant. There has however been an urban warming effect, which Salinger (1981) discusses.

Estimated missing value for: spring 1980, 12.8.

15. Lincoln, H32641

There have been three site changes at Lincoln over the 1928-1986 period. The 1944-1963 site was taken as the one with the best exposure, so all other periods were adjusted to this. The 1928-1943 period was significantly warmer in all seasons. It was adjusted by -0.5°, -0.8°, -0.7°, -0.4° in autumn, winter, spring and summer up to 28 April 1944. The site from 7 May 1964 to 15 July 1975 was significantly warmer in autumn and winter. Adjustment was made by -0.3°C in both of these seasons. The final site change was on 15 July 1975. Data from this period were significantly cooler in spring, and an adjustment of +0.2°C was made for this season.

There were no missing values.

16. Ashburton, H31971

There were two site changes at Ashburton, on 5 Oct 1939 and 19 May 1950. The second site was compared with the third, taking the mean differences from Balmoral, Christchurch, Lincoln and Waimate. The second site proved to be significantly cooler in autumn, spring and summer and was adjusted by 0.2°, 0.4° and 0.4°C in each of these seasons. The first site was then compared with the other two combined. Autumn, spring and summer temperatures were significantly cooler and were adjusted by 0.3°, 0.4° and 0.5°C.

Estimated missing values for: winter 1939, 4.8; spring 1982, 11.7.

17. Waimate, H41701

There was a site change at Waimate in August, 1939. Comparisons, before and after, were made with Balmoral, Christchurch, Lincoln and Ashburton. Temperatures were significantly warmer in all seasons after the site change. The 1928 to August 1936 data were adjusted upwards by 0.6°, 0.3°, 0.4° and 0.5°C in autumn, winter, spring and summer.

Estimated missing value for: winter 1936, 6.6

18. Alexandra, I59234

A site change occurred in September 1963. Before and after comparisons were made with Naseby and Ophir. There was no significant difference in mean temperatures in any season, so no adjustment was made.

Estimated missing values for: spring 1983, 11.6; autumn 1985, 10.8.

19. Gore, I68093, I68191, I68192,

Data were combined for three stations; East Gore, Gore Borough and Gore DSIR. Salinger (1980) noted a warming in East Gore temperatures between 1960 and 1965 when it closed. Gore Borough data were available from 1942-1972, but was only used from 1960-1972, when it closed. The DSIR station opened in August 1971. The first two sites were compared and no significant difference was found between the two. The latter site was adjusted to these two. The DSIR site was significantly cooler than the other two in all seasons. Adjustments of 0.5°, 0.3°, 0.8°, 0.8°C were made in autumn, winter, spring and summer.

Estimated missing values for: summer 1971, 15.6; spring 1971, 10.7.

APPENDIX B

Example output from principal component analysis

Analysis of barley yield and related climate data

Eigenvectors

District	YIELD1	YIELD2	YIELD3
North Auckland	0.110502	-0.143088	0.546258
South Auckland	0.248849	0.303687	-0.334991
Gisborne	0.295957	-0.344172	0.020365
Hawkes Bay	0.337746	-0.103112	0.378923
Taranaki	0.269764	0.473180	0.132410
Wellington	0.362508	0.300862	-0.042741
Marlborough	0.339469	-0.327479	0.135702
Nelson	0.398833	-0.170001	0.054786
Canterbury	0.399507	-0.028708	-0.246518
Otago	0.177594	-0.369814	-0.586193
Southland	0.233589	0.412392	0.014730

Station	WRAIN1	WRAIN2	WRAIN3
Mangonui	0.127792	0.477724	-0.036109
Ruakura	0.303357	0.190162	0.254789
Te Aroha	0.230081	0.454432	-0.153109
Napier	0.162723	0.346529	-0.153749
New Plymouth	0.245821	-0.060824	0.366997
Palmerston North	0.258371	-0.079547	0.469030
Masterton	0.291720	0.132667	0.200391
Nelson	0.238331	-0.363434	-0.163905
Blenheim	0.257630	-0.257019	-0.308100
Christchurch	0.316395	-0.027566	-0.168529
Waimate	0.339476	-0.002378	-0.242956
Alexandra	0.200026	-0.411712	0.007644
Oamaru	0.336705	-0.002172	-0.217420
Dunedin	0.314885	-0.108181	-0.006654
Invercargill	0.094264	-0.035713	0.485047

Station	SPRAIN1	SPRAIN2	SPRAIN3
Mangonui	0.164987	0.486833	0.243907
Ruakura	0.311136	0.319671	-0.185987
Te Aroha	0.170512	0.490830	0.106270
Napier	-0.003290	0.257374	0.415361
New Plymouth	0.331223	0.137836	-0.221285
Palmerston North	0.293356	-0.180220	-0.220671
Masterton	0.274455	0.075181	0.144268
Nelson	0.262333	0.103187	-0.399189
Blenheim	0.339052	0.053601	-0.239805
Christchurch	0.295926	-0.156231	0.329477
Waimate	0.312777	-0.260216	0.316182
Alexandra	0.223283	-0.256779	0.005366
Oamaru	0.278449	-0.198773	0.395171
Dunedin	0.275179	-0.270441	-0.051007
Invercargill	0.059221	-0.110875	-0.139461

Station	SURAIN1	SURAIN2	SURAIN3
Mangonui	0.237654	-0.287186	0.297742
Ruakura	0.325015	-0.212022	0.177236
Te Aroha	0.273023	-0.249436	0.153157
Napier	0.180830	-0.341352	-0.336139
New Plymouth	0.288450	-0.171068	0.220362
Palmerston North	0.267121	-0.183454	0.144182
Masterton	0.199012	-0.234013	-0.335021
Nelson	0.293886	-0.035329	0.063489
Blenheim	0.337613	0.098002	-0.026132
Christchurch	0.281425	0.190389	-0.388800
Waimate	0.293328	0.312712	-0.225668
Alexandra	0.189873	0.273210	0.269639
Oamaru	0.289524	0.371472	-0.159795
Dunedin	0.225213	0.394174	0.108813
Invercargill	-0.017094	0.251500	0.494993

Station	WTEMP1	WTEMP2	WTEMP3
Waipoua forest	0.244906	-0.295320	0.162069
Te Aroha	0.274043	-0.302096	0.220792
Ruakura	0.280376	-0.297378	0.219467
Napier	0.293126	-0.196024	-0.333804
New Plymouth	0.309462	-0.128981	-0.055396
Palmerston North	0.311207	-0.088600	0.020805
Masterton	0.282702	-0.114062	-0.575065
Appleby	0.293047	-0.022678	0.410595
Blenheim	0.293625	0.121547	0.217962
Christchurch	0.295104	0.203714	-0.301308
Waimate	0.266740	0.335644	-0.145614
Alexandra	0.211147	0.521390	0.315440
Gore	0.230086	0.464626	-0.060036

Station	SPTEMP1	SPTEMP2	SPTEMP3
Waipoua forest	0.253734	-0.308809	0.087648
Te Aroha	0.283168	-0.302625	-0.165850
Ruakura	0.272815	-0.423496	-0.033832
Napier	0.250000	-0.104053	0.608109
New Plymouth	0.291924	-0.226014	-0.148089
Palmerston North	0.305490	-0.150593	-0.057939
Masterton	0.293545	0.051846	0.040442
Appleby	0.285763	0.011869	-0.273555
Blenheim	0.295655	0.069219	0.218096
Christchurch	0.282389	0.285500	0.281236
Waimate	0.247544	0.492033	0.275488
Alexandra	0.271786	0.300904	-0.421806
Gore	0.264258	0.356859	-0.334128

Station	SUTEMP1	SUTEMP2	SUTEMP3
Waipoua forest	0.275585	-0.212522	0.211597
Te Aroha	0.272852	-0.334236	0.325875
Ruakura	0.282948	-0.264349	0.118777
Napier	0.258511	0.439121	0.563953
New Plymouth	0.281844	-0.259092	0.039411
Palmerston North	0.289501	-0.079611	0.059698
Masterton	0.283592	0.227889	0.150772
Appleby	0.281286	-0.218370	-0.082682
Blenheim	0.280950	0.202238	-0.048235
Christchurch	0.272867	0.424585	-0.142805
Waimate	0.271034	0.378653	-0.352703
Alexandra	0.278571	-0.198295	-0.401524
Gore	0.274725	-0.058786	-0.416959

