THE INFLUENCE OF WEATHER ON
DAIRY PRODUCTION

(An Analysis of the Relationship Between
Meteorological Variations and Fluctuations
in Dairy Production in the Manawatu
1939 - 1970)

A Thesis Presented in Partial Fulfilment
of the Requirements for the Degree of
Master of Arts in Geography at
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by

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1972

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PREFACE

In recognition of New Zealand's pastoral potential Sears (1961:65) wrote:

> "New Zealand has a tremendous climatic advantage for grassland agriculture, ...
>
> "This is very simply because of New Zealand's great climatic advantage for cheap high-productivity pastures, ...
>
> "New Zealand's continued, but not extreme, soil moisture, moderate temperatures, and adequate sunlight are all of great value to high-production pasture growth. ... The New Zealand climate is also very suitable for the continued outdoor husbandry of European breeds of sheep and cattle."

It would seem, however, that too few studies have been made of the relationship between climatic situations and primary production in New Zealand.

One might offer, in justification of an inquiry into the relationship between climate and dairy production, the importance of dairying to the New Zealand economy. The initial impetus to investigate this relationship was motivated by the author's interest in the farming scene and an appreciation of the importance of climate and weather in agricultural practices.

This thesis is essentially an exercise in applied climatology and makes no claim to be anything more. The study is aimed primarily at investigating the impact of measured physical parameters on an agricultural activity. It is hoped that some of the results might be valuable, even if only to stimulate further research into a situation which has been rather too blithely accepted.

ACKNOWLEDGEMENTS

In preparing this thesis I was fortunate to receive assistance from many people. In particular I wish to acknowledge:

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Chapter One

INTRODUCTION

Two main approaches are apparent in studies relating meteorological or climatological phenomena to aspects of New Zealand's agricultural production.

The first approach is based upon scientific experiments conducted in agricultural research institutions and generally reckons with the measured effects of specific (usually controlled) meteorological inputs upon either an animate or vegetative recipient, principally the latter. It is the purely physical relationships indicated which dominate interest in this area and the outcomes are most wisely respected as empirical results gained from an experimental situation, and often a measure of caution is necessary in any extrapolation of these results as guidelines to practical situations.

Similar relationships have been the objects of studies at less refined levels. Such investigation, usually being statistical in nature, has been conducted up to the national level. At times interest has centered on the effects of climatic extremes or accidents although in these cases it has usually been with some view to economic or social repercussions.

The second main approach to agroclimatological problems in New Zealand has been mainly concerned with the economic implications of weather variations and with management policies consequential to weather factors, or with expectation of predicted weather patterns. Some studies have attempted to link forms of agricultural production to weather factors in a statistical manner avoiding the problem of farm management practices. Such investigations have often considered the national pattern and several forms of primary production.

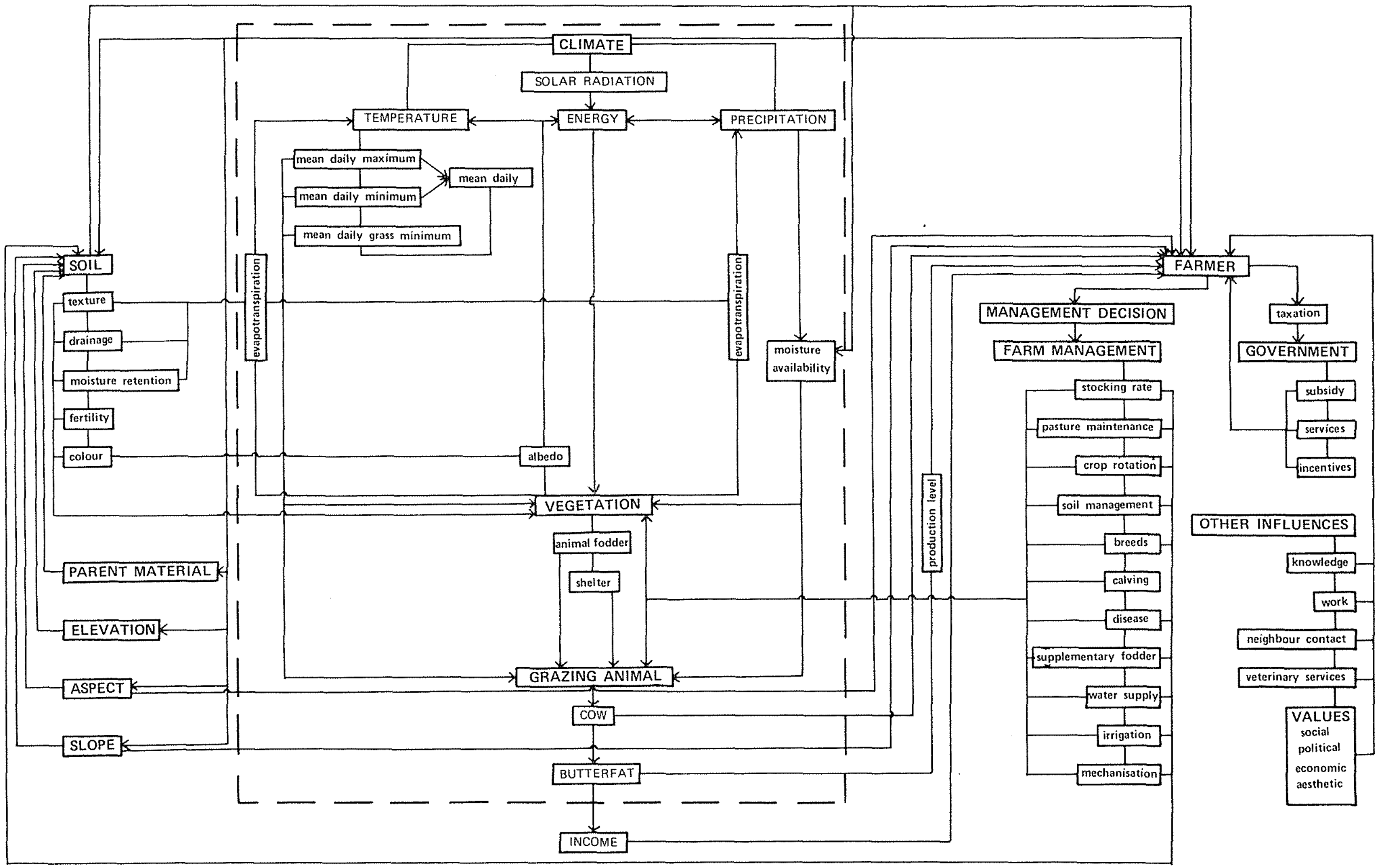
This study is concerned with meteorological effects upon the dairy industry at a meso-scale where the magnitude of the investigation is less than the national level while not reaching the intricacy of a controlled experimental set-up. It is intended to establish the importance of meteorological conditions with reference to dairy production in a specific spatial and temporal context. The area and time period chosen is outlined in Chapter Three.

Figure 1 shows a system relating physical factors to the dairy farming situation. Emphasis is placed upon the measured meteorological factors used in the analysis and their links with the dairying situation as these are the objects of the study. This thesis is concerned primarily with the influence of physical parameters essentially outside the control of the farmer.

The whole situation may be viewed as an energy cascade from the source of solar radiation through its utilisation by animal and plant life to produce a marketable product, in this case butterfat. Many of the minor relationships within the system are intricate and various feedback effects occur. These are not all depicted in the generalisation that is figure 1. The analysis made, however, does not treat the operations within the system as unknown (i.e. as a 'black-box' situation) but attempts to reason,

fig. 1

THE RELATIONSHIPS BETWEEN PHYSICAL FACTORS AND DAIRY PRODUCTION



A.R.T.

on the basis of past research and intuitive belief, the magnitude and direction of some of the connections between the operative variables.

While the 'controls' present in the form of human intervention were more difficult to account for and assess some effort was made to resolve these in the model which was developed.

Strong belief in the presence of a physical relationship between variations in atmospheric conditions and dairy production fluctuations stimulated the introduction of a working hypothesis proposing that such variations in dairy production are related in a cause-and-effect manner to meteorological variations. It has already been shown at a more general level (Maunder, 1965, 1968) that butterfat, as a measure of dairy production, is statistically related to climatological inputs. Although this indication does not prove any physical relationship to be present it materially substantiates considerable belief in one.

Any results derived and presented in this research may be of value in complementing those obtained by Maunder (1965, 1968), Curry (1958), and Walker (1964) in particular. The present work reviews only one form of agricultural production and in most senses the climate-dairy production relationship is approached at a more refined level with more parameters measured. It may further emphasise the commonly accepted importance of weather variability in New Zealand's pastoral industries, specifically dairying.

The thesis falls into five further chapters.

Firstly, the spatial dimensions of the areal unit involved are outlined. In order to create a working base for a physical study such as this the physiography and climate of the area are discussed.

Chapter Three defines the temporal limitations of the study. Also discussed is the nature of the variables selected for the analysis; their selection is justified and comments are made upon adjustments considered, modifications attempted, and calculations made involving these variables before they were incorporated into the analysis.

Chapter Four outlines the mode of analysis adopted. The model is developed and the conditions under which it is used elaborated upon.

Chapter Five contains the results of the statistical analysis. The specific hypotheses investigated are reported upon and the degree to which the model is appropriate becomes evident.

Chapter Six concludes upon the results. They are discussed in the light of other research and the expected outcomes of this analysis. The applicability of this type of analysis in the situation examined is discussed and prediction models established.

Appendix G is a readily accessible reference to some of the statistical parameters and notation used in the text.

Chapter Two

THE AREA STUDIED

Section A: The Area Defined

The introduction advanced a cause for conducting a study of the relationship between climatic conditions and butterfat yield within the area and period suggested. It is now necessary to define the areal extent of the region chosen and to justify this choice. An indication of the region's boundary and location with respect to the whole of the North Island is given in figure 2.

Climatic data are recorded at established meteorological stations under the jurisdiction of the New Zealand Meteorological Service. The use of such point data for an area involves spatial interpolation between these recordings which introduces probable error, the reduction of which is welcome. One means of reducing this error would be to select an area exhibiting, as far as is possible, homogeneity of relief. Ideally, therefore, the region should have been selected with exclusive respect to the physical environment.

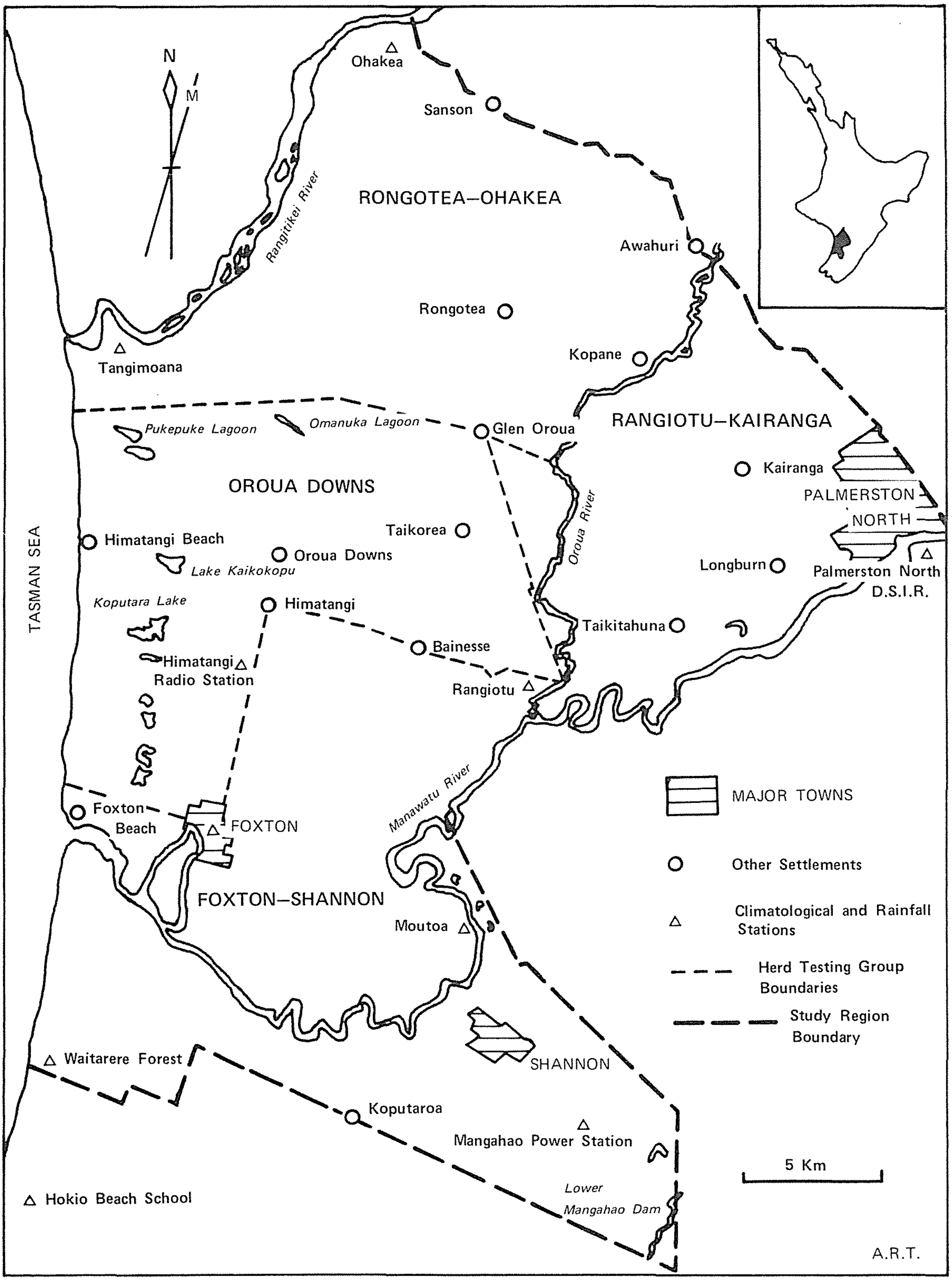
Placing an arbitrary boundary around an area of homogeneous relief seemed better orientated at this stage than the establishment of objectively defined limits, for this latter exercise would have been particularly laborious. In either case, however, severe problems would have been encountered in the subsequent availability of butterfat data. This information is recorded according to herd testing groups, the boundaries of which are administratively determined. Unless these groups were used as a basis for the study's areal distinction the location of farm records would have created considerable problems as interest was focused only on those farms for which butterfat records were available. Chosing the area on physical grounds alone would not have indicated which farm records were available for selection. For this reason the delimitation of the region was based upon the uncommon administrative boundaries of four adjacent herd testing groups of the Wellington-Hawkes Bay Herd Improvement Association. The common boundaries of these four groups are shown in figure 2. At the time this area was adopted for study (March 1971) the four groups comprised: Foxton - Shannon, Oroua Downs, Rangiotu - Kairanga, and Rongotea - Ohakea.

Although chosen according to the boundaries of these groups, a region of near physical homogeneity was achieved by the selection of groups covering what was subjectively considered a region of similar relief. The extent to which this demand was satisfied is illustrated in the following section.

Over the period studied any boundary changes associated with the above four groups have been mainly in the form of amalgamation with, and separation from, each other or groups lying adjacent but outside the area selected. The problems encountered with this phenomenon will be reviewed below when the process of sample selection is discussed (Chapter Three).

fig. 2

LOCATION



Section B: The Region's Physical Characteristics

The physiography of the region is given for two reasons. Firstly, it shows that certain elements of the physical environment are essentially homogeneous throughout the region, which satisfies the demands imposed by the necessity to interpolate for climatic conditions. Secondly, it aids in justifying the groupings made of soil types used to determine soil moisture availability to plants. A general description of the area's climatic regime is also presented.

Geology

A belt of sand, in the form of dunes and plains, extends up to 19 kilometers inland from the coastal boundary (as defined in figure 2). This sand country, representing the most recent stage in the geological development of the Manawatu coastal lowland, has formed over the last few thousand years.[1]

Cowie (1963) considers that the sand country of this area belongs to three phases.[2] A foredune enfronts the entire coast and is largely a result of human influence acting through vegetation removal and consequent accelerated erosion which has provided the necessary dune building material. This foredune, designated the Waitarere Phase, exists as the most recent evidence of sand country development.

Inland from the foredune is a belt of young dunes containing pumiceous material of Central North Island origin.

Cowie, terming this the Motuiti Phase, dates it at up to 1,000 years in age.[3]

The Foxton Phase lies behind the Motuiti and is dated by Cowie as originating between 2,000 and 4,000 years B.P. The demarcation between these two latter phases is evidenced in a series of small lakes alligned parallel to the coastline.

Plains of undifferentiated alluvium (sand, silt, and gravel) of Holocene age account for much of the remaining area. Small peat deposits occur as inliers within this alluvial material. The underlying Tertiary sediments of the region have undergone a structural downwarping resulting in a feature which is locally termed the Kairanga Trough. The gradual subsidence of the trough has invited the deposition of much alluvial debris which makes up a large part of the flood plains of the Manawatu and Oroua Rivers.

In the northernmost sector of the region a formation of Late Pleistocene age (the Rapanui Formation) extends southwards. It consists of local basal conglomerates, dune sands, volcanic sands, marine sands, and lignite bands. A very small portion of the same formation underlies that part of Palmerston North City incorporated in the region.

Adjacent to Palmerston North, and lying in juxtaposition to the above mentioned Rapanui Formation, are formations of Castlecliffian gravels, sands, and silts extending only slightly into the study area.

In the southeast the area extends into hill country with marine terraces comprising products laid down in the last glacial and the preceding interglacial (Hawera Series). The older terraces are more dissected than the younger terraces.

Relief

Seldom does the relief amplitude of the sand country exceed 45 metres. The unstable foredune, with its gentle windward and steeper leeward slope, rises to nine metres above sea level. The less regular dunes of the Motuiti Phase reach greater heights. The sand country of the Foxton Phase exhibits two major dune types. Between the Rangitikei and Manawatu Rivers hummocky, 'canoe-shaped' dunes with adjoining tails extend inland crossing the dome of the Himatangi Anticline in an apparently unaffected manner. South of the Manawatu River elongate-blowout dunes are common with their crescentic shape and wings trailing into the prevailing wind (Cowie et al., 1967). Sand plains dominate the areas between these dune wings.

The alluvial flood plain is low-lying and level, not reaching altitudes greater than 15.2 metres above sea level. This subdivision reaches its greatest extent through the Kairanga Trough.

Anticlinal structures, formed by the uplift of basement greywacke, have raised the surface of the northernmost sector of the region. Here the very southern ends of the Mt. Stewart-Halcombe and Feilding Anticlines combine to elevate the surface to just above 90 metres above sea level. The Himatangi Anticline, which fails to reach 60 metres in elevation, and the Levin Anticline in the south, are of low relief amplitude. An isolated point, Mt. Cook, to the east of the Himatangi Anticline but still within the Foxton Phase of the sand country, rises to 60 metres above sea level.

The southeastern corner of the region extends into the dissected Hawera Terraces which rise as high as 550 metres above sea level.

Soils

Soil moisture-holding properties are important aspects of the moisture availability parameter which was included as a climatic factor in the analytical model (Chapter Four). Hence it is apposite to discuss the soils of the area drawing particular attention to their moisture-holding characteristics. Figure 3 depicts the soils of the region.[4]

Several soil mapping units are employed in figure 3, the soils being referred to by these units in the following discussion. Included as soil units are the soil series, the soil complex, the soil association, and hill and steepland soils (Taylor and Pohlen, 1962).[5]

The soil series[6] groups soil types[7] with similar modal profiles, similar temperature and moisture regimes, and similar or the same parent materials. The soil complex[8] contains two or more soil types which cannot be differentiated on ordinary detailed soil maps.

fig. 3 LEGEND SOIL TYPES OF THE STUDY REGION

1 Unstabilised sand

Sand Country Soils

2 Hokio–Waitarere association
3 Himatangi–Foxton association
4 Pukepuke–Foxton association
5 Awahou–Foxton association
6 Carnarvon black–Foxton association
7 Carnarvon brown–Foxton association
8 Pukepuke–Omanuka association
9 Waitarere–Hokio association
10 Foxton–Himatangi association
11 Foxton–Omanuka association

River Flat and Terrace Soils

12 Rangitikei sand
13 Karapoti black sandy loam
14 Manawatu silt loam
15 Kairanga silt loam
16 Kairanga loam
17 Te Arakura fine sandy loam
18 Te Arakura silt loam
19 Parewanui silt loam
20 Opiki silt loam
21 Meanee–Farndon Complex

Peaty Soils

22 Makerua peaty loam
23 Makerua peaty silt loam
24 Rongotea peaty loam

Dissected Terrace Land and Rolling Hill Country Soils

yellow–grey loams

25 Ohakea silt loam
26 Tokomaru silt loam
27 Marton silt loam
28 Halcombe silt loam

yellow–brown loams

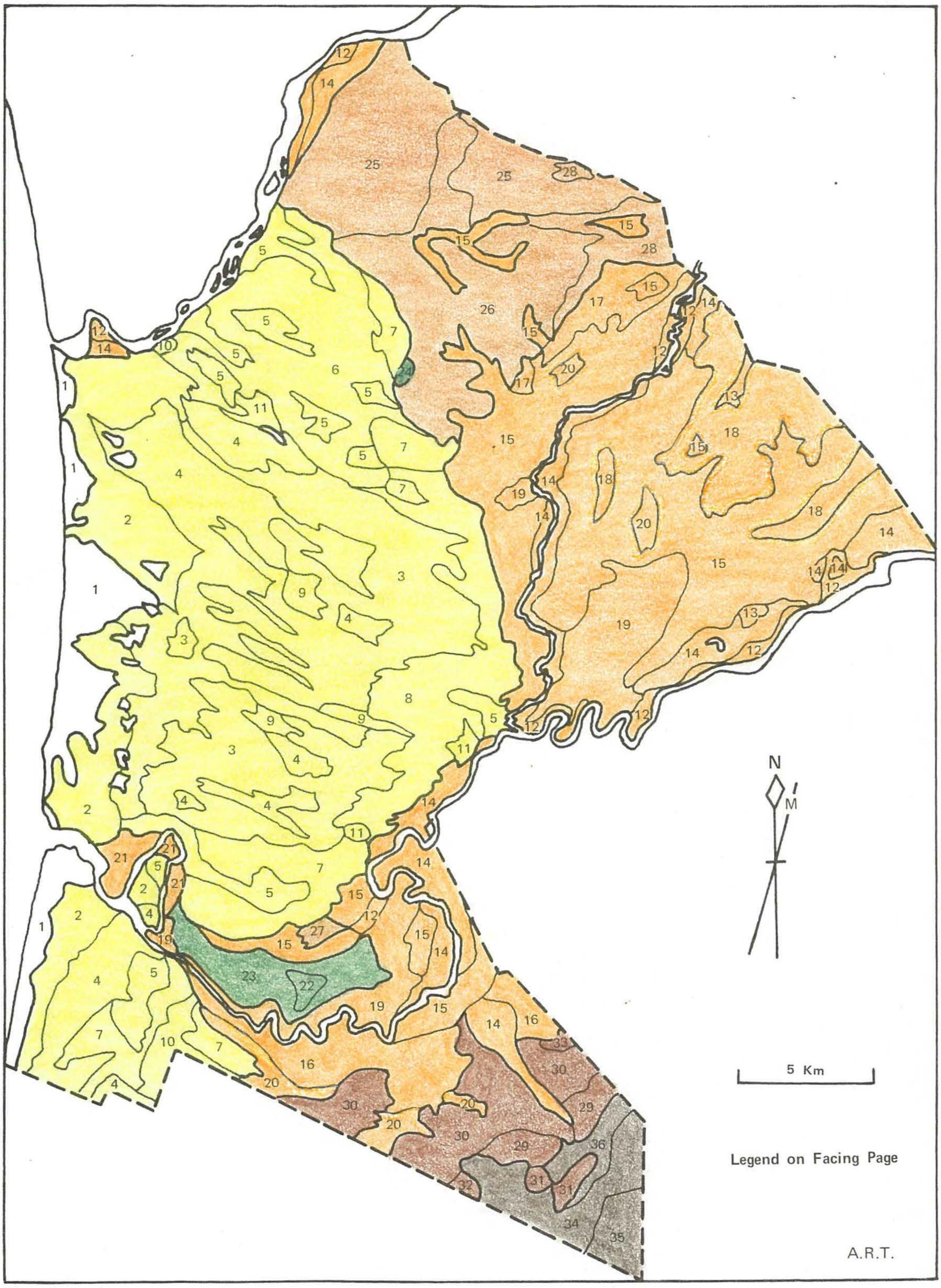
29 Dannevirke silt loam
30 Kiwitea silt loam
31 Matamau silt loam
32 Heretaunga silt loam
33 Kokotau silt loam

Steepland Soils

34 Ruahine steepland soil
35 Rimutaka steepland soil
36 Makara steepland soil

fig. 3

SOIL TYPES



Source:

Compiled from: Provisional Soil Map of Oroua County, H.S. Gibbs & C.S. Harris, Soil Bureau D.S.I.R., 1956.
Provisional Soil Map of Horowhenua County, H.S. Gibbs, C.S. Harris, & J.D. Cowie, Soil Bureau D.S.I.R., 1957.
Draft Soil Map of Kairanga County, J.D. Cowie
Soil Map of Manawatu County, Computation Sheet, D.S.I.R., Palmerston North.

Hill soils and steepland soils[9] are so grouped to facilitate mapping, avoiding overmultiplication of series names and to indicate existent relationships between hill soils and their rolling or steep slope components. Differences between these soils may result from slope variations, which are thus used to distinguish between these soils where parent materials and soil forming processes are similar. The soil association[10] consists of a pattern of associated soil units occurring in repetition in the landscape.

Most of the parent material of the sand country soils is greywacke from the Tararua-Ruahine Ranges, supplemented by sandstones and mudstones of Tertiary age from the range flanks and by material from the Central North Island and Egmont volcanoes. Sorting during river, beach, and wind transport has provided sediment containing little silt and clay for the coastal area.

A repeated pattern of sand dune, sand plain, and peaty swamp charactèrises the region's sand country landscape. Drainage variations, largely the product of this relief, have given rise to soil sequences following this landscape pattern, and the sand country soils have been mapped as associations according to this repetition. The associations referred to are those named by Cowie *et al*. (1967).[11]

The Himatangi-Foxton association includes soils developed on the drier inland areas of the less consolidated portions of the Motuiti Phase. These freely and excessively drained soils are widespread.

The Foxton-Himatangi association also forms part of this weakly consolidated portion of the Motuiti. Again, excessively drained soils are dominant. This association includes the same range of soils as the Himatangi-Foxton except that it boasts a larger proportion of dune sands.

The soils of the more consolidated part of the Foxton Phase of sand development exhibit similar drainage characteristics to the Himatangi-Foxton association soils and belong to the Awahou-Foxton association. These soils, however, do not dry off as severely.