APPENDIX C

Extracts from the 'Orchardist of New Zealand' summaries of growing seasons

Table C1

Stonefruit: Central Otago

Growing season	Comments
1963-1964	Season peaked three weeks later than average.
1964-1965	1964 the driest year on record (211mm). Drought broken in 1965. A successful stonefruit season.
1965-1966	Poor fruit set in stonefruit because of cool south-west winds over the blossom period.
1966-1967	Damaging frost on 4 November. Stonefruit not as badly affected as pipfruit due to greater frost protection. Average crops.
1967-1968	Spring frosts, crops still average. Apricot crop lighter than average. Late season with unsettled weather. January rainfall well below average.
1968-1969	Heavy frosts in first half of October. Overall fruit crops expected to be down by 25%. Plums and nectarines badly affected. For the third successive year a late start to harvest.
1969-1970	Fruit setting conditions unfavourable. Two severe localised frosts in October. Prospects excellent. Bad weather in December/January depleted the cherry and apricot crops.
1970-1971	120-130 mm of snow on 23 September, then two heavy frosts. All but wiped out the apricot crop. Stonefruit production only 18% of previous year.
1971-1972	Localised gales caused some damage to apricot trees on night of 10-11 Sept. Localised frost damage in late Sept. Apricot ripening delayed by cool weather.
1972-1973	An average season. Good quality crop.
1973-1974	Heavy fruit set. Little problem with frost. Heavy crops, good quality. Cold weather delayed ripening of apricots.
1974-1975	No damaging frosts. Three localised hail storms in January. Crops down on previous seasons.
1975-1976	Spring frosts at the end of Sept. reduced the Roxburgh crop. Apricot crop only two thirds of average, others in good supply.
1976-1977	Unsettled spring weather delayed the apricot crop. Wet periods reduced the cherry crop to 50% of average. Wet weather caused serious cracking and brown rot in apricots.

1977-1978	Very wet, cold spring gave poor fruit set. Trees were late to full bloom, harvest was light. Very light to average crop overall.
1978-1979	Harvest season excellent. Above average crop.
1979-1980	Season started poorly. December conditions favourable although rain caused cracking in cherries. Rain and wind damage to other stonefruit later. Conditions improved.
1980-1981	One of the best seasons for many years. From late spring, weather hot and dry, with well timed rain. Season earlier than previous years. Short season, good quality fruit.
1981-1982	Mild winter, relatively frost free spring. Heavy fruit set. Harvest affected by adverse weather.

Table C2
Stonefruit: Hawkes Bay

Growing season	Comments
1965-1966	Stonefruit crop affected by frost, although losses greater with pipfruit.
1966-1967	Severe storm on 11 Dec.
1967-1968	Good growing conditions. Violent storm in April, main harvest over.
1968-1969	Indications for a good crop. Severe winds, heavy rain, late frost and hail.
1969-1970	Heavy blossom, good fruit set. Frost affected early plum varieties leading to fruit drop.
1970-1971	Good peach crop expected.
1971-1972	Heavy blossom on all stonefruit except for some plum varieties. Prolonged period of rain in early March caused considerable losses in some crops. Golden Queen peaches were the hardest hit. Some losses through dropping and scald from hot weather after the rain.
1972-1973	Gale force winds just after Xmas caused considerable losses, mainly to plums and peaches in more exposed areas.
1973-1974	Production up on last year. Conditions favourable.
1974-1975	Crop substantially down because of poor fruit set and floods earlier in the year.
1975-1976	Prospects excellent, good blossom. Weather following generally unfavourable. Below average sunshine, heavy rain and cold temperatures early in 1976. Hail storm and gales in Feb. Fruit size down.
1976-1977	Cold conditions and persistent rain during blossom. Below average fruit set. Also hail and frost damage. Crops down.
1977-1978	Crops down for second year in a row, with a poor spring.
1978-1979	Heavy frost, hail, persistent rain and gale force winds, at different times. Wettest March for 75 years, 325 mm in 17 days.
1979-1980	Excellent year. Fine settled weather through the main harvest.
1980-1981	Dry winter. Relatively dry, warm, windy spring, excellent for fruit set. Generally favourable conditions throughout the harvest period.
1981-1982	Mild winter, good blossom. Ideal pollination conditions. Gale force winds, drought, devastating hail storm in January.

Table C3

Pipfruit: Hawkes Bay

Growing season	Comments
1954-1955	Severe late frost reduced crop. Larger than expected crop.
1955-1956	Weather conditions favourable for most of the season. Record crop.
1956-1957	Climatic conditions in spring caused more russet than normal. Conditions at harvest favourable. Good crop.
1957-1958	Favourable conditions. Dry weather through late summer and autumn reduced size. Record crop.
1958-1959	Unfavourable spring conditions caused russet. Apple crop slightly above average. Record pear crop.
1959-1960	More rain than usual in the latter part of harvest. All time record apple crop. Pears above average.
1960-1961	More rain than usual throughout growing and harvest season. Some russet problems as a result. Moderate apple crop. Heavy pear crop.
1961-1962	Very wet winter and early spring. A very dry summer, favourable for a record crop.
1962-1963	No comments
1963-1964	Prevalence of russet and damaging Nov. frost reduced crop. Dry summer and autumn. High frequency of strong westerlies in Jan. Reduced crop.
1964-1965	A dry summer, followed by good autumn conditions. One of best ever crops, down on last year in quantity, but excellent quality.
1965-1966	Heavy frost damage in November 1965.
1966-1967	Bad weather before and after Xmas delayed ripening. Fruit didn't size with very dry weather.
1967-1968	Storm damage in April. Losses high, mostly through fruit drop.
1968-1969	Crop down due to frost damage and an "off" season. Severe hail storm hit some growers in mid Jan. Had to contend with severe winds, heavy rain, late frosts and hail.
1969-1970	No comments.
1970-1971	Excellent season. Good for an "off" year.
1971-1972	Heavy blossom.
1972-1973	Dec. gales caused some branch rub damage. Sun scald over a hot summer.
1973-1974	Little damage from an early storm. Good growing and harvest season. Some damage to Granny Smith with April gales. Crop down.

1974-1975	Gale force winds caused some damage on several occasions, as did flooding in a few orchards.
1975-1976	Weather generally unfavourable with below average sunshine, heavy rain and cold temperatures early in the year. Hail storm and gales in Feb. Fruit size down.
1976-1977	Cold weather and persistent rain over the blossom period resulted in poor fruit set. Also some frost and hail damage. Granny Smith worst affected.
1977-1978	Reasonably heavy frosts, helped thin out the crop. High yields, fruit size above average.
1978-1979	Heavy frosts, hail, persistent rain and gales. Wettest March in 75 years at Hastings, difficult for harvest. Southerly on 31 Mar. caused considerable damage to Granny Smith particularly.
1979-1980	Very heavy blossom, good fruit set. Fine settled weather through to main harvest. Storms in Mar., little damage. High yields.
1980-1981	Dry winter. Relatively dry, warm, windy spring. Excellent for good fruit set. Generally favourable conditions throughout the harvest. Good crop.
1981-1982	Mild winter, with excellent blossom and ideal pollination conditions. Gale force winds, drought and a hailstorm (affecting 100 orchards) all caused losses. A disappointing crop.