Waitarere sand is the dominant member of the Waitarere-Hokio association with the Hokio soils being the minor partner. This excessively drained association includes part of the recently stabilised sand dunes and sand plains of the Waitarere Phase.

Present also on this sand phase is the allied Hokio-Waitarere association which contains the same soil types. Both these soils have low moisture retention capacities. The water table is generally low and drainage is excessive, with the exception of the Hokio sand and its peaty phase in which the water table is high for most of the year.

Drainage is imperfect or poor and the water table high in the soils of the Pukepuke-Foxton association, formed on the Motuiti Phase. Similar drainage conditions are found in the soils of the Pukepuke-Omanuka association. This association occupies relatively low-lying areas of the sand country which receive seepage from adjacent elevated land.

The Carnarvon black-Foxton and Carnarvon brown-Foxton associations are both related to the older Foxton Phase, the major difference between the associations being the topsoil colour. The drainage characteristics of both these are similar to the Pukepuke-Foxton association.

The Foxton-Omanuka association soils range from well-drained Foxton black sands on the dunes to poorly-drained Omanuka soils of the peat swamps (soils also common to the latter four soils above).

Relief is less marked on the river flats and terraces than on the sand country and for this reason the soil mapping (after Cowie *et al.*, 1967) was based upon series rather than upon associations. Soil series are groupings of types and phases exhibiting similar profiles although differing in horizon texture, stoniness, or slightly in natural drainage.

Those soils which are friable and have free internal drainage include the Rangitikei, Manawatu, and Karapoti series. The soil texture of the Rangitikei series is coarse (being sandy) and drainage excessive although complete summer drying is often prevented by seepage from higher ground.

Most of the Manawatu series soils are well-drained, but hold moisture during dry periods. The soils in this series are undifferentiated in figure 3.

The soils of the Karapoti series, marked in figure 3 as Karapoti black sandy loam, are freely draining and tend to dry out in summer.

Soils of the Parewanui series have been classed as 'rapidly accumulating' (Kear, 1965). This series includes the poorly-drained Parewanui silt loam only and is found on low-lying river flats where seepage from higher ground keeps the water table high during most of the year.

The soils of the Kairanga series exhibit drainage characteristics intermediate between the heavy textured Parewanui soils and the more lightly-textured recent river levee soils. Within this series the Kairanga silt loam is better draining than the Kairanga loam. The water table of these soils is usually kept high by seepage from surrounding higher land.

The internal drainage of the Te Arakura series is poor and a seasonally high water table is characteristic.

Soils of the Meanee-Farndon complex have developed where innundation by saline flood waters has increased the soil's soluble salt content and retarded pasture growth. Artificial drainage is essential for the establishment of pasture on such soils.

"In the swampy, very low-lying parts of the river flats where drainage is very poor and where there is little accumulation of alluvium, the remains of plants decompose very slowly and accumulate as peat" (Cowie, 1964:34). These soils include Opiki soils and Makerua peaty silt loam where the peat is not greater than 10 inches (25.4 centimetres) in thickness, and Makerua peaty loam where the depth of peat exceeds this measurement. Rongotea peaty loam is not extensive.

Cowie (1964) recognises two soil groups on the more dissected terrace lands and rolling hill country.

The yellow-grey earths which dry out during the summer months are classed as 'well-drained' even though during the winter their subsoils swell up and become impervious and waterlogged. Included in this group are the Ohakea, Tokomaru, Milson, and Marton soils. Milson silt loam represents a transition between the lighter Tokomaru silt loam and the heavier textured Marton silt loam. Halcombe silt loam is also a yellow-grey earth.

The yellow-brown loams include somewhat better drained soils and show a better developed soil structure than the yellow-grey earths. Soils included within this group are the Dannevirke, Kiwitea, Heretaunga, Matamau, and Kokotau soils.

The steepland soils include the Rimutaka, Ruahine, and Makara steepland soils. Although thin iron films may be present on the gentler slopes indicating poor drainage, these soils are generally well-drained. Their importance in this study is minimal.

Thus, most of the soils of the study region are generally well drained although seepage from higher ground may prevent their complete drying out during the summer months. The more low-lying areas contain some boggy peat inliers.

Climate

Watts (1947) examined a 1096 day period from July 1943 to June 1946 by studying 6 a.m. weather charts for Central New Zealand.[12] He demonstrated that during this period the weather of this area was controlled by anticyclones 19 per cent of the time. Cold fronts and their associated following conditions accounted for the weather experienced on 35 per cent of the days. Maunder (1971a) has further divided Watts' figures to show the weather in this area to be 'controlled' by northwesterly, westerly, or southwesterly winds with their often associated wet and cloudy conditions 41 per cent of the time. Northerly or easterly conditions were experienced about eight per cent of the time and colder easterly to southerly conditions about 16 to 17 per cent of the time.

Various weather conditions are associated with the passage of different pressure systems over the region.[13] Fine weather with light to moderate southwesterly breezes is usually characteristic of the eastern side of an anticyclone, but the airflow generally changes to northwesterly bringing cloud as the anticyclone progresses across the country.

Cold fronts have been shown (Watts, 1947) to have about a six per cent frequency in Central New Zealand. With the passage of the front the wind direction changes from northwesterly through to southerly. Cloudy conditions are the rule and occasional heavy rain may fall with colder air temperatures and further rain following in the wake of the front. Most of the rain in the

Manawatu region originates in these conditions although the importance of warm fronts in this respect is not insignificant.

Weather conditions associated with the cold front are dependent upon the direction of airflow behind the front (Maunder, 1971a). If this is northwesterly then the study region receives considerable cloud. Winds with a stronger westerly component bring moderate to heavy precipitation and westerly to southerly winds result in similar phenomena although the southern portion of the area receives less precipitation. The region is fairly well sheltered if the airflow is southwesterly to southerly, and southerly to southeasterly winds assure a rapid clearance following the passage of the frontal disturbance.

Mention of frontal weather can only be made in the presence of some discussion of wave-depressions, especially in the New Zealand context for:

> "It lies in the path of wave-depressions whose warm and cold fronts affect it, and it is particularly liable in its western parts to receive the deluges which occur when warm, moist, uprising northwesterly air associated with a front of the former nature comes into contact with the New Zealand mountain system" (Garnier, 1958:55).

Maunder (1971a) again recognises differing weather conditions reliant upon the extent of wave deformation of the cold front. The area receives low cloud cover when a wave develops on a cold front yet to reach New Zealand, but if the front has moved onto the country and a wave develops to the northwest this wave moves southeastward along the front bringing additional heavy rain for periods sometimes greater than 48 hours. Should the wave develop after the passage of the front and move south or southeastward then the front may return as a warm front with warm, humid north-westerly airflow to the Manawatu. This region, however, usually remains clear if the front has moved well to the east of New Zealand prior to wave deformation.

Strong northwesterly winds are experienced when wave-depressions occur south of New Zealand and there is a strong zonal flow over the country. Similar conditions prevail when a series of cold fronts - sometimes non-frontal troughs (Hill, 1959) - travel in disturbed southwesterly airflows. The concurrent wind shift is usually from northerly or northwesterly, through to southwesterly or southerly.

Less common meteorological phenomena experienced include tropical cyclones and tornadoes. The former only occasionally affect this western region as, for example, when hurricane force winds battered the area on 10 April 1968 during the infamous 'Wahine' storm. Locally-destructive tornadoes are likewise not common. Thunderstorms are most frequent in winter with an after-noon majority, usually being associated with cold fronts or north-westerly orographic conditions. Hail, too, is associated with cold fronts or instability showers in disturbed southwesterlies, especially in winter or spring. Snow is particularly rare and fog uncommon. Table I displays some further information on such meteorological aspects as mean days of thunder, mean days of hail, mean days of ground frost, and mean cloud amounts.

A number of rainfall and climatological stations operate, or have operated, in the region. The recordings made at these installations enable some quantitative generalisations to be

TABLE I: Thunder, Hail, Ground Frost, and Cloud Data for Various Manawatu Climatological Stations

Variable	Climat. Stn and Period	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Mean Days Thunder	Palm. Nth. D.S.I.R.* 1929-1965	0.4	0.4	0.1	0.1	0.2	0.4	0.1	0.2	0.0	0.2	0.2	0.3	2.6
	Ohakea 1940-1970	0.5	0.6	0.3	0.4	0.4	1.0	0.3	0.5	0.8	0.5	0.6	0.9	6.8
	Waitarere Forest 1959-1970	0.5	0.4	0.0	0.2	0.2	0.3	0.2	0.4	0.2	0.3	0.4	0.4	3.5
Mean Days Hail	Palm. Nth D.S.I.R. 1928-1965	0.1	0.0	0.0	0.0	0.0	0.2	0.1	0.2	0.2	0.2	0.2	0.0	1.2
	Ohakea 1940-1970	N.A.	N.A.	N.A.	0.3	0.5	1.1	0.7	0.8	0.7	0.7	0.5	0.2	5.5
	Waitarere Forest 1959-1970	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.2	0.2	0.1	0.1	0.0	1.2

Continued over ...

TABLE I: Thunder, Hail, Ground Frost, and Cloud Data for Various Manawatu Climatological Stations
- continued

Variable	Climat. Stn and Period	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Mean Days Ground Frost (Below 0.17°C)	Palm. Nth D.S.I.R. 1928-1970	0.2	0.4	1.0	1.9	7.2	11.2	14.0	11.4	6.7	3.3	1.1	0.1	59.5
	Ohakea 1940-1970	N.A.	N.A.	N.A.	0.2	1.4	5.2	7.0	4.7	1.5	0.5	0.1	0.0	20.6
	Waitarere Forest 1959-1970	0.2	0.1	0.2	3.7	7.7	11.7	14.0	12.2	5.3	3.3	1.2	0.2	59.8
Mean Cloud Amounts (Full Cover = 8.0)	Palm. Nth D.S.I.R. 1928-1965**	5.6	5.5	5.5	5.4	5.4	5.5	5.4	5.4	5.6	6.0	6.0	5.8	5.6
	Ohakea 1940-1965***	5.8	5.5	5.4	5.1	5.2	5.3	5.2	5.3	5.4	6.0	6.0	5.9	5.5
	Waitarere Forest 1959-1965**	4.7	4.4	5.2	4.1	4.9	4.5	4.8	4.4	4.9	5.3	5.3	4.8	4.8

* Palmerston North Department of Scientific and Industrial Research, hereafter Palm. Nth. D.S.I.R.
** Observation at 0900 hours *** Observation at 0930 hours N.A. = Not Available
Source: New Zealand Meteorological Service unpublished records.

made about the climate here.

In particular, a comprehensive picture of the region's rainfall distribution can be constructed. Table II embodies means of precipitation figures recorded at such stations while figure 4 illustrates their location. In general, annual precipitation (figure 4)[14] increases inland although its variability does not alter greatly. June and July are the wettest months and February and March the driest. Of the months for which data were analysed (August to March inclusive) October and December appear to receive the heaviest rainfall. The areas receiving lighter precipitation suffer more frequent drought. Initial scanning of the water balance and butterfat data (Chapter Three) over well-known drought periods[15] suggests that, in some cases, the drought was severe and markedly affected butterfat production. Garnier (1951), using Thornthwaite's 1948 equation, indicated the region as one to exhibit moisture deficiency. Gabites (1960) estimated the average daily rate of water loss by evaporation from pasture to range between 0.05 and 0.13 inches (1.27 and 3.30 millimetres) over the eight months from September to April inclusive.

Garnier (1958) reflects that 'Middle New Zealand', wherein the study area is located, is one of mean temperatures, mild winters and warm summers with a small mean annual temperature range relative to the rest of New Zealand. The area has a comparatively large mean diurnal temperature range which is greater inland near Palmerston North where there is less coastal maritime influence. This range is greatest in summer and least in winter.

TABLE II: Precipitation for Manawatu Rainfall Stations (inches)

Rainfall Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth D.S.I.R. 1928-1970	mean	3.29	2.84	2.64	3.15	3.37	3.96	3.33	3.44	2.80	3.41	3.09	3.86	39.18
	no. obs	42	42	42	43	43	43	43	43	43	43	43	43	42
	std dev.	1.76	1.65	1.66	1.29	1.74	2.16	1.34	1.56	1.42	1.66	1.49	2.06	4.88
Ohakea 1940-1970	mean	2.76	2.53	2.59	2.75	3.22	3.65	3.19	3.16	2.56	3.36	2.76	3.42	35.95
	no. obs	30	30	30	30	30	30	30	30	30	31	31	31	30
	std dev.	1.45	1.31	1.54	1.15	1.77	1.83	1.27	1.37	1.56	1.62	1.36	1.92	4.61
Waitarere Forest 1948-1970	mean	2.49	2.53	2.34	2.67	3.20	3.42	3.26	3.05	2.43	2.82	2.73	3.27	34.21
	no. obs	22	22	22	21	22	22	22	23	23	23	23	23	21
	std dev.	1.32	1.19	1.48	1.71	1.19	1.50	1.52	1.42	1.67	1.72	1.53	1.93	5.48
Foxton 1912-1970	mean	2.39	2.43	2.15	2.54	3.22	3.41	3.13	3.12	2.53	3.03	2.76	2.92	33.63
	no. obs	58	58	58	58	58	58	58	58	58	59	59	59	58
	std dev.	1.38	1.44	1.34	1.34	1.87	1.66	1.50	1.44	1.26	1.58	1.44	1.78	5.26
Hokio Beach School 1964-1970	mean	2.71	1.83	2.53	2.75	2.78	3.21	3.60	3.47	3.08	2.53	2.15	3.76	34.40
	no. obs	6	6	6	7	7	7	7	7	7	7	7	7	6
	std dev.	0.94	0.65	1.60	2.25	1.20	1.39	2.01	1.92	2.39	1.55	1.28	1.65	5.50
Tangimoana 1923-1949	mean	2.53	3.09	2.12	2.90	3.50	3.55	2.98	3.08	2.64	3.26	2.59	2.82	35.06
	no. obs	27	27	27	27	27	27	27	27	27	27	27	27	27
	std dev.	1.31	1.93	1.28	1.20	1.90	1.85	1.49	1.43	1.25	1.79	1.10	1.76	4.99

Continued over ...

TABLE II: Precipitation for Manawatu Rainfall Stations (inches) - continued

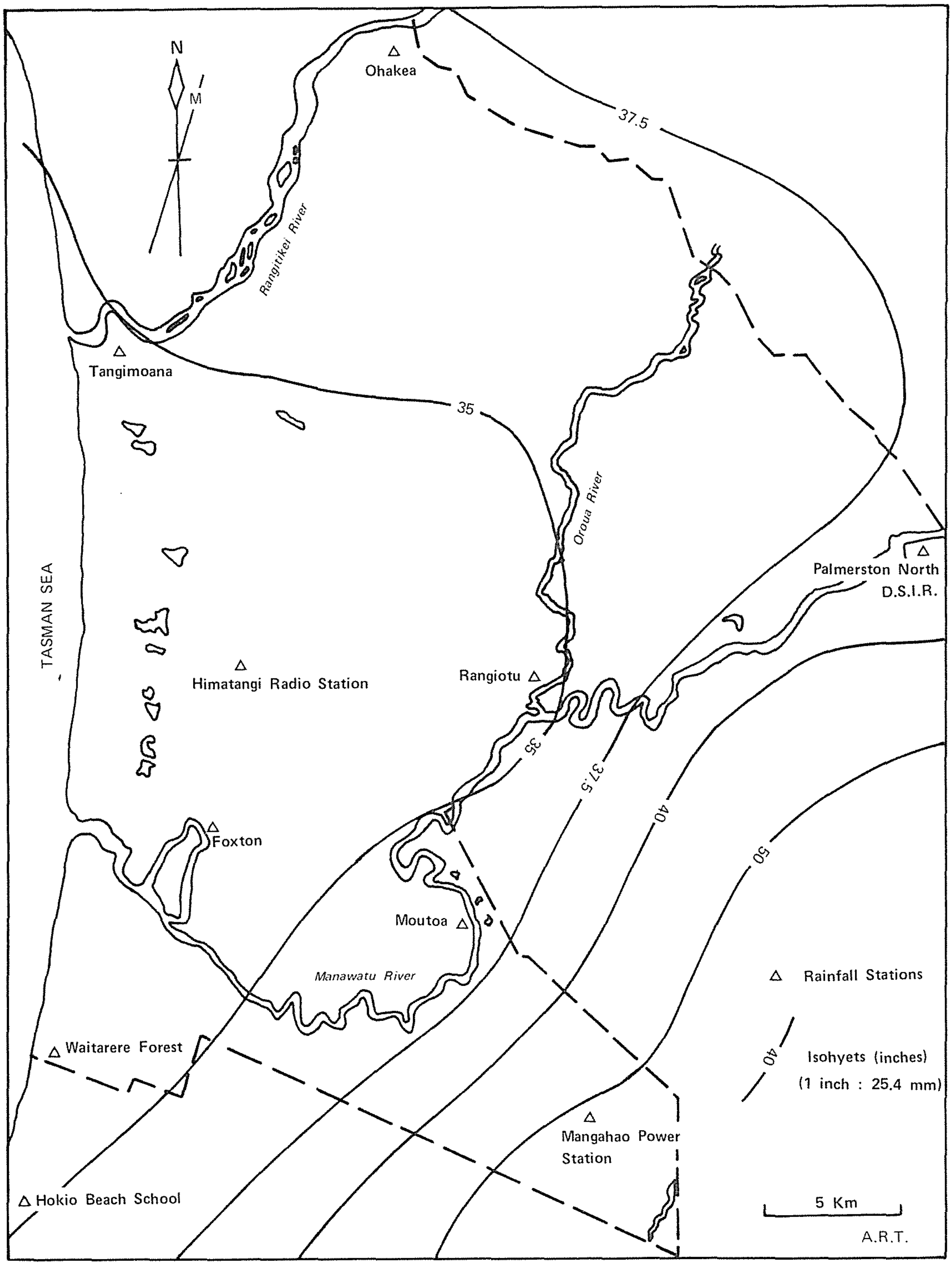
Rainfall Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Moutoa 1941-1970	mean	3.05	2.91	2.58	2.84	3.62	3.85	3.80	3.63	2.97	3.73	3.09	3.53	39.60
	no. obs	29	29	29	29	29	29	29	29	29	30	30	30	29
	std dev.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Mangahao Power Stn 1923-1970	mean	3.75	3.66	3.39	3.78	4.83	5.12	4.68	4.53	4.08	4.94	4.08	4.85	51.69
	no. obs	47	47	47	47	47	47	47	47	47	47	48	48	47
	std dev.	1.86	1.84	1.71	1.69	2.31	2.34	2.08	1.79	1.95	2.29	1.93	2.43	7.52
Himatangi Radio Stn 1962-1970	mean	2.42	1.77	2.56	3.24	3.05	3.49	3.57	3.40	2.78	2.68	2.75	4.16	35.82
	no. obs	8	9	9	9	9	9	9	9	9	9	9	9	8
	std dev.	0.73	0.63	1.74	2.31	1.04	1.62	1.90	1.42	1.75	1.89	1.39	1.93	6.58
Rangiotu 1951-1970	mean	2.87	2.39	2.38	2.90	3.34	3.37	3.38	3.23	2.58	3.12	3.33	3.76	36.65
	no.obs	19	19	20	20	20	20	20	20	20	20	20	20	19
	std dev.	1.40	1.04	1.42	1.44	1.45	1.80	1.35	1.94	1.55	1.86	1.70	2.03	6.03

no. obs = number of years for which observations were complete
std dev. = standard deviation
N.A. = not available

Source: New Zealand Meteorological Service unpublished records. (At the time of data collection these records had not been fully converted to metric units.)

fig. 4

ANNUAL RAINFALL DISTRIBUTION



Source: New Zealand Meteorological Service, unpublished map.

The mean monthly temperatures[16] portrayed in Table III indicate similar atmospheric temperature conditions over the area with the warmest month of January or February ranging between 17.4° and 17.7°C, and the coolest of July between 7.6° and 8.3°C. The coolest month of the period analysed was consistently August wherein the mean ranged from 8.9° to 9.3°C.

A similar pattern exists with mean daily maximum temperatures (Table IV and note 16), July registering the lowest and February the highest. Again, July displays the lowest mean daily minimum temperature and January or February the highest (Table V and note 16). Of the months analysed, August registered the lowest mean daily minimum temperature as well as the lowest mean daily grass minimum temperature (Table VI).

In terms of hours of bright sunshine (Table VII)[17] the more inland climatological station at the Palmerston North D.S.I.R. was apparently more affected by cloud cover (Table I), probably due to the proximity of the North Island's main axial range in association with winds from westerly directions. The windy nature of the region keeps the atmosphere constantly turbulent resulting in a fairly high receipt of bright sunshine, especially near the coast. In all cases, June is the month recording the lowest value and January the highest, a direct reflection of the winter and summer solstices respectively.

Relative humidity, as recorded at 0900 hours (Table VII) - consequently a parameter of restricted value - reaches a high in the months of June and July at all stations. November, December, and January exhibit the lowest relative humidity values.

TABLE III: Mean Daily Temperature for Manawatu Climatological Stations (°C)

Climat. Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth. D.S.I.R. 1928-1970	mean	17.2	17.4	16.2	13.7	10.8	8.5	7.8	8.9	10.6	12.4	14.1	16.1	12.8
	no. obs	41	41	41	41	41	41	41	41	41	41	41	41	41
	std dev.	1.3	1.4	1.2	1.2	1.1	0.9	0.9	0.8	0.8	1.0	0.9	1.2	0.5
Ohakea 1940-1970	mean	17.5	17.7	16.6	13.9	11.2	9.1	8.3	9.3	11.0	12.7	14.3	16.2	13.2
	no. obs	31	31	31	31	31	31	31	31	31	31	31	31	31
	std dev.	1.1	1.1	1.1	1.1	1.0	0.8	0.8	0.7	0.5	1.0	0.8	1.1	0.4
Waitarere Forest 1962-1970	mean	17.5	17.0	16.5	13.4	10.6	8.4	7.6	9.0	10.6	12.4	13.9	16.1	12.8
	no. obs	9	9	9	9	9	9	9	9	9	9	9	9	9
	std dev.	1.2	1.0	1.4	1.0	1.2	1.2	1.2	1.1	0.8	1.0	0.7	0.9	0.4

no. obs = number of years for which observations were complete
std dev. = standard deviation

Source: New Zealand Meteorological Service unpublished records.

TABLE IV: Mean Daily Maximum Temperature for Manawatu Climatological Stations (°C)

Climat. Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth D.S.I.R. 1930-1970	mean	21.8	22.2	20.8	18.1	14.9	12.5	11.8	13.1	14.7	16.6	18.4	20.6	17.1
	no. obs	41	41	41	41	41	41	41	41	40	41	41	41	40
	std dev.	1.6	1.5	1.4	1.1	1.2	0.9	0.8	0.8	0.8	1.2	1.1	1.6	0.6
Ohakea 1940-1970	mean	22.1	22.4	21.2	18.2	15.3	12.9	12.4	13.3	15.1	16.8	18.6	20.6	17.4
	no. obs	31	31	31	31	31	31	31	31	31	31	31	31	31
	std dev.	1.3	1.3	1.3	1.1	1.2	0.7	0.6	0.8	0.7	1.1	0.9	1.3	0.5
Waitarere Forest 1962-1970	mean	21.9	22.2	21.2	18.2	15.4	13.0	12.3	13.4	14.8	16.5	18.2	20.6	17.3
	no. obs	9	9	9	9	9	9	9	9	9	9	9	9	9
	std dev.	1.7	1.0	1.4	0.7	0.9	0.7	0.7	0.8	1.0	1.0	1.2	1.0	0.5

no. obs = number of years for which observations were complete
std dev. = standard deviation

Source: New Zealand Meteorological Service unpublished records.

TABLE V: Mean Daily Minimum Temperature for Manawatu Climatological Stations (°C)

Climat. Stn and Period	Parameter	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Palm. Nth. D.S.I.R. 1930-1970	mean	12.6	12.7	11.5	9.3	6.6	4.5	3.8	4.8	6.4	8.1	9.7	11.6	8.4
	no. obs	41	40	41	41	41	41	41	41	41	41	41	41	40
	std dev.	1.2	1.5	1.2	1.5	1.2	1.1	1.2	0.9	0.9	1.0	1.0	1.0	0.5
Ohakea 1940-1970	mean	12.9	13.0	11.9	9.6	7.1	5.2	4.3	5.2	6.9	8.5	10.0	11.8	8.9
	no. obs	31	31	31	31	31	31	31	31	31	31	31	31	31
	std dev.	1.0	1.1	1.0	1.2	1.0	1.1	1.1	0.9	0.6	1.0	0.8	0.9	0.4
Waitarere Forest 1962-1970	mean	13.1	11.8	11.7	8.6	5.8	3.9	2.9	4.6	6.3	8.2	9.7	11.7	8.2
	no. obs	9	9	9	9	9	9	9	9	9	9	9	9	9
	std dev.	0.8	1.4	0.8	1.5	1.7	1.7	1.8	1.4	1.2	1.3	0.7	1.1	0.4

no. obs = number of years for which observations were complete
std dev. = standard deviation

Source: New Zealand Meteorological Service unpublished records.

TABLE VI: Mean Daily Grass Minimum Temperature for Manawatu Climatological Stations (°C)

Climat. Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth D.S.I.R. 1930-1970	mean	9.0	9.1	7.8	5.6	2.9	0.9	0.2	1.1	2.8	4.8	6.4	8.1	4.9
	no. obs	40	39	40	39	41	41	41	41	41	41	41	41	39
	std dev.	1.6	1.9	1.4	2.0	1.5	1.4	1.4	1.5	1.3	1.6	1.1	1.6	0.9
Ohakea 1947-1970	mean	11.1	11.4	10.3	7.6	5.2	3.3	2.2	3.0	4.7	6.6	8.2	10.4	6.9
	no. obs	23	23	23	23	23	23	23	23	23	23	24	24	23
	std dev.	1.3	1.4	1.2	1.5	1.3	1.1	1.2	0.9	0.8	1.1	0.9	1.0	0.5
Waitarere Forest 1962-1970	mean	11.1	9.7	9.7	6.2	3.8	1.6	0.6	1.9	3.7	6.0	7.4	9.9	5.9
	no. obs	9	9	9	9	9	9	9	9	9	9	9	9	9
	std dev.	0.8	1.8	0.8	1.2	1.8	1.7	1.9	1.6	1.4	1.7	1.0	1.3	0.4

no. obs = number of years for which observations were complete
std dev. = standard deviation

Source: New Zealand Meteorological Service unpublished records.