Table C4
Pipfruit: Nelson

Growing season	Comments
1954-1955	Heavy rains, followed by a period of dry weather. Record crop.
1955-1956	Good climatic conditions produced a crop of medium to large sized fruit. A record crop of apples. Pear crop down on last year.
1956-1957	Unfavourable conditions in late 1956, delayed fruit maturation.
1957-1958	Heavy, localised hail damage. Crop down.
1958-1959	An extremely favourable growing season. Record crop.
1959-1960	Late frosts in several areas severely reduced some crops. Crop down.
1960-1961	Dry spring. Heavy rain in Jan. Above average crop.
1961-1962	Good weather for blossom and fruit set. Good spread of rainfall over the pre-harvest period. Large crop.
1962-1963	Very wet winter and spring conditions. Crop well below average.
1963-1964	Heavy fruit set. Dry in late spring and in summer, seriously affected sizing. Heavy rain at the end of Feb. helped later varieties.
1964-1965	Good growing conditions in early summer. Lack of January rainfall affected sizing. Later rain helped mid to late season varieties. Season a little late. Above average crop.
1965-1966	Near gale force winds and heavy rain throughout Nelson district near the end of March. Light damage.
1966-1967	Very dry weather, affected sizing. Crop down.
1967-1968	Drought conditions in early March had a direct affect on fruit size. Crop lighter than expected due to alternating wet and dry conditions.
1968-1969	No comments
1969-1970	Some frost and hail damage. Otherwise a good season.
1970-1971	Storm on 4 Jan. caused some localised losses.
1971-1972	November rain boosted prospects for a good season.
1972-1973	Worst ever drought, combined with extreme temperatures reduced crop size and led to sunburn damage.
1973-1974	Early season drought and some hail damage. Size down.
1974-1975	Widespread hail storm on 18 Oct., and hail on four other occasions. Most growers affected. Cyclone Alison caused some damage on 11 Mar.
1975-1976	Very good weather to the end of Jan., with ample moisture. Conditions deteriorated, with reduced fruit size. High winds and a heavy rain storm caused losses to the Granny Smith crop.

1976-1977	Wet spring led to poor fruit set. The worst hail storm ever experienced hit on 22 Dec. Nelson was declared a climatic disaster area.
1977-1978	Drought through to April affected fruit size. Harvest was late, conditions dry.
1978-1979	Fairly good spring. Dry from Dec. to the end of Feb. Later rain helped mid-season varieties. Some localised hail damage.
1979-1980	Oct.-Apr., wetter and cooler then average. Smaller sized fruit, especially Granny Smith.
1980-1981	Two localised hail storms in late Nov. and early Dec. Two months of drought affected some orchards. Rain early in March helped avert total disaster.
1981-1982	Season started well, with good fruit set. Heavy fruit drop. Two devastating hail storms affected about 30 orchards. Long periods of cool, wet weather before Xmas. Good weather in the New Year.

APPENDIX D

Effect on yield of shelterbelts

Table D1

Shelter type	Crop(s)	Yield effect	Author(s)
Mixed species	groundnut pigeonpea pearl millet	↑ 40-43% ↑ 39-47% ↑ 23-64%	Reddi et al, 1981
Mixed species	wheat mustard	increased yield of both	Vora et al, 1982
Eucalyptus camaldufensis	wheat cotton	no effect max yield at 60-70 m min yield at 15-30 and 165-180 m	Sheikh et al, 1982
Mixed species	grain and other crops	↑ by about 5%	Anikanov et al, 1982
Mixed species	wheat barley	irr'd fields ↑ 7.9%, non-irr'd fields ↑ 11.3% irr'd fields ↑ 12.3%, non-irr'd fields ↑ 13.7%	Titova et al, 1982
Ulmus pumila var arborea	cotton lucerne	significant increase	Orazov, 1982
Unspecified	field crops	increased	Jeddeloh, 79/80
Unspecified	grain	permeable ↑ 0.7-0.8 t/ha dense ↓ 0.24-0.26 t/ha	Vasilev,1980
Unspecified	wheat	highest yld at 10-20 m, below av. at 5 m from shelter	Sheikh et al, 1976
Unspecified	winter wheat hybrid maize sunflower	cf no shelter ↑ ylds, ↑ protein & gluten	Labaznikov, 1977

Unspecified	apples	permeable 59.2 kg/tree semi-perm. 35.9 kg/tree impermeable 43.3 kg/tree	Adrianov, 1975
Unspecified	cotton	↑ 0.3-0.6 t/ha	Molchanova, 1980
Unspecified	winter wheat	↑ yield	Gorgainov et al, 1981
Dalbergia sissoo Eucalyptus citriodora Populus deltoides Salmania malabasica	Pavan wheat	Signif. ↑ yield under D. sissoo cf other spp	Khattak et al, 1981
Unspecified	wheat maize	av. increase 14-21%; 0.6-1.1% more protein	Peev et al, 1982
Unspecified	sunflower grains	return of 2.16 roubles per 1 rouble invested	Labaznikov, 1979
Robinia pseudoacacia	sugar beet	32% higher than unprotected field during windstorm	Dzhodzhov, et al, 1980
Birch	wheat	↑ of 100-740 kg/ha in drought yrs	Ivanov, 1980
Tamarix gallica T. gallica + Arundo domex T. gallica + A. domex + Calligonum polygonoides	wheat	↑ by 8-15%, greatest effect with 2 & 3 row belts	Rehman, 1978
Acacia arabica Dalbergia sissoo	wheat	yield ↓ by shading from 2-9 m	Sheikh et al, 1978
Tilia cordata with birch, larch, poplars. Birch with Caragana arborescens	grass	improved yld with shelter	Kharitonov, 1979
Unspecified	winter wheat spring barley maize sunflower silage maize	↑ 15.6% ↑ 11.6% ↑ 20.4% ↑ 35.1% ↑ 32.4%	Keleberda et al, 1978

Unspecified	grain	av. ↑ 400 kg /ha, dry yrs ↑ 20-40%, favourable yrs ↑ 10-20%	Pilipenko, 1977
Young shelter Old shelter	wheat maize wheat maize	↑ 6-7% ↑ 8-9% ↑ 18-21% ↑ 9-34%	Dimitrov et al, 1977
Mulberry Pomegranate Quercus castaneifolia Poplar	cotton	1972 ↑ 500 kg/ha; 1973 (unfavourable year) ↑ 2900 kg/ha	Bukov et al, 1976
Unspecified	grain	1975 (v. dry year) ↑ from 70-680 kg/ha	Anikanov, 1976
A range of tree species	wheat	1967-1973, ↑ in protected zone	Aydemir, 1975
portable slat fencing	soybeans	↑ yield	Miller et al, 1973
Corn	sugar beets	25% ↑ in favourable years	Brown et al, 1972
Tall wheatgrass (Agropyron elongatum)	winter wheat (Triticum aestivum)	↑ in dry years	Aase et al, 1974
slat fence wind barrier	dry beans	↑ yields	Rosenberg, 1966b

APPENDIX E

Instrument calibration and measurement

Anemometers

The anemometers used were all Synchrotac Type 732 generating cup anemometers, with AC voltage output generated by a 10 pole alternator. An extensive calibration had been carried out 10 years ago but these instruments had not been in use for several years. It was therefore considered wise to carry out a calibration check in the low speed wind tunnel of the Mechanical Engineering Department of the University of Canterbury. This was done over a wind speed range of about 2 to 20 ms^{-1}. Actual air velocity (v) was derived from the relationship:

$$v = 4\left(\frac{qT}{288}\right)^{1/2}$$

where q is the dynamic head, measured from a manometer and T is the air temperature in °C. AC voltage (V) for each anemometer was measured at the set wind speeds. As the CR7 recorded frequency past the poles, AC volts had to be converted to frequency (f). This was done using a relationship derived from the manufacturers data:

$$f = 2.554*V^{0.968}$$

In programming the CR7 allowance had to be made for both the execution interval (10secs) and the number of counts per revolution (5), giving a multiplier of 0.02.

The calibration carried out at the start of the field work, Aug/Sept 1987, gave relationships consistent with those derived earlier. However subsequent calibration checks gave a consistently different result. As this latter result was repeated several times over the course of the field study it was taken as true. There was a consistent difficulty in obtaining accurate values at low wind speeds, compounded by the relatively high starting threshold of these anemometers. The manufacturers data showed a linear relationship except at wind speeds below 3 ms^{-1}, where there was a marked drop off. This required the fitting of a curve for low wind speeds and an overall curvilinear relationship. The more recent calibrations did not show this drop off, mostly because of the difficulty of measurement below 2
ms^{-1}. The data from these calibration checks is given graphically in Figs E1-E6 along with the fitted regression lines. All gave a linear relationship within the range of wind speeds measured. Correlation coefficients (r) and estimated standard deviations (s) about the regression lines are included on the relevant graphs.