TABLE VII: Hours of Bright Sunshine for Manawatu Climatological or Sunshine Stations

Climat. or Sunshine Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth D.S.I.R. 1935-1970	mean	210.1	185.4	170.7	138.1	116.3	93.8	104.6	125.8	139.1	158.2	174.6	193.4	1811.0
	no. obs	36	36	36	36	36	36	36	36	36	36	36	36	36
	std dev.	33.8	30.1	29.2	22.2	21.2	15.7	22.6	23.1	26.8	30.0	31.5	28.8	107.7
Ohakea 1954-1970	mean	242.4	207.4	186.0	162.4	130.3	109.8	113.4	136.8	163.7	189.3	206.3	221.5	2069.3
	no. obs	17	17	17	17	17	17	17	17	17	17	17	17	17
	std dev.	35.2	31.8	27.6	20.5	23.0	13.5	19.2	19.9	34.1	29.1	29.3	33.3	68.2
Foxton 1954-1970	mean	237.6	203.8	182.8	159.4	134.8	110.8	116.0	143.6	160.9	185.3	199.8	215.4	2050.2
	no. obs	17	17	17	17	17	17	17	17	17	17	17	17	16
	std dev.	40.0	31.3	24.3	19.6	19.5	15.2	21.2	24.0	33.3	24.6	25.4	36.1	82.9

no. obs = number of years for which observations were complete
std dev. = standard deviation

Source: New Zealand Meteorological Service unpublished records.

TABLE VIII: Mean Daily Relative Humidity for Manawatu Climatological Stations (per cent)

Climat. Stn and Period	Month												Annual
	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth D.S.I.R. 1928-1970*	73	74	77	81	83	85	85	81	78	75	73	73	78
Ohakea 1940-1970*	70	72	76	80	83	84	85	82	78	84	70	70	77
Waitarere Forest 1959-1970*	76	77	80	84	88	88	89	87	82	79	75	74	82

* Readings taken at 0900 hours

Source: New Zealand Meteorological Service unpublished records.

Cook Strait acts as a wind funnel such that the dominant wind directed into the Manawatu is northwesterly or westerly. Maunder (1971b) has shown that day time sea breezes disturb the broad pattern of wind flow, especially during the summer months. The same writer has attributed the higher mean wind speed of the year's last three months to the southward movement of the pressure system increasing the north-south pressure gradient. The lowest speeds are accounted for by the general southerly position of the anticyclones in February and March. Wind runs are available for the Palmerston North D.S.I.R. station (Table IX), but are not considered very revealing as variations in wind speed are not indicated.[18] The figures presented for days of gale are interesting in that the seaward stations experienced a much higher frequency of gale-force winds, but the subjective nature of recording this factor and the shorter time period for which observations have been made at the more coastal stations make these figures somewhat suspect.

Section C: Farm Location and Climatic Interpolation

The location of the sample farms (discussed in the following chapter) is portrayed in figure 5. The random selection of farms indicated here ensured an unbiased sample. A visual inspection of farm location maps (page 63) indicated (at least superficially) that the sample reflected the overall density of possible sampling points as well.

Few possible sampling points were available in the area

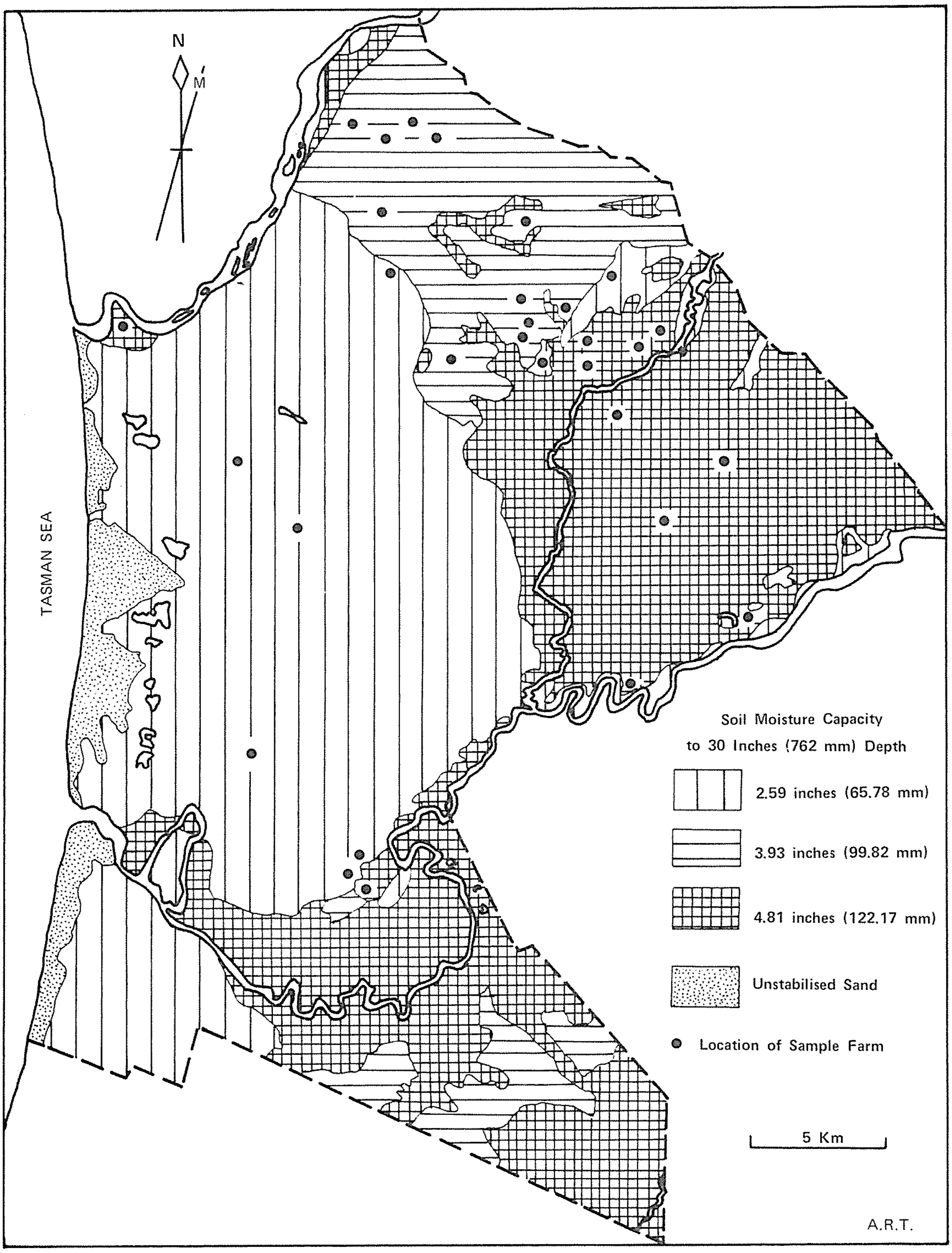
TABLE IX: Wind Data for Manawatu Climatological Stations

Climat. Stn and Period	Parameter	Month												Annual
		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
Palm. Nth D.S.I.R. 1928-1960	mean wind runs (Km)	260.7	238.1	225.3	206.0	201.2	188.3	188.3	209.2	239.7	246.2	254.2	244.6	225.3
Palm. Nth D.S.I.R. 1961-1965*	mean wind runs (Km)	280.0	257.4	251.0	220.4	209.2	230.1	217.2	206.0	262.3	254.2	323.4	257.4	233.3
Palm. Nth D.S.I.R. 1929-1965	days gale	0.2	0.0	0.0	0.1	0.0	0.1	0.0	0.2	0.2	0.1	0.0	0.1	1.0
Ohakea 1940-1965	days gale	0.3	0.1	0.1	0.2	0.1	0.2	0.1	0.4	0.3	0.2	1.0	0.6	3.6
Waitarere Forest 1959-1965	days gale	1.0	0.3	0.0	0.3	0.7	1.6	0.0	0.3	0.1	0.6	1.6	0.6	6.1

* Pine trees felled nearby, April 1961

Source: New Zealand Meteorological Service unpublished records.

fig. 5 SOIL MOISTURE CAPACITY AND SAMPLE LOCATION



of elevated land located in the southeast corner of the study region, and indeed the resultant sample contained no points within this area. The validity of climatic interpolation previously referred to is shown. That is, the actual area with which the analysis is concerned is one of reasonably homogeneous relief.

Climatic conditions differ across the region, especially insofar as the water balance is concerned. Accordingly, adjustment was made in this parameter, but in no others (Chapter Three).

Notes:

1 Heerdegen (1972) gives an account of this Recent geologic development.

2 The classification of these three phases of dune building into the Foxton, Motuiti, and Waitarere Phases, from oldest to youngest respectively, is that of Cowie (1963) who has adopted local names for their differentiation.

3 The Motuiti Phase may have been triggered by a large Central North Island volcanic eruption about 1,700 years B.P. (Heerdegen, 1972).

4 Difficulties were encountered in composing figure 2 because published maps of the soils of the whole area were not available. The task was completed using both published maps and draft maps held by the Soils Division of the Palmerston North D.S.I.R.

5 Taylor and Pohlen (1962) discuss these units of soil mapping as a guide to the field study of New Zealand soils.

6 The soil series is named after a locality in which it is found to be well developed, or where it was first recognised.

7

> "The soil type is the basic unit of soil mapping. In the field an endeavour is made to subdivide the soil covering an area into a number of homogeneous or near-homogeneous segments so that these may be classified and predictions made as to their behaviour under various conditions. Each of these segments is a soil type.
>
> "Each soil type is a unique combination of internal characters and site features which are assessed in the field and in the laboratory by chemical, physical, biological, and mineralogical studies of the soil horizons including the parent material, and by examination of the form and other characteristics of the site" (Taylor and Pohlen, 1962:135).

8 The soil complex does not form a separate category in soil classification and is thus alloted a composite name based upon its principal constituents.

9 Hill soils and steepland soils are named according to localities in which they are present.

10 Soil associations are named according to their composition with the most important soils appearing in the association names with respect to their relative importance. Cowie *et al*. (1967) give as an example the Carnavon black-Foxton association with Carnavon black sandy loam as the dominant member and the other main members being Carnavon black loamy sand, Omanuka peaty loam, Omanuka peaty loam (shallow phase), and Foxton black sand. Awahou sandy loam and Awahou loamy sand are minor members. The principal components occupy between 10 and 70 per cent of the area of the association, and the minor members less than 10 per cent.

11 Cowie *et al*. (1967) give an account of these soils by type as well as by association, bringing out their structural and mineralogical properties. Cowie also discusses, in general, the types of vegetation supported by the soils, their potential, and the farming systems practised on them.

12 The area referred to by Watts (1947) extended south of a line between New Plymouth and Napier to a line between Farewell Spit and Cape Campbell.

13 Garnier (1958) provides several useful case studies in map form of the passage of different characteristic pressure systems over New Zealand.

14 Other sources of precipitation maps which cover this area are: Seelye (1945), Watts (1947), Garnier (1958), and Maunder (1966, 1971b).

15 For example, the dairying seasons: 1954/55,
1959/60,
and 1969/70.

16 The areal extent of the region is such that it contains few climatological stations which have consistently recorded temperature data. For this reason no attempt was made to construct isothermal maps of the area and the reader is referred to Watts (1947:127), Garnier (1958:20, 22, & 24), and Maunder (1971b:249, 252-253, & 255) for more general national patterns of temperature recordings.

17 The same comments as in note 16 above apply. Cartographical representation of the national situation may be located in De Lisle (1966:1002-1003) and Maunder (1971b:248).

18 An interesting aspect is the general increase in miles of wind run recorded after the felling of trees, growing in close proximity to the station, in 1961.

Chapter Three

THE DATA

Butterfat levels are one indication of dairy production and were chosen as a measure of such for this analysis. The meteorological data selected incorporate variates of six weather input factors. In addition one time variable was included.

A. The Butterfat Variable

Justification of the use of butterfat test recordings as measures of dairy production is founded on the grounds of data availability. Records of milk production on a quantity basis have not been preserved for long periods in the region. Enquiries into the availability of this type of record revealed that smaller dairy companies, upon amalgamation with larger companies, had often destroyed existing records. Even if these records had been available for the period required in many instances they would have indicated production per farm and not production per cow. To establish the actual number of cows in milk on each particular farm producing these quantities was not feasible. Information of this nature is seldom released by authorities wishing to protect the rights of individual farmers. The mode of analysis employed (Chapter Four) demanded data of a productivity form and butterfat levels satisfied this.

Any data collected on a per farm basis would have involved difficulties where major changes in stock population and farm management had been undertaken. Butterfat levels, as a measure, obviate the necessity to account for both these facets.

Changes in dairy cow breeds are an important factor affecting levels of butterfat production. In recent years such changes have often been from the traditional Jersey breed into Freisian where farms have gone over to city milk supply operations. It is argued that those farms supplying town milk treatment plants are concerned more with greater milk quantity than with high butterfat levels because the economic return is based upon quantity (hence the introduction of the high quantity producing cow, the Freisian, to replace the high butterfat producing Jersey which generally gives lower quantities of milk). Expectations were that town milk suppliers had less reason to test their herds for butterfat production and so the available testings reflected those farmers still supplying co-operative dairy companies, and those that were, therefore, less likely to have changed to heavier breeds.

Further justification of the use of butterfat as a variable stemmed from it being the base of many forms of manufactured dairy products. As alluded to above, it is also the most consistent basis of economic payout to the supplier of dairy companies not directly concerned with the supply of city milk.

Butterfat percentages, on a monthly basis, have been recorded by the Wellington-Hawkes Bay Herd Improvement Association. These results are available for each individual farm testing its cows through the Association as a measure of productivity and as an aid in culling animals. Farmers may obtain their testing results for either of these reasons.