Fig. E1 Calibration of anemometer 78/840

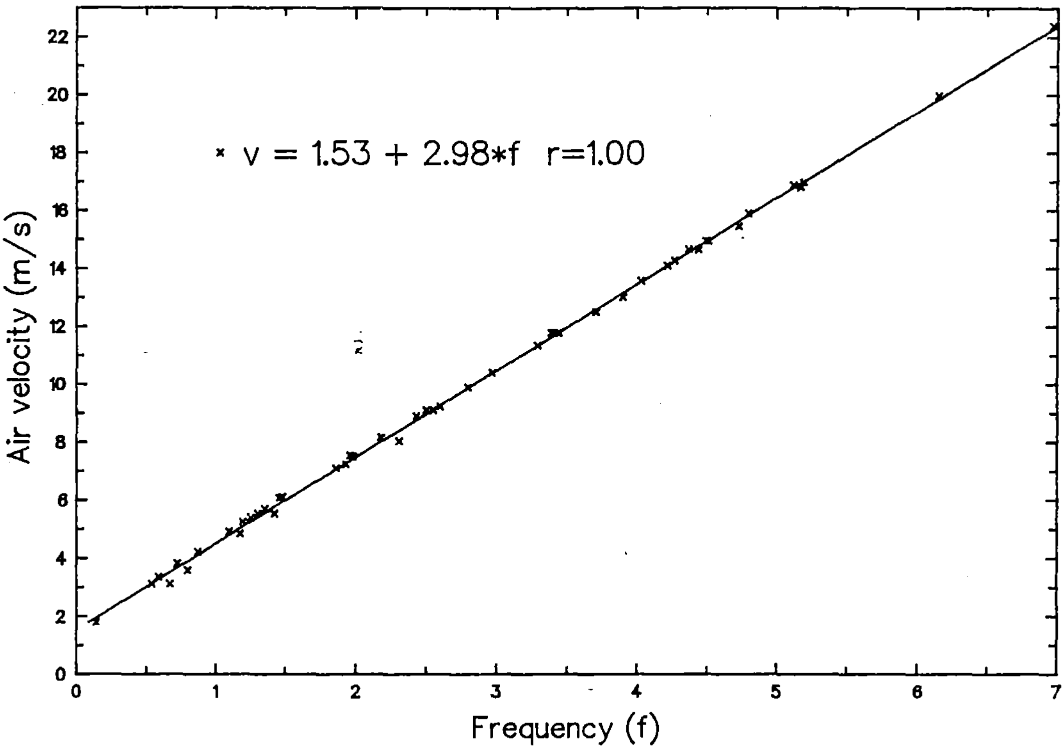


Fig. E2 Calibration of anemometer 75/664

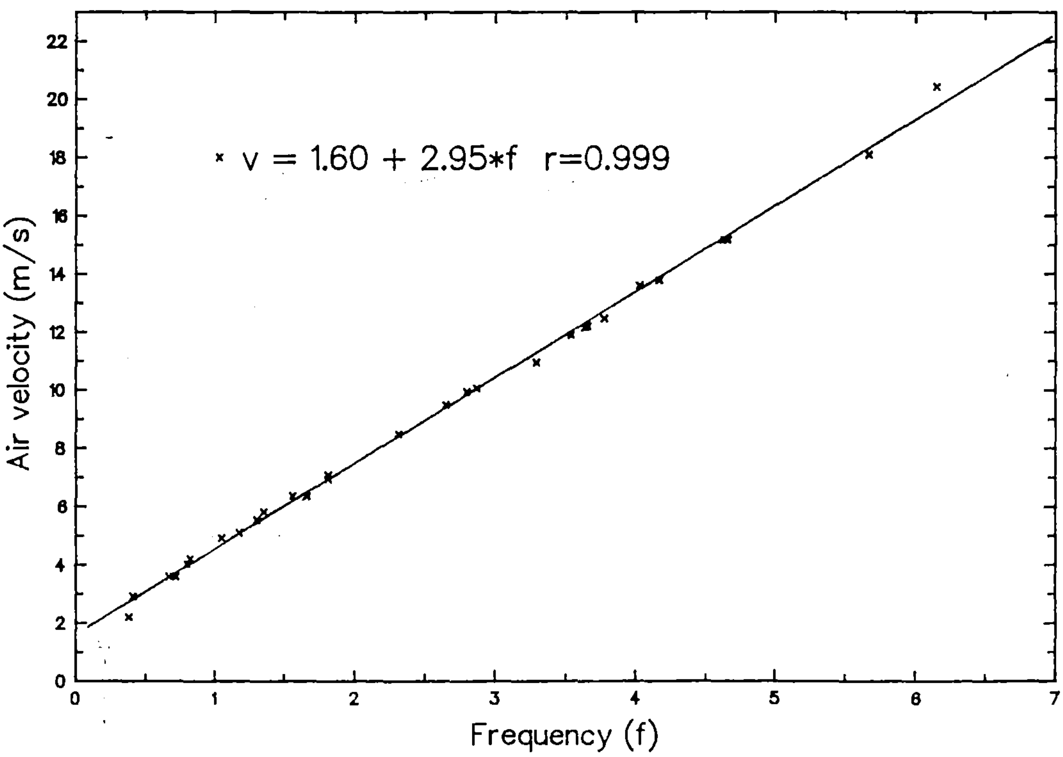


Fig. E3 Calibration of anemometer 78/839

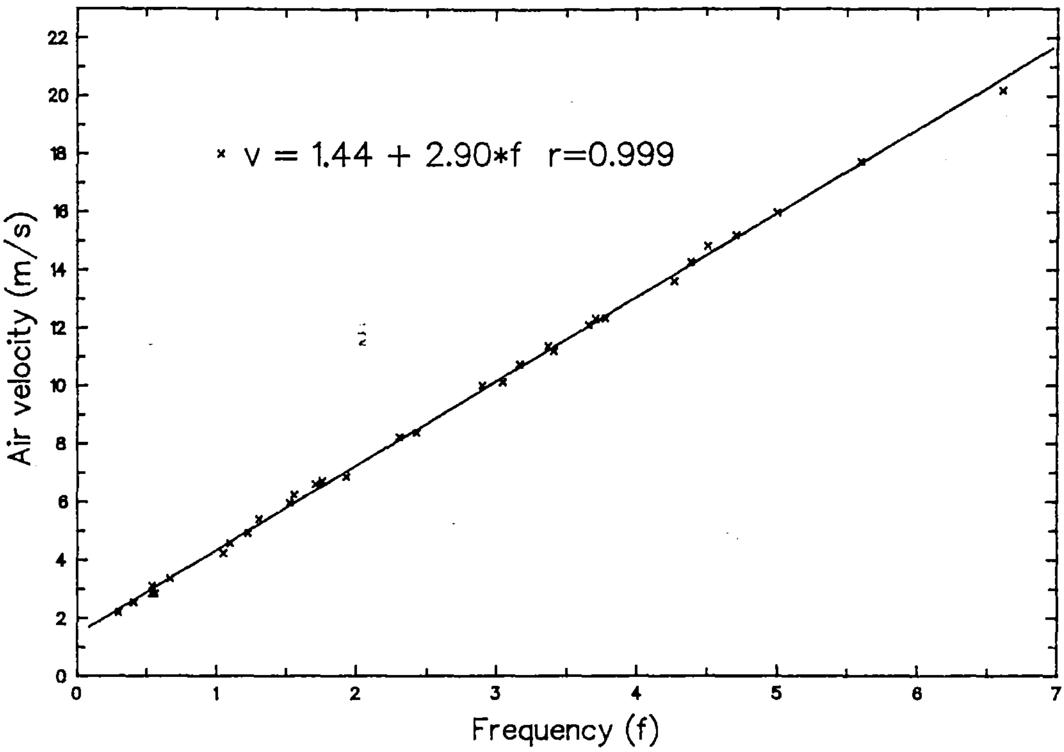


Fig. E4 Calibration of anemometer 78/820

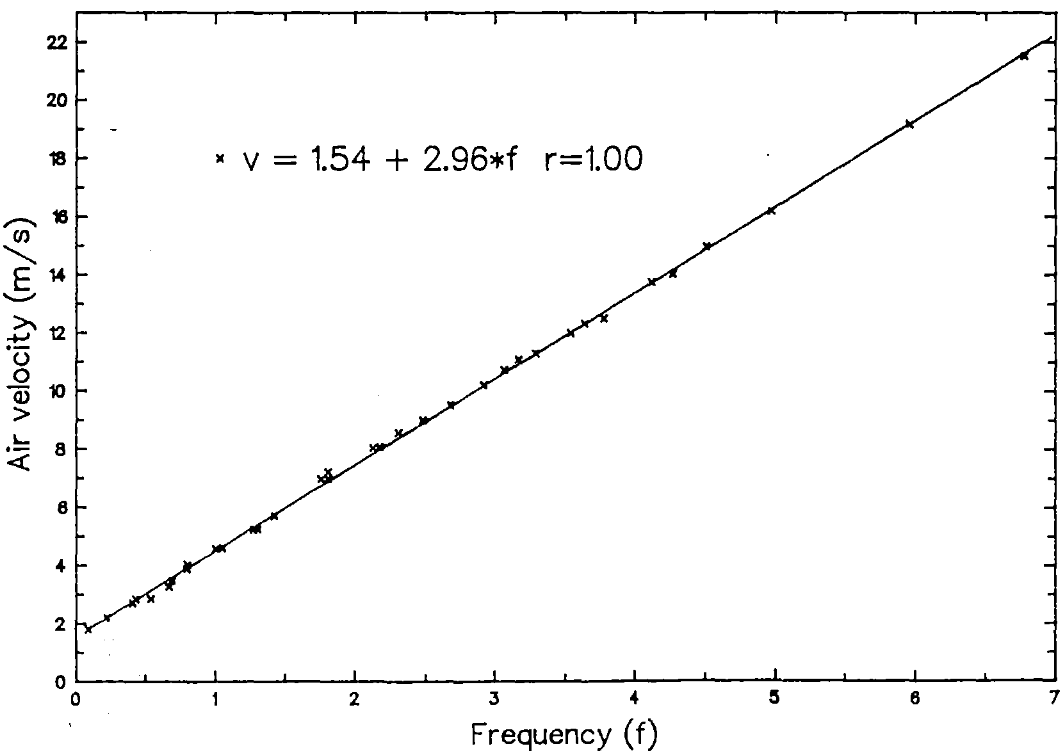


Fig. E5 Calibration of anemometer 78/828

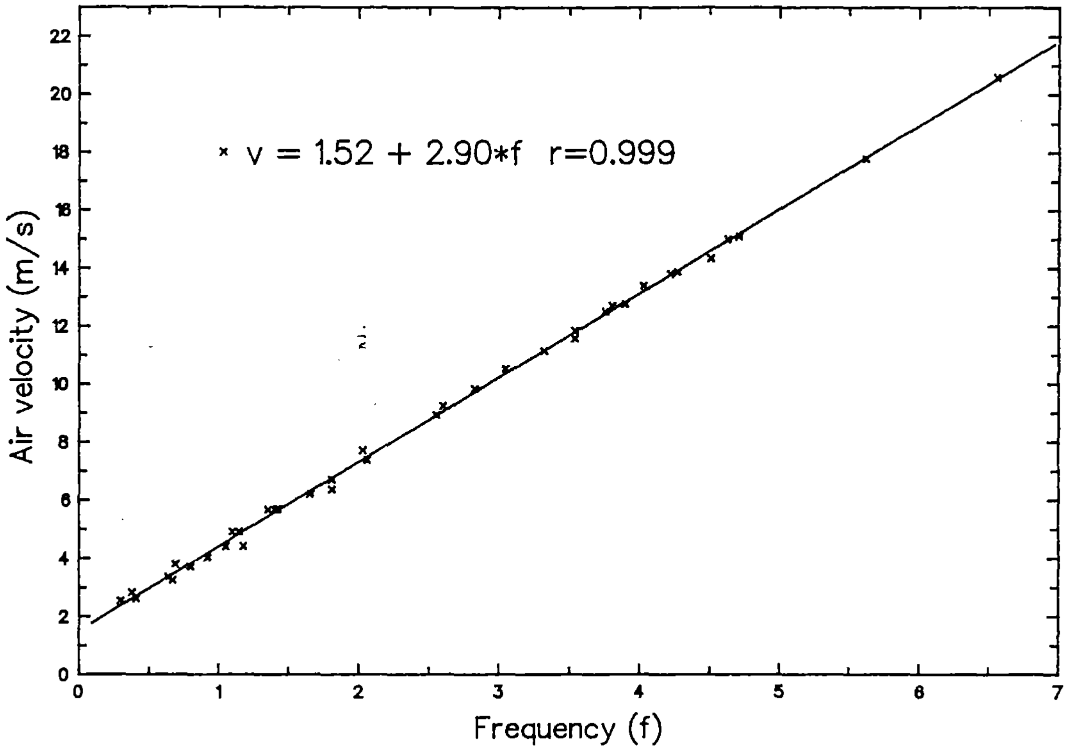
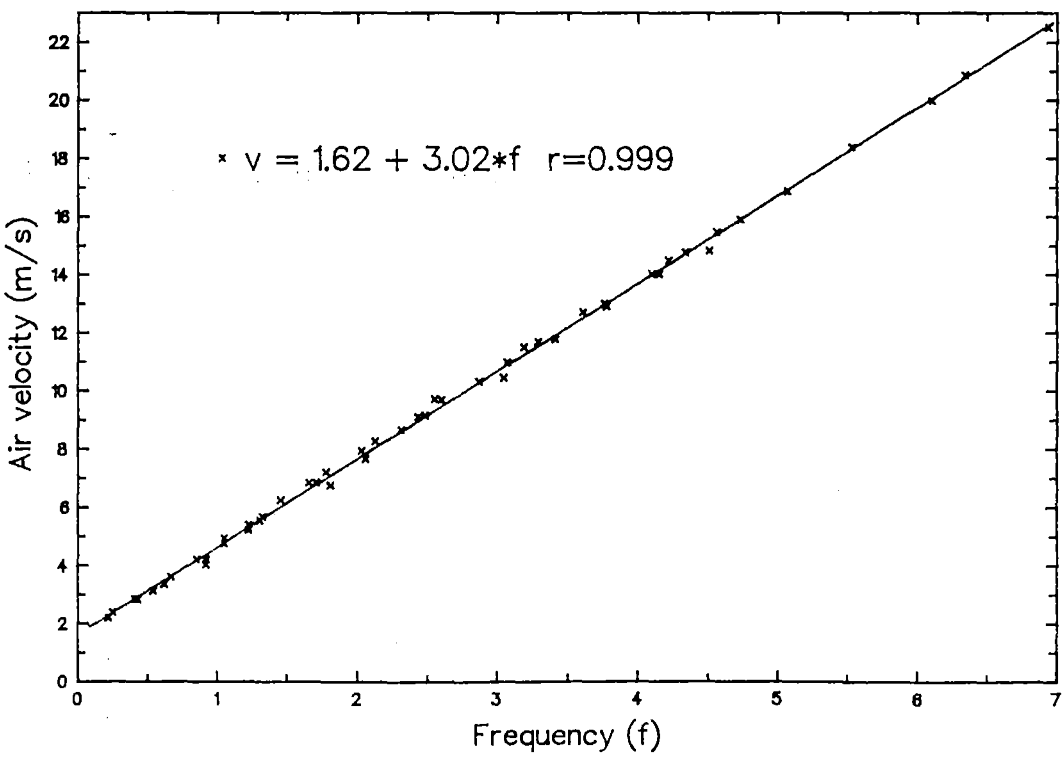


Fig. E6 Calibration of anemometer 78/815



Temperature probes

The temperature probes used were YSI (Yellow Springs Instruments) thermilinear[R] components # 44212. These consisted of a thermistor composite, consisting of three YSI thermistors packaged together in a single sensor and a resistor composite, consisting of three separate metal film resistors. A further 10K resistor had to be incorporated into the connection with the CR7. From this overall resistance (R_T) was:

$$R_T = \frac{(V_{in}*10K)}{V_{out}} - 10K$$

From the manufacturers performance equation for °C:

$$R_T = (-129.163)T + 13698.3$$

With a Vin of 1500 mV :

$$T = 183.48 - \frac{116130}{V_{out}} \quad °C$$

The temperature probes were calibrated against a -1 to 50 °C mercury thermometer, accurate to 0.1 °C, over a temperature range of 0 to 40 °C. The relationships were strongly linear as shown in Figs. E7-E12. Initial field testing of the temperature probes showed the resistor casings to be subject to weather influences, so modification was required. This involved both replacement of the original resistors and the encasing of the composites in resin. On the basis of the strongly linear relationship apparent earlier a two point calibration was then carried out, at 0 and 40 °C. A final field calibration was carried out with all six probes mounted on a single crossarm, taking one as a standard. Final adjustments were made to the calibration equations on the basis of these calibration checks. Problems were experienced in the field with three probes showing faults at various times over the period of measurement. The cause was not readily apparent with each and so some juggling of these instruments was necessary to obtain measurements from the most relevant heights. With no basis for comparison of temperature profiles it was most important to obtain measurements from nearer the ground to allow for ET estimation and comparison of measured temperature and derived variables with the standard meteorological data. A reliable probe was also kept at the top of the mast so that inversion and strongly lapse conditions could be recorded.