After locating these farms[1] it was possible to sample the total herd testing population within the defined region and time period. The overwhelming number of records of herd testings available made it necessary to obtain a sample of recordings with which to work. In search of this sample all farmers thought to be testing in this region on a particular farm at any time during the 31 dairying seasons from 1939-1940 to 1969-1970 were sampled at random to obtain a sample of 30.[2] Overall, a total of 186 butterfat observations, as averaged from these 30 farms, became available.[3] Not all herds, however, were tested on the same day of the month, and before this mean value could be obtained it was necessary to adjust most butterfat recordings to the 15th day of each month. In the case of February the adjustment was made to the 14th day.

The sample selected was thus random in structure, satisfying a demand imposed by the later discussed methods of statistical analysis. The mean butterfat percentage, as calculated from these 30 farms, is an estimate of the mean for the total population of farms carrying out herd testing in the region, and trends associated with these 30 farms will reflect those in the total population.

B. The Meteorological Variables

The meteorological data used in the analysis were taken from recordings made at four New Zealand Meteorological Service climatological stations located within, or adjacent to, the boundary of the study area. These stations are indicated in Table X.

TABLE X: Meteorological Stations From Which Data Used in the Analyses Were Taken

Station	New Zealand Meteorological Service Code Number	Location			
Ohakea	E05231	40	12S	175	32E
Palmerston North D.S.I.R.	E05363	40	23S	175	35E
Waitarere Forest	E05521	40	33S	175	12E
Foxton*	E05421	40	28S	175	17E

* Foxton data were used only for sunshine hours, a parameter not measured at Waitarere Forest.

Appendix A contains information on site changes of the Ohakea and Palmerston North D.S.I.R. climatological stations.

The meteorological variables included in the analysis were, for each month:

(1) water balance;
(2) mean daily solar radiation;
(3) mean daily temperature;
(4) mean daily maximum temperature;
(5) mean daily minimum temperature;
and (6) mean daily grass minimum temperature.

The inclusion of these meteorological factors in the analysis found justification in a considerable volume of literature on climate-plant growth relationships, or climate-animal physiology studies, most of which have been pursued at various agricultural research centres in New Zealand, Australia, the United Kingdom and the United States of America. Various agroclimatological studies, not directly concerned with first order effects, but more with climatic effects upon commodity production, have also indicated the importance of certain variables.

Water Balance

A principle of limiting factors is stated by Buckman and Brady (1969:19) as follows. "The level of crop production can be no greater than that allowed by the most limiting of the essential plant growth factors." Soil moisture availability is considered an essential, perhaps the most limiting, factor in the growth of dairying pasture and a measure of this factor was sought as a parameter affecting the variation of butterfat yield.

It becomes necessary at this stage to define three terms. Field capacity is the stage at which all water subject to gravitational movement has drained out. Wilting point is the level reached when the uptake of water from the soil by a plant no longer maintains pace with its requirement. Between these two we have plant-available water.

Moisture has been shown by many scientists[4] to be of vital importance to plant growth. On the purely climatological side,[5] the concept of potential evapotranspiration was developed with opposing views arising as to the actual water movement rates involved in this process. Two schools of thought appear to be present. One suggests a constant amount of plant-available water over the range from field capacity to wilting point while the other denies this, generally claiming that an exponential relationship exists. On the side of more practical agriculture[6] the concept of drought is accepted and its effects upon various forms of agricultural activity assessed.

Regardless of the approach to the moisture factor general agreement is present that several meteorological and non-meteorological variables are highly interdependent in affecting moisture supply to plants. There is also mutual consent over the importance of moisture supply to plant growth. Some of the research presented on irrigation experiments serves further to highlight this.[7]

It was considered essential to include some moisture parameter in the analysis. Maunder (1965, 1968) has established the importance of rainfall variations in Australasian agricultural production. Given the importance of moisture to plant growth and Maunder's success in this sphere, it was reasonable to assume that some refinement of the hydrological input, over and above rainfall, in the form of soil moisture availability would be a valid variable for inclusion in the model.

In the selection of a moisture parameter consideration was granted to the presence of differing soil conditions (Chapter Two). Intuitively, this decision gave the model greater validity than would have been gained from the inclusion of a simple precipitation variable which excluded the effects of varying soil conditions.

The most important soil characteristic influencing available water capacity (AWC) may be texture. Salter and Williams (1965b), working at the National Vegetable Research Station, Wellesbourne, Warwick, determined the AWC of 27 soils and moisture characteristics (i.e. the rates at which this water was released etc.) of 20 of these soils by methods shown previously (1965a) to be most representative of field conditions. They claim (1965b:313) that "despite the variations found in the AWC of soils in the same textural class, the data nevertheless indicate that texture is the basic factor determining the moisture characteristics of soils." Although their study was conducted mainly on arable soils, after cultivation and prior to the sowing of crops, the results obtained appear to be consistent with other research. Gradwell (1968, 1971), working on Waikato soils and North Auckland soils, found this soil texture-AWC correlation not inconsistent with his results. He has quoted Petersen *et al.* (1968) who established a similar relationship in Pennsylvania. The results obtained in the above mentioned research appear to be well supported.[8]

Notwithstanding the importance of texture, Salter and Williams (1965b:311) write that "many factors other than texture influence the capacity of soils to retain available-water (Jamison, 1956) for soils within the same textural class can vary widely in AWC ...".[9] Soil structure, *slight* differences in textural composition (sic), and organic matter content are offered as influential factors. Buckman and Brady (1969) point out that organic matter has a favourable influence on soil structure and, consequently, porosity. They further suggest that deeper soils have a greater AWC whereas hard pans restrict the availability of water and reduce root penetration. Sandy layers also effectively reduce a soil's AWC.

Salt concentration is considered to be insignificant in most humid-region soils. Osmotic pressure effects in the soil solution will tend to decrease the range of available moisture.

Gradwell (1968)[10] referred to the possible importance of parent material, management, and biological regimes, and later (1971) added dry bulk density and the presence of large, easily drained pores, as important factors in explaining AWC.

Water balance was not directly available as a meteorological variable and it required computation involving knowledge of the specific soil for which it was calculated. The procedure for obtaining the water balance figures is outlined below.

The calculation of a soil's AWC required a decision as to what depth of soil was to be considered. To this end some indication of the rooting depths of common pasture plants in different soils was sought. The late Mr D.B. Edmond (pers. comm.), plant ecologist with the Palmerston North D.S.I.R. Grasslands Division, believed such an estimation to be impractical because of the great variations in rooting depths observed and the lack of information on the ability of various plant species to draw moisture from depths greater than their rooting systems. Mr J.D. Cowie (pers. comm.), soil scientist with the Palmerston

North D.S.I.R., indicated that an arbitrary rooting depth of 30 inches (0.762 metres) would be the most satisfactory estimation one could make. Mr M.W. Gradwell (pers. comm.), soil scientist with the New Zealand D.S.I.R. Soil Bureau at Lower Hutt, agreed that 30 inches seemed a reasonable operating depth for soils with a compact B horizon, although he suggested partial extraction was possible at greater depths tapering away to zero a foot or two below this depth. He also maintained that soils with loose, friable B horizons could offer extraction to a greater depth as they show a deeper extension of profuse rooting. Gradwell suggested that it might be valuable to attempt extrapolating to around 50 inches (1.270 metres). He also recalled some experiments performed by W.A. Jaques in which grass roots cut at two feet (0.610 metres) in depth reduced growth whereas cutting at three feet (0.914 metres) did not.

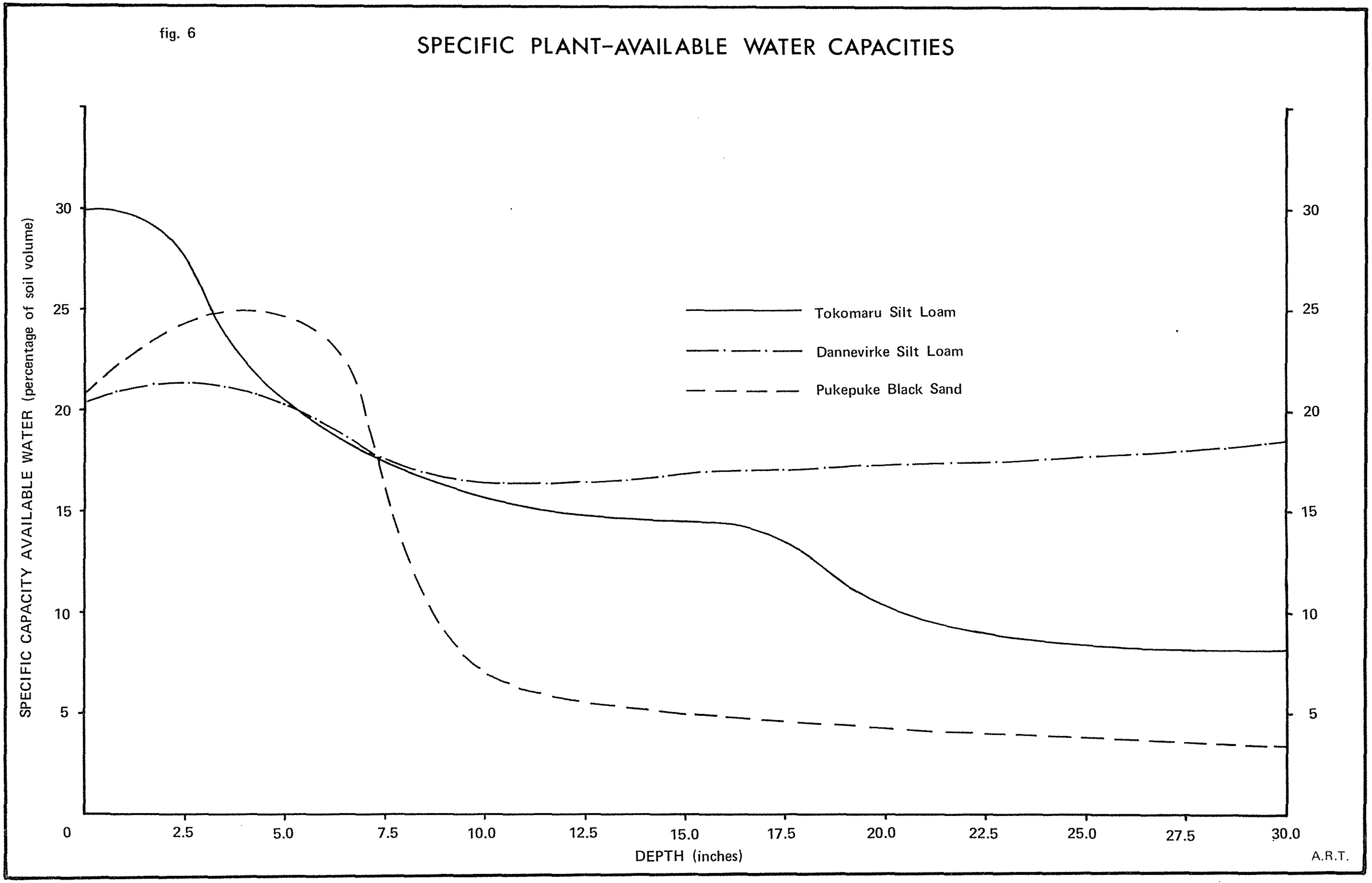
Gradwell (pers. comm.) supplied specific plant-available soil water capacities (in percentage of soil volume) at different depths in soil profiles for six soils tested in the region.[11] Those soils for which figures were supplied are: Pukepuke black sand, Tokomaru silt loam, Marton silt loam, Dannevirke silt loam, Matamau silt loam, and Kokotau silt loam. Mr J.A. Pollock of the Department of Soil Science, Massey University, aided in grouping the soil types of the region (figure 5) under three of the above soil types according to the characteristics exhibited by the soils in field examination. The three soil types chosen were: Pukepuke black sand, Tokomaru silt loam, and Dannevirke silt loam.

The actual plant-available water was obtained from the specific plant-available soil water capacity figures given by Gradwell. Curves were plotted showing specific plant-available water capacities (in percentage of soil volume) against depth of soil. The resultant curves (figure 6) indicated that any extrapolation beyond 30 inches on the basis of the figures supplied would have been dubious and 30 inches is accepted as the depth from which plant-available water is extracted. An estimate of the area under the curves was obtained with a planimeter, the average of the closest two of three readings being taken as the best estimate. This result was checked by measuring the area under each curve drawn to one inch depth and comparing the recording with the results established through multiplying the specific-capacity figures at that depth by the depth increment over which these apply (i.e. one inch). The resultant AWC's to 30 inches of the three relevant soils are:

Pukepuke black sand ... 2.59 inches
Tokomaru silt loam .... 3.93 inches
Dannevirke silt loam .. 4.81 inches

The above three figures were supplied to the New Zealand Meteorological Service which ran its daily water balance programme (Appendix B), based on the 1948 Thornthwaite equation,[12] for the AWC's given and the three meteorological stations indicated above. Rickard (1957) showed Thornthwaite's 1948 equation to be reliable for Ashburton soil and other conditions, but did have reservations about the extension of his results to other areas. Among other data, the monthly sums of daily water deficit were supplied in the print-outs. In the analysis made the actual water deficits indicated were weighted in favour of the number of butterfat

fig. 6


SPECIFIC PLANT-AVAILABLE WATER CAPACITIES
SPECIFIC CAPACITY AVAILABLE WATER (percentage of soil volume)
30
25
20
15
10
5
0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
27.5
30.0
DEPTH (inches)
Tokomaru Silt Loam
Dannevirke Silt Loam
Pukepuke Black Sand
A.R.T.

observations recorded on the particular soil moisture grouping. This was done so that undue weight was not given to moisture variates calculated for areas where few farms were located. For example, if more recordings going into the butterfat average were made on one particular soil grouping the AWC calculated for that soil received greater weight.