Wind direction

Wind direction was needed for the main wind sectors for characterization of site roughness for each sector as mentioned earlier. A wind vane of simple design was built using one from the NZAEI as a prototype. It basically consisted of a 360° potentiometer in a casing, connected with a well balanced stainless steel arm, with a brass point and a perspex tail fin. The only problem was the presence of a blank spot in the potentiometer, which covered only a few degrees.

Fig. E7 Calibration of temperature probe 1 (tp1)

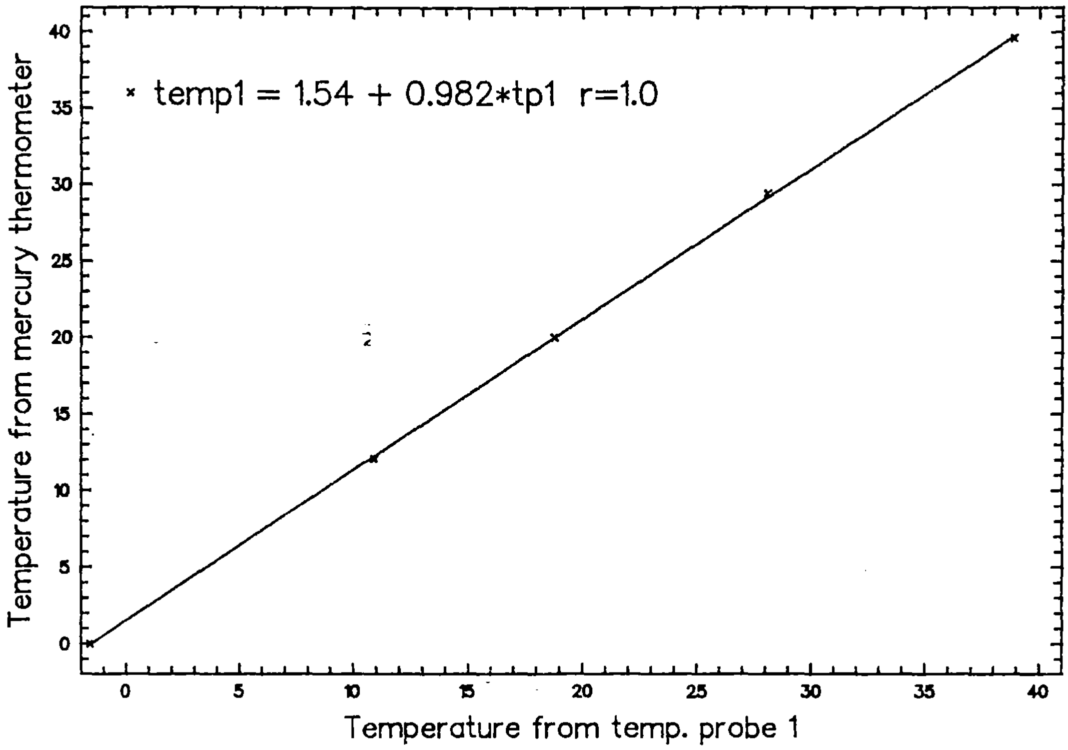


Fig. E8 Calibration of temperature probe 2 (tp2)

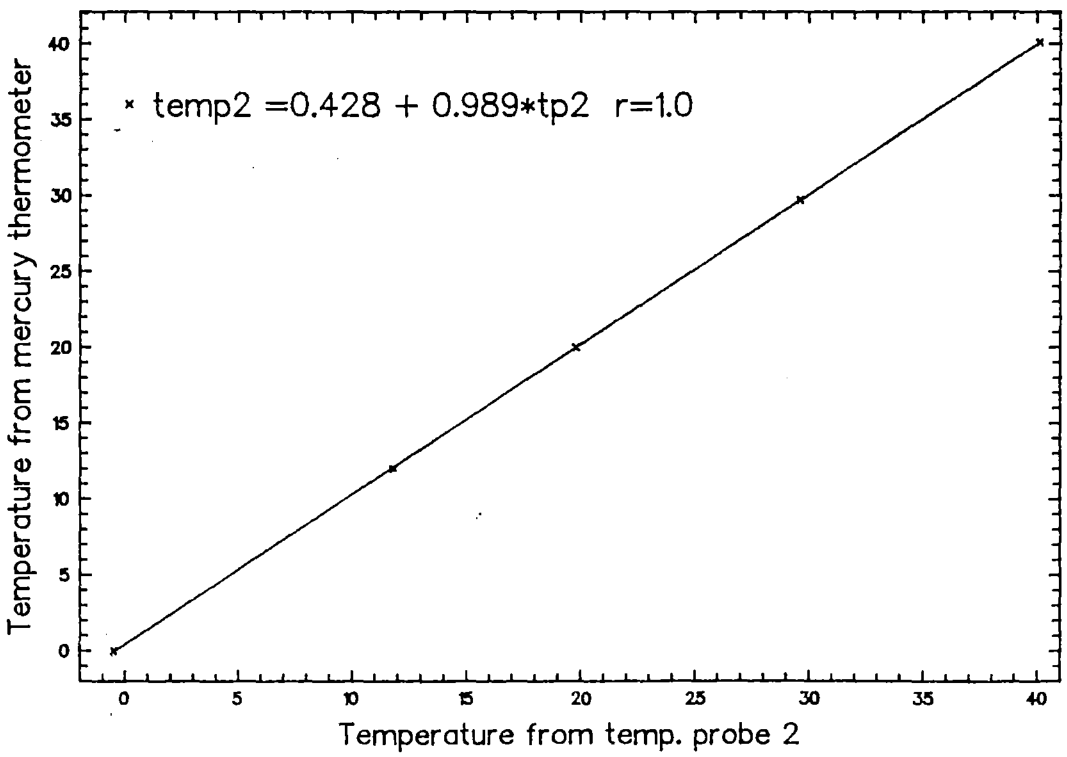


Fig. E9 Calibration of temperature probe 3 (tp3)