Solar Radiation

Little research appears to have been carried out on the effects of solar radiation upon animal physiology. Solar radiation would appear, however, to be an important variable insofar as pasture growth is concerned.[13] What follows is thus basically an account of some of the investigations conducted into this latter relationship and serves as powerful justification for the inclusion of a radiation parameter in the model.

Many of the experiments involving solar radiation have been conducted in an effort to investigate the joint effects of changes in solar radiation and temperature. This is so of Mitchell's work in particular.

Increased shading or light shortages have been shown to adversely affect various growth characteristics in one or more of the following species: perennial ryegrass (Lolium perenne L.), cocksfoot (Dactylis glomerata L.), paspalum (Paspalum dilatatum Poir.), white clover (Trifolium repens), subterranean clover (T. subteraneum L.), lotus major (Lotus uliginosus Schkuhr.), Yorkshire fog (Holcus lanatus L.), browntop (Agrostis tenuis Sibth.), and short-rotation ryegrass (L. perenne x L. multiflorum Lam.) (Sprague, 1943; Blackman and Wilson, 1951; Blackman and Black, 1959a, 1959b; Mitchell, 1954, 1955, 1956a, 1956b; Mitchell and Coles, 1955; Mitchell and Lucanus, 1962; Brougham, 1956, 1959; Bean, 1964; Ivory, 1964).

Mitchell (1955:18) contends that "even within the same species, large differences in size and shape of the leaves may be induced by differences in temperature and light intensity or by defoliation."[14] Brougham (1955)[15] has partially explained the growth rate and botanical composition of pasture in terms of inter-species light competition. A statistically significant ($p < 0.01$) positive effect of radiation on herbage production was demonstrated. One important aspect of Brougham's work was the indication that some lagged effects could have been present also. Too much light has been shown to limit the growth of short-grazed summer pastures (Mitchell, 1959).

Some workers have given less weight to the importance of the effects of solar radiation fluctuations on pasture growth (Black, 1955; Crowder et al., 1955 quoted by Weihing, 1963).[16]

Ivory (1964)[17] maintains that the plant makes some adjustment to light levels in that "it would appear that the efficiency of light utilisation increases with decreases in light intensity."[18] A summary statement by Ivory (1964:11) is valuable:

> "It is apparent from these considerations that inherent growth habit (size, inclination, orientation, height distribution and horizontal dispersion of leaves) and physiological and morphological adaption of these

> attributes to changes in level of incoming solar radiation will determine the maximum net photosynthetic rate per ground area that a pasture crop can achieve."

As in the case of the water balance parameter, where cognisance is taken of Maunder's (1965) success with rainfall as a variable, Maunder's success with sunshine hours as a variable supports the inclusion of solar radiation as a variable in the analysis.[19] "Other factors shown to be important for above average butterfat production were relatively cool and cloudy conditions, especially if these occurred early or late in season" (Maunder, 1968:43).

Of the climatological stations in, or adjacent to, the region, Ohakea only has recorded solar radiation directly (with an Epply solarimeter). Palmerston North D.S.I.R. has recorded hours of bright sunshine as has Foxton which is chosen in lieu of Waitarere Forest for which no recordings of either bright sunshine or solar radiation have been made.

It was decided to use mean daily incoming radiation (sun and sky) received on a horizontal surface as a meteorological parameter and thus the bright sunshine hours recorded at the two stations not directly recording incoming radiation required conversion to a measure of langleys per day.[20] To this end a modified version of the 1924 Angstrom equation was used. This revised equation is given by De Lisle (1966:997) as:

$$Q/Q_o = a + b\,(n/N)$$

where, Q is the total radiation per unit time received on a horizontal unit area on the earth's surface (hereafter referred to as 'solar radiation'), and thus the parameter sought;

Q_o is the radiation received in unit time on a horizontal unit area 'outside' the atmosphere, i.e. the solar constant;

n is the bright sunshine per unit time;

N is the astronomically possible sunshine per unit time;

and a and b are constants.

The procedure and assumptions involved in using this equation are outlined in Appendix C.

Temperature

Research has demonstrated that a moderate temperature increase will give rise to an increase in growth rates associated with the species mentioned above (pp. 52-53) (Sprague, 1943, Black, 1955; Crowder, 1955 quoted by Weihing, 1963; Mitchell, 1955, 1956a, 1956b, 1956c, 1958, 1959; Mitchell and Lucanus, 1960, 1962; Brougham, 1956, 1959). The temperature conditions in which most of these experiments were conducted were similar to temperatures which might be expected in the study region.

The effects of daily temperature ranges, diurnal temperature ranges, and temperature extremes have been examined. Brougham (1959) has also established the statistically significant

($p < 0.05$) positive effect of temperature range on total herbage parameters. "These analyses show that, in this locality /Palmerston North D.S.I.R./ during the winter and spring months, weekly fluctuations in the growth rate of ryegrass and consequently total herbage were associated with fluctuations in light and temperature range. However, during the summer and early autumn when clover was the dominant component of the pasture, weekly fluctuations in the growth rate of this species were associated mainly with fluctuations in temperature" (Brougham, 1959:293). The technical results obtained showed that in winter and spring a weekly fluctuation of 1°F (0.56°C) could be associated with a change in ryegrass growth of 19 pounds of dry matter per acre per week while in summer and early autumn a 1°F (0.56°C) change in maximum temperature was linked with a weekly growth rate change in clover of about 40 pounds of dry matter per acre per week.[21]

Although recent technological advances in the field of irrigation partially invalidate Corkill's (1955:65) claim, that "of the many environmental factors which govern pasture growth, temperature and moisture are perhaps the two which are least influenced by the efforts of man", the importance of temperature is still vital. Corkill states that there are two periods each year in which growth falls short of the requirement of the dairy cow; late winter/early spring- caused mainly by low temperatures and excess moisture, and late summer- caused mainly by lack of moisture and high temperatures.[22]

Some workers have emphasised the importance of soil temperature conditions (Blackman, 1936; Evans et al., 1964).

Soil temperatures were indicated by the latter writers to be more important than air temperatures.

Whereas Crowder (1955), as quoted by Weihing (1963), established correlation coefficients between forage yield and temperature as follows:

	November	- December	ρ	= 0.75;
	January	- February	ρ	= 0.89;
and	March	- April	ρ	= 0.98, (Northern Hemisphere),

Black (1955) concluded that growth rates were independent of a weekly mean temperature range of 46.7°F (8.2°C) to 77.3°F (25.5°C).

Extremes of some meteorological variables affect the dairy cow's physiological functioning, but otherwise these animals are regarded as fairly tolerant to variations in atmospheric conditions.

> "Warm-blooded animals maintain a constant body temperature even under widely variable conditions of external temperature, heat absorbtion and internal heat production. A stable body temperature allows the physiological process to function always at the same level of efficiency and thus permits the animal to live without restriction in a wide range of climatological environments" (Hancock, 1954:90).

Hancock has intensively reviewed research into the direct effects of climate on milk production and only the broad generalities established in the work will be presented here.[23] These discoveries have been supported by other workers.[24]

Gains in animal body heat stem from heat produced in body function maintenance and heat absorbed from solar radiation, while losses occur through evaporation, radiation, conduction, and convection. These processes are dependent upon the temperature gradient between the animal's skin and surroundings, absolute humidity, and air movement. Hancock (1954) maintains that over a wide range of atmospheric conditions heat emission, rather than conservation, is the major problem of the lactating dairy cow. He indicates that in temperatures up to 65°F (18.3°C) most body heat is lost through conduction, convection, and radiation, whereas above this level evaporation increases in significance. "The critical temperature for European cattle lies at approximately 70°F (21.1°C)" (Hancock, 1954:91). At this level body temperature begins to exceed normal. Temperatures as low as 5°F (-15.0°C) can be well withstood by cattle.

Reports on the research into the effects of low temperatures indicate that lower temperatures increase butterfat percentage (Brooks, 1895; Ragsdale and Brody, 1922; Sementovskaya and Garkavi, 1950). A contradictory case is cited by Witzel and Barrett (1944) who found that temperature fluctuations had no apparent effect on milk production. Psychrometric room experiments, however, have shown decreases in milk yield and increases in butterfat percentages to be associated with temperature reductions (Hays, 1926; Ragsdale _et al._, 1949).

Higher temperatures have been shown to increase butterfat while decreasing milk yield (White and Judkins, 1918; Weaver and Matthews, 1928; Brooks, 1931). Others have maintained that both milk yield and butterfat decrease with temperature increases (Spier, 1909; Ragsdale and Turner, 1922; Davis, 1947; Heinemann, 1947; Hancock and Payne, 1953).

High milk yields and associated low butterfat tests were found by Haarlaas (1941). This facet of opposed butterfat and milk yield trends corroborated the work of Regan and Richardson (1938).

Temperature-controlled room experiments have likewise resulted in conflicting evidence over the direction of temperature effects upon butterfat production. Increased temperatures were found to increase butterfat production when acclimatisation was not allowed (Hays, 1926; and Hancock, 1954). Barrett (1935) found small, non-significant decreases in milk and butterfat yield with increased temperatures. Rick and Lee (1948) noted no effects at temperatures up to 110°F (43.3°C). Hancock (1954), however, showed that prolonged exposure to high temperatures led to a decrease in butterfat content. The results of Ragsdale _et al._ (1948, 1949, 1950, 1951) are summarised by Hancock (1954:98):

> "The milk yield in European evolved cattle begins to decline with temperatures above 70°F [21.1°C] .... Butterfat percentage decreased slightly from 50° to 90°F [10° to 32.2°C], after which a sharp decrease of 10-40 percent occurred" and "temperatures in the range of 40°-70°F [4.4° - 21.1°C] (or even 30° - 75°F [-1.1° - 23.9°C]) have no influence on milk yield. At temperatures below this range milk yields tend to decrease ....
>
> "At temperatures above 70°F [21.1°C] milk yield decreases slowly at first, but after 80°F [26.7°C] there is a sudden drop. Butterfat percentage decreases up to 80°F [26.7°C] but increases sharply thereafter."

Quartermain (1962a, 1962b) considered the position of the Jersey dairy cow and suggested that the economic importance of it suffering from thermal stress in the Manawatu summer would be slight. Brumby (1955) has investigated the grazing behaviour of animals under different weather conditions and pointed to the effects of temperature and wind. Correlation analyses between air temperatures and body temperatures have been attempted by Gaalaas (1945) and Seath and Miller (1946), but their specific works may be consulted for further details.[25]

The analysis by Maunder (1965) showed temperature to be an important variable in butterfat production,[26] though his study does not attempt to place the cause directly on either physiological or pasturage factors. It is again reasoned that the success of temperature variables in Maunder's agroclimatological model goes some way towards justifying their inclusion in this research.

On the above evidence it was deemed desirable to include temperature variables in the model. In the context of this discussion the following variables were justifiably incorporated: mean daily temperature, mean daily maximum temperature, mean daily minimum temperature, and mean daily grass minimum temperature, each on a monthly basis. These variables were used as recorded by the meteorological stations and no adjustment or modification of any value was attempted.

C. The Time Variable

In an effort to account for suspected technological, management, and husbandary-induced butterfat increases over time a time variable was included. This variable was increased arithmetically from the first dairying season considered through to the last. Maunder (1965) found two time variables valuable (one a second order term), but a linear term only was included here. Some further discussion of time trend problems is presented in the following chapter.

Notes:

1 The location of farms with available records was effected through the use of Manawatu Farm Location maps (Nos. 3 and 4) produced by the Combined Manawatu Lions Clubs and Oroua Young Farmers Clubs and maps supplied by the Palmerston North branch of the New Zealand Government Valuation Department.

2 One problem in the sampling design had to be overcome. The combination, separation, and recombination of the administrative herd testing groups at various times meant that farms actually outside the area of interest were available sampling points. It follows that if such a farm was randomly selected it was rejected from the sample and a further selection made.

3 In the final analysis a maximum of 183 of these means was employed due to the non-availability of a few corresponding meteorological variables.

4 For example, Richards and Wadleigh (1952), Jantti and Kramer (1956), Brougham (1956, 1959), Hudson (1957), Stanhill (1960), Lucanus *et al*. (1960), Denmead and Shaw (1962), and Mitchell and Kerr (1966), who have directly mentioned pasture growth rates as affected by moisture availability.

5 Climatological work on water balance aspects includes; Penman (1949, 1968), Thornthwaite (1948), Thornthwaite and Mather (1955), Thornthwaite and Hare (1965), Veihmeyer and Hendrickson (1950), Musgrave (1955), Rickard (1957), Pierce (1958), Bierhuizen (1958), and Chang (1968).

6 The examinations of Corkill (1955), Davey (1962), and Johnston (1962) are interesting in this respect.

7 For example, Taylor and Slater (1955), Thornthwaite and Mather (1955), and Bone and Tayler (1963a, 1963b).

8 For example, Wilcox and Spilsbury (1941), Wilcox (1949), Gaiser (1952), Heinonen (1954), and Broadfoot and Burke (1958) who suggest, along with Salter and Williams (1965a, 1965b), Gradwell (1968, 1971), and Petersen *et al*. (1968), that the AWC of soils increases from coarse-textured sand to a maximum with medium-textured soils. Jamison and Kroth (1958) maintain that AWC is greatest in the finest-textured soils.