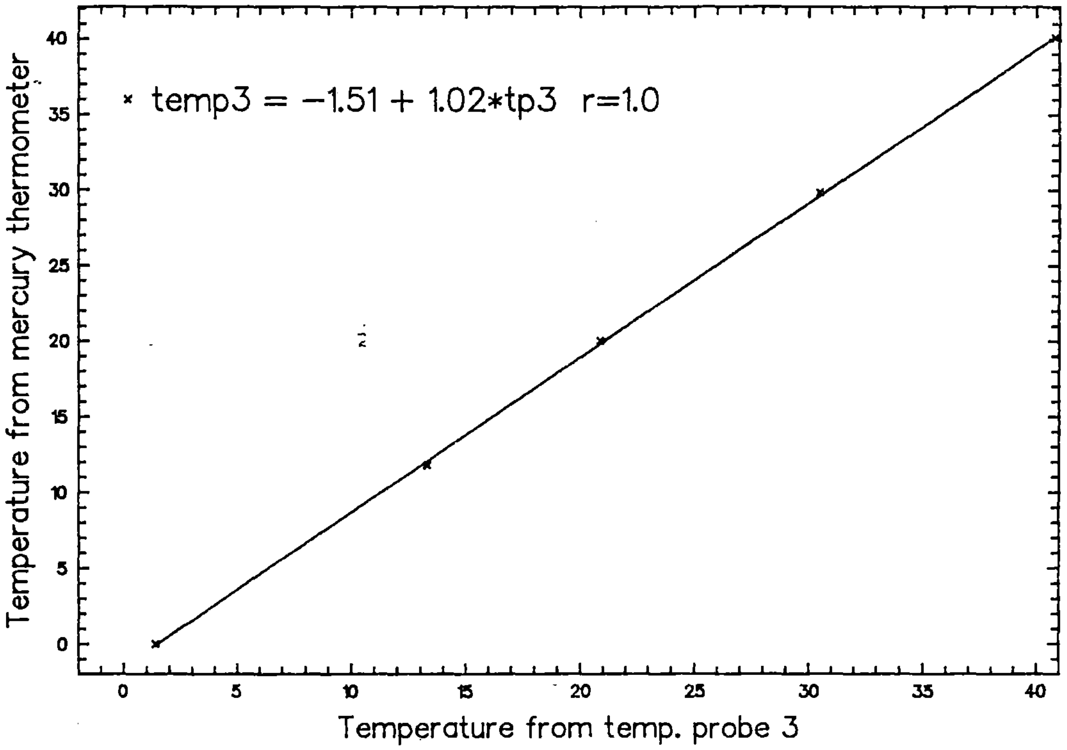


Fig. E10 Calibration of temperature probe 4 (tp4)

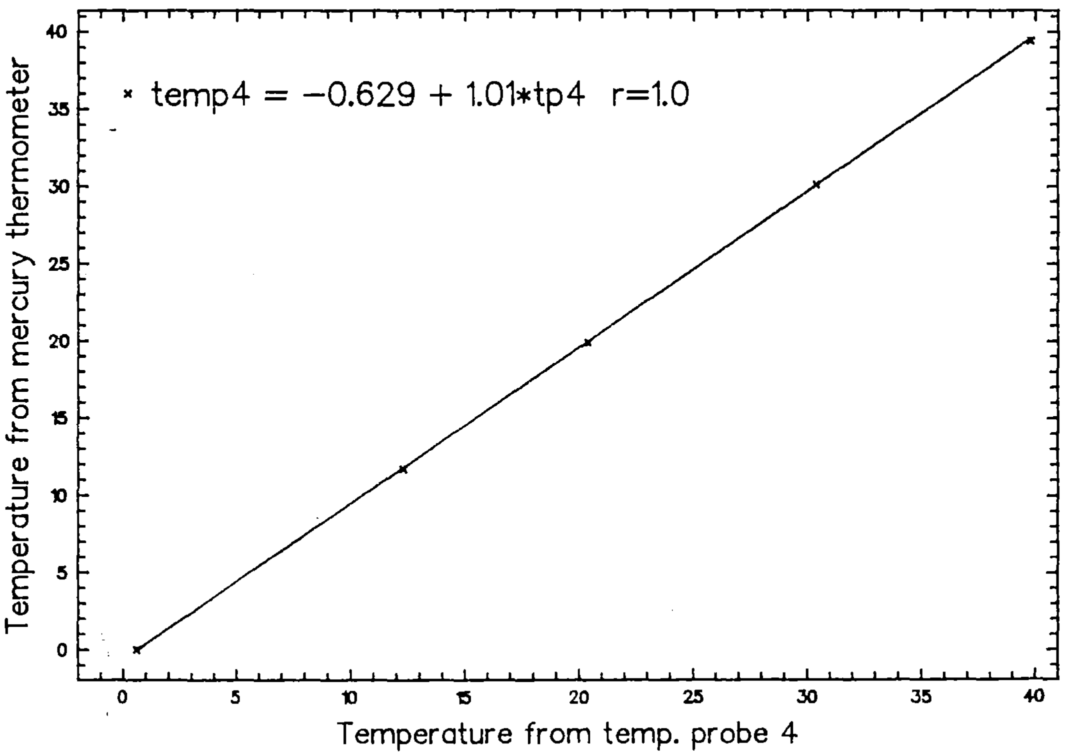


Fig. E11 Calibration of temperature probe 5 (tp5)

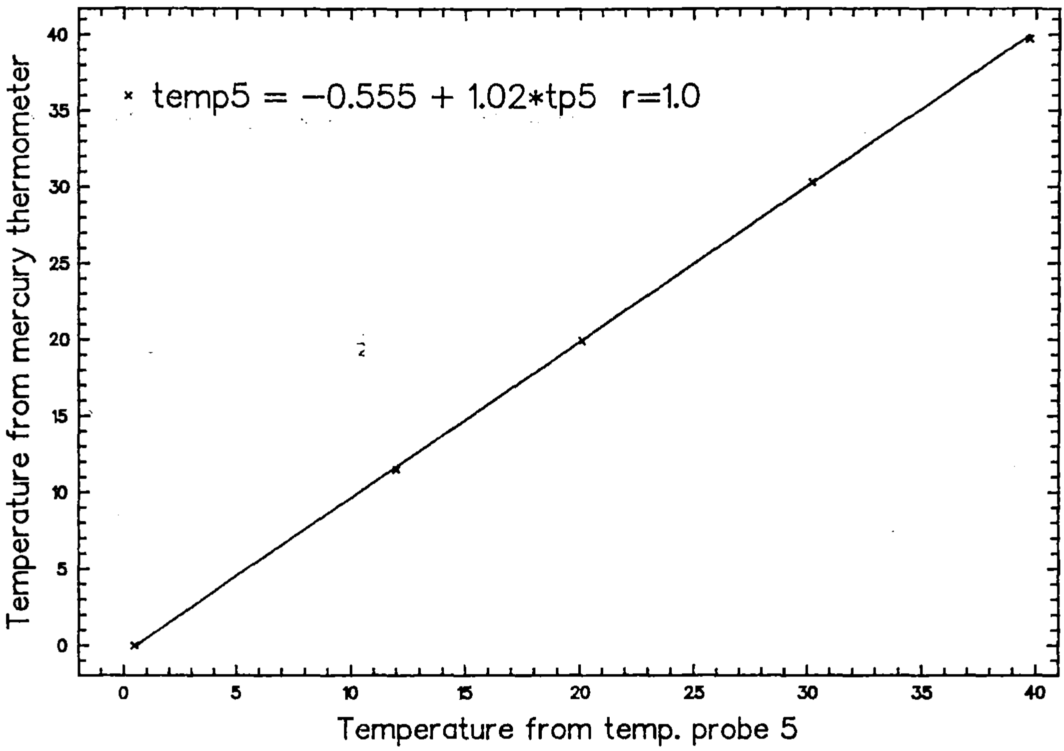
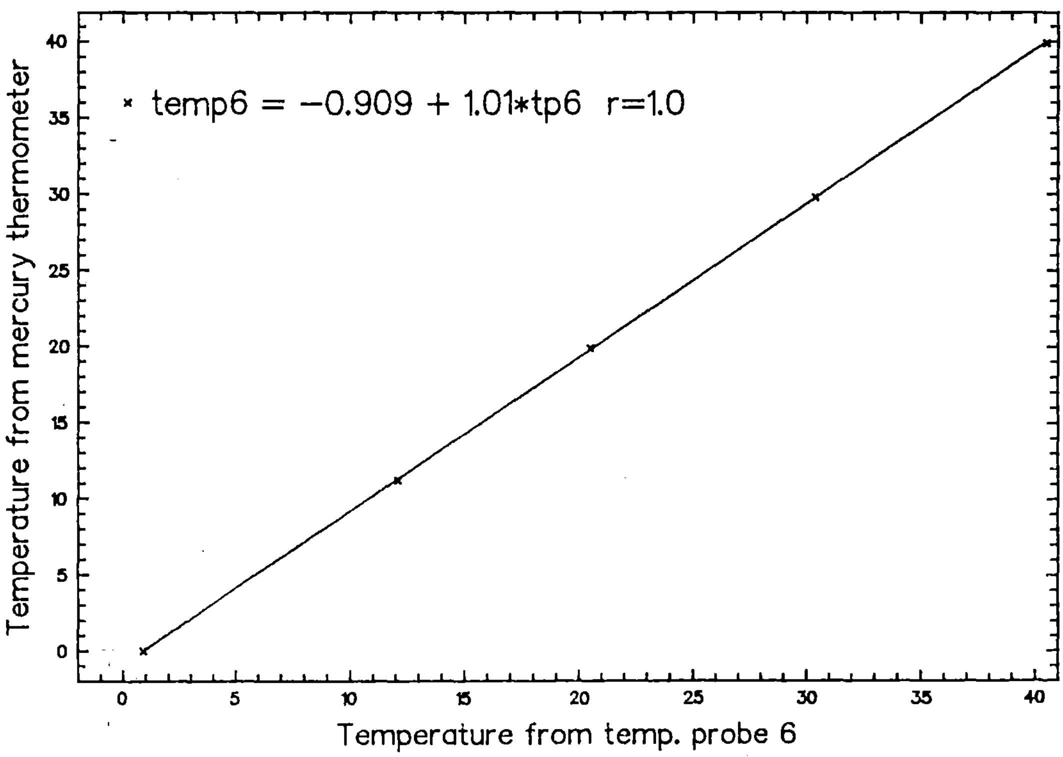


Fig. E12 Calibration of temperature probe 6 (tp6)



This was set to the south east, the sector from which the wind blows least frequently in Canterbury. A compass bearing was taken at each site and the blank spot set to this sector prior to the raising of the mast. As a general check on the performance of this wind vane hourly data was obtained from the Christchurch Met. Office at Christchurch Airport for each period of measurement. This latter site is more directly exposed to easterlies and generally sheltered by the Banks Peninsula from the South East. The Lincoln area is sheltered from the East, so except under strong easterly conditions surface Easterly winds normally turn to the North east by the time the reach Lincoln. Lincoln is also more exposed to the South East. Another important difference was the method of data collection. The mast gave hourly averages, whereas the Met Office takes readings on the hour. Taking these factors into account the mast wind vane proved to be generally consistent with the airport.

Relative humidity probes

The relative humidity probes used were especially configured for use with the CR7. They contained a Phys-Chemical Research PCRC-11 RH sensor and a Fenwal Electronics UUT51J1 thermistor. The temperature was given a worst case accuracy of ± 0.4 °C over the range -33 °C to +48 °C. The accuracy of the RH sensor was given as being typically better than ± 5% over the 12 to 100% RH range. These were enclosed in small screens, built from caravan vents and fitted with a mounting bracket. A field check with a whirling psychrometer showed both to be generally consistent with this, although one tended to read consistently a few percent lower than the other. These instruments were not considered sufficiently finely calibrated for a Bowen ratio determination of evapotranspiration. In general they were both mounted at the same height and an average reading taken. From temperature recorded at the same height (2.58m) it was possible to determine saturated vapour pressure using Tetens relationship:

$$es = 0.61078*EXP\left(\frac{17.269*T}{T + 237.30}\right) \quad kPa$$

where e_s is the saturated vapour pressure and T is temperature in °C. The conversion to mbar is times a factor of 10. By differentiating this equation the slope of the saturated vapour pressure curve (s) is derived, such that:

$$s = 17.269*e_s*((T + 237.30)^{-1} - T*(T + 237.30)^{-2})$$

Vapour pressure can also be determined from the relationship:

$$e_a = RH*e_s$$

Net radiation

Net radiation was measured from a height of 2.58m for input into estimation of evapotranspiration. The instrument used was a SRI 4 net radiometer. The manufacturers accuracy of calibration was given as ± 2.5%. The conversion factor for mV to Wm^{-2} was 22.05. Dry nitrogen gas was used for keeping the polythene hemispheres inflated. Holes in the hemispheres occurred a couple of times as a result of bird damage in one instance and lack of care in handling in the other. On these occasions replacement of the hemispheres was necessary. The gas cylinder was replaced as a matter of course at the start of measurement at each site.

It had been intended to measure solar radiation at each site as well but this was not initiated. However with this in mind, and in case of a failure of the net radiometer, a relationship was derived between the two variables, using data recorded in the vicinity of the Natural Resources Engineering Department, Lincoln College. A total of 77 observations were made and from this data a regression equation was derived. The data and regression line are presented in Fig E13. The result was very close to that obtained by Jamieson (1979) as can be seen below.

	Obs	Regression Equation	r	std dev
Jamieson(1979)	556	Rn = -23 + 0.598*Rs	0.983	27.0 Wm^{-2}
Kenny	77	Rn = -23.1 + 0.648*Rs	0.99	25.3 Wm^{-2}

The main difference, related to the number of observations was the absence of hot nor'west conditions and the resultant relatively high Rn values with low Rs in the latter experiment. Hence the slightly steeper slope and improved correlation.

Incorrect programming of the CR7 did lead to errors in recording of net radiation at the first field site. As solar radiation was not measured for this period an alternative method of estimation had to be developed. Daily solar radiation data was available from the Christchurch Weather Office at the Christchurch airport was regressed against the daytime net radiation data as recorded at the next three field sites. Although the field sites had different degrees of shelter individual site regressions showed little difference on a daily basis, hence the combining of the data from the three sites. The scatter diagram and regression line are presented in Fig. E14. The correlation coefficient of 0.978 suggests a good relationship between the two. This is despite differences in cloud cover that do occur between the airport and the Lincoln area.

Over the period of measurement airport solar radiation data was being used for estimation of net radiation at the Broadfields, Lincoln climate station. For the analysis it was considered more accurate and more consistent to use the field measured net radiation for input into evapotranspiration estimation from both the standard climate station data and the mast data. The one exception was when airport solar radiation data was used to estimate the missing net radiation data as described above.

Fig. E13 Hourly Rn versus hourly Rs at Lincoln

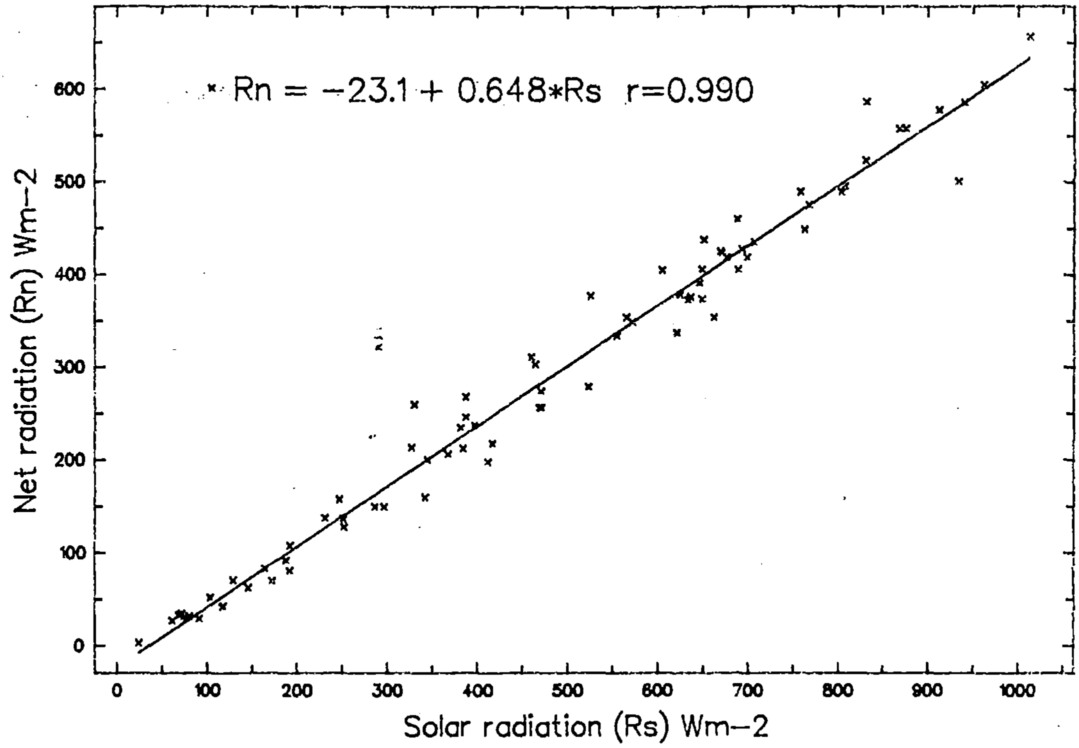


Fig. E14 Daytime Rn (Lincoln) versus daily Rs (ChCh Airport)