9 Jamison as referred to is: Jamison, V.C. (1956) "Pertinent Factors Governing the Availability of Soil Moisture to Plants", Soil Sci., 76:143-51.

10 Gradwell is concerned with explaining the lack of difference in AWC of four Waikato soils.

11 Gradwell has indicated that Soil Bureau workers examined a few sites in the region. Their method was to plant gypsum blocks at various depths and read the blocks through summer. They found complete extraction to depths between two and three feet (i.e. wilting point was attained at this depth).

12 The reader is referred to Thornthwaite, C.W. (1948) "An Approach Toward a Rational Classification of Climate", Geogrl. Rev., 38:56-94.

13 A considerable volume of literature on the effects of solar radiation upon pasture growth may be located in various journals of the agricultural and related sciences. The bibliography lists some of the most relevant of these periodicals.

14 The 1955, 1956 and 1959 trials of Mitchell and the 1959 trials of Brougham were conducted on Manawatu silt loam approximately 800 yards distant from the Palmerston North D.S.I.R. climatological station.

15 Brougham (1959) "The Effects of Season and Weather on the Growth Rate of a Ryegrass and Clover Pasture", N.Z. Jl. agric. Res., 2:283-95, presents the results of a correlation and regression analysis of herbage production and climatic factors (Table 2, p. 290 and Table 3, p. 291).

16 Weihing regressed ryegrass (*Lolium multiflorum* Lam.) growth against solar radiation and temperature and generated the correlation coefficients:

$$\rho = 0.74 \text{ (solar radiation)};$$

$$\rho = 0.84 \text{ (temperature)};$$

and established the estimation equation:

$$Y = -495.72 + 17.0256X_1 - 0.1036X_2$$

where X_1 is temperature
and X_2 is temperature^2.

17 Ivory, D.A. (1964) Light and the Growth of Prairie Grass (*Bromus wildenovii*) and Short-rotation Ryegrass (*Lolium perenne* x *L. multiflorum*) Swards, M. Ag. Sci. (Hons) Thesis Univ. of Canterbury. Ivory quotes several other research workers, but mainly Mitchell, who found similar results.

18 The generalisations made to this point are given further consideration by Evans et al. (1964) "Environmental Control of Growth" in C. Barnard ed. Grasses and Grasslands, 102-25. Drawing heavily upon the work of Brougham and Mitchell in particular, they deal at length with the effects of temperature and light upon common New Zealand pasture species.

19 In an analysis of seasonal butterfat production Maunder included sunshine figures for November, December, January, and February. His statistical results are presented in an unpublished Ph.D. thesis (1965).

20 One langley is equivalent to one calorie per square centimetre (1ly = 1 cal cm^{-2}).

21 See note 15 above.

22 This effect is presented graphically in Duckham, A.N. (1963) The Farming Year: 279.

23 For the full review consult Hancock, J. (1954) "The Direct Influence of Climate on Milk Production", Dairy Sci. Abstr., 16 (2): 89-102.

24 Those authors whose work Hancock (1954) has reviewed may be referred to after consulting Hancock. The bibliography in this thesis does not contain reference to all the reviewed works, but does include the supporting works not reviewed by Hancock.

25 Gaalaas (1945) achieved a correlation of + 0.57 (± 0.0079) between average body temperature of cows and air temperatures in high humidity conditions over the air temperature range 50° to 95°F (10.0° to 35.0°C). The respiration rate over the same temperature range was correlated at + 0.77 (± 0.0048). Seath and Miller (1946) obtained partial correlation coefficients of + 0.624 and + 0.534 between air temperature and body temperature while holding humidity constant.

26 Maunder's (1965) correlation indicated the requirement of a 'cool' November and February with a 'warm', but 'wet' January for above average butterfat production in the North Island, New Zealand. His model regressed seasonal butterfat production on mean temperature for the months October to February inclusive.

Chapter Four

THE AGROCLIMATOLOGICAL MODEL

Chapter One introduced a working hypothesis which is restated here prior to the statement of specific hypotheses of the agroclimatological relationships under investigation. The generalisation to be established is that varying meteorological conditions are associated with variations in dairy production in a cause-and-effect manner. The development of the model below was based upon assumptions implicit in this generalisation.

Specifically, the model was structured to enable the testing of the following hypotheses about agroclimatological relationships believed to exist in the region. These hypotheses are that:

(1) butterfat production is related to moisture availability;

(2) butterfat production is related to solar radiation;

(3) butterfat production is related to mean daily temperature;

(4) butterfat production is related to mean daily maximum temperature;

(5) butterfat production is related to mean daily minimum temperature;

and (6) butterfat production is related to mean daily grass minimum temperature.

These six relationships were examined using the data indicated in Chapter Three. Listing these hypotheses as above imparts, at this stage, no hierarchical importance for this could be established only by the mathematical analysis to follow.

Chapter Three vindicated the selection of the meteorological variables included as measures of climatic input, and the six hypotheses, as formal statements of the connections suggested therein, follow from that discussion.

Preliminary acceptance of the two principles, that several meteorological factors are important in determining levels of butterfat production, and that they operate upon this in a cause-and-effect manner, promoted the suggestion that the model to be developed should examine the statistical relationships between the variables involved and should be multivariate in form. If the model (the assumptions for which are presented in Appendix D) satisfies certain statistical requirements (Appendices D and E), it may be used for prediction purposes. It was also recognised that the situation in which the relationship was investigated must remain, or be assumed to remain, unchanged into future periods before the model could be used for estimation or prediction purposes. Any extension of the mathematical relationships observed to indications of physical relationships between the variables must be argued on substantive grounds.

Time series data (sequences of observations ordered through time) were used in this analysis. With respect to problems associated with the use of time series data,[1] some form of analytical technique suited to the handling of multivariate time series problems appeared initially preferable for use here. Miller and Kahn (1962), basing most of their discussion upon

Kendall (1948), considered time series analysis by dividing time series into three categories: trends; cycles; and random components. Any one time series may, or may not, include all three components.

A visual inspection of the data indicated the obvious presence of a seasonal effect in the problem at hand, with a peak in butterfat production occurring at the end of the season (March as considered here). Miller and Kahn (1962:347) write: "Kendall suggests that 'seasonal effect' may be eliminated or removed from a time series by proper choice of time interval." Butterfat observations taken on a seasonal basis could have satisfied this criterion, but the desired level of investigation was monthly ruling out any such remedy.[2] To remove seasonal effects from monthly recordings is indicated (Wallis and Roberts, 1956) sometimes to be a complicated procedure and for this reason it was avoided here. Furthermore, this type of correction does not appear to have been attempted in this field. Maunder (1965), for example, considered butterfat data at a seasonal level, thus satisfying Kendall's suggestion. It is recognised, however, that failure to remove these effects reduced the effectiveness of the analysis.

Trends may be accounted for by the inclusion of a term, or terms, that smooth the curve; a process that can prove rather difficult and involve the inclusion of several terms, some of which may be high order, in the polynomial if the trend is either complicated or irregular.

Substantive reasoning indicates that joint functional relations should hold in most instances where meteorological or climatic variables are thought to affect agricultural production, as the lack of complete independence between meteorological or climatic variables, along with the suspected difference in degree of effect of these factors upon agricultural output, argues in favour of relations of this type. Evidence of interdependence among the meteorological variables chosen is implicit in the knowledge that these variables are each, in some way, a function of solar radiation.[3] Differences in the degree of impact of meteorological factors upon agricultural output is evidenced in the research results referred to in the previous chapter.

Ezekiel and Fox (1959:357)[4] state:

> "The joint function may be determined either by fitting some appropriate algebraic function, or by graphic processes. Only in rare cases will there be a good logical basis for judging the form of the joint function to be expected. In most cases, therefore, even the algebraic equation must be selected with some reference to its ability to represent the type of joint function shown in the data, as empirically determined by some form of graphic examination."

They further state (1959:373-374) that "given a large enough sample, and sufficiently high correlation, it should be possible to determine joint functions in three or more independent variables".

This latter aim can be realised through building subordinate joint regression functions into one regression function, but, as the number of variables to be included exceeds three to four, large samples and high correlations are required to establish the model. The contention here is that neither of these criteria were known to have been satisfied. Judging the form of a function to suit the expressed relationship in this case would have been hazardous although logical grounds were present for debating that certain aspects of a joint regression surface could be expected. The number of variables to be included, and their intricate interrelationships, moreover, made either any estimation or graphical fitting of a joint regression equation difficult, laborious, and dangerous.

At this point it is convenient to discuss why some form of factor analysis[5] was not considered a desirable investigatory method. Factor analysis was designed to show how many factors are important in explaining a situation and so ideally it is more suited to a problem in which the number of variables is high; say 50 to 100. "Basically, factor analysis is a technique which can be used to take a large number of operational indices and reduce these to a smaller number of conceptual variables" (Blalock, 1960:383). Combinations of the variables that are the most important components of the entire set of variables are considered as factors.

Factor analysis can be used to sort out interrelationships among variables (Blalock, 1960; Thompson, 1967). The statistically most influential factors, based on weather parameters, controlling dairy production may be indicated. Although useful in eliminating redundant variables, factor analysis can generate meaningless factors. The exercise is of little value unless the factors can be identified as having some substantive meaning.

Since multiple regression and multiple correlation techniques provide indications of these relationships without combinatorial factors entering the analysis, and since the relationship of the stated dependent variable to the independent or regressor variables (see Appendix D) can be equally assessed, factor analysis was disregarded. Factor analysis, associated with preliminary cluster analysis, might, however, have proven useful in isolating, initially, the most important variables for further research.

By ignoring the possibility of joint relations, the regression model was simplified, removing some of the problems associated with joint regression surfaces. Although the use of multiple curvilinear regression overcomes some of these difficulties, problems inherent in using the number of variables desired remain. Unless an established relationship is already known from earlier research, or unless a simple logical basis exists for curve prediction, it is again difficult to forecast the function of the climatic input-dairy output relationship. Algebraic and graphical curve fitting again involves the logistical problems allied to joint regression surface analysis. Even though a curvilinear function is difficult to obtain, the reasoning that at some critical level successive climatic inputs would result in diminishing returns of butterfat production indicates that a polynomial incorporating higher than first order terms is probably more realistic than a linear expression.

Maunder (1965) established a multiple regression equation for climatic input and agricultural output in 27 New Zealand counties. One second degree time variable was included along with one first order time variable and 13 first order climatic variables. The form of his model was suggested by several trial analyses of Southland County data. Temporal and financial limitations made such trials impractical in this case. Maunder's success with 14 first order terms, nevertheless, serves as strong justification for the method of analysis finally adopted in this work.

Since it was not known to what extent any meteorological factors influenced dairy production in the region under examination, it appears rational to argue that the climatic input in the analysis should be maximised. Achieving this meant the incorporation of many variables and thus, for the reasons suggested above, simplification of the order of the mathematical model. In pursuit of the study's objectives interest was focused more upon the significance of the various meteorological elements under scrutiny and the degree to which they explain the relationship, than upon the evolution of an expression perfectly indicative of the agro-climatological relationship. Meteorological variables do not totally determine butterfat production and establishing a mathematical model covering them all and all non-meteorological influences was not practical. The results of this research may point to those variables which could be made use of in a more powerful model more explicitly establishing the effects of climate upon the dairy industry.

A first order polynomial function was chosen on these bases. The general model is:

$$Y = b_o + \sum_{i=1}^{19} b_i X_i + E$$

and the mode of analysis was stepwise linear regression where:

Y = butterfat yield on a monthly basis;

b_o is a constant;

X_1 is a time variable such that the dairying seasons are ranked with 1939-40 equivalent to 1, 1940-41 equivalent to 2 etc.;

$X_2 \ldots X_{19}$ are meteorological variables taking monthly weather values for eighteen meteorological variables (Table XI);

E is an unobservable random variable such that the expected value of $E = 0$ with variance σ^2;

b_i (b=1, ..., 19) are estimators of the population parameters.

The restrictions governing the use of this model and the assumptions made accompanying its use are discussed in Appendices D and E. The procedural steps taken in the implementation of the model are outlined in Appendix F.

Dairy production during the months October to March inclusive (i.e. those for which this analysis is made) is based primarily upon grass growth which in turn is dependent upon weather inputs, the effects of which do not always operate immediately. All decisions made as to the number of months for which to lag each variable were made on substantive grounds.

While the moisture available to plants could possibly be expected to be cummulatively important for the season, it was not included as a lagged variable for longer than three months. Lagged solar radiation, however, could possibly have been expected

TABLE XI: The Meteorological Variables Used in the Analysis

X_2	water balance in time (t)*
X_3	water balance in time (t-1)*
X_4	water balance in time (t-2)*
X_5	solar radiation in time (t)
X_6	solar radiation in time ((t-1)
X_7	solar radiation in time (t-2)
X_8	mean daily temperature in time (t)
X_9	mean daily temperature in time (t-1)
X_{10}	mean daily temperature in time (t-2)
X_{11}	mean daily maximum temperature in time (t)
X_{12}	mean daily maximum temperature in time (t-1)
X_{13}	mean daily maximum temperature in time (t-2)
X_{14}	mean daily minimum temperature in time (t)
X_{15}	mean daily minimum temperature in time (t-1)
X_{16}	mean daily minimum temperature in time (t-2)
X_{17}	mean daily grass minimum temperature in time (t)
X_{18}	mean daily grass minimum temperature in time (t-1)
X_{19}	mean daily grass minimum temperature in time (t-2)

where, (t) is the month of the butterfat test
(t-1) is the month prior to the butterfat test
(t-2) is two months prior to the butterfat test.

* 'Water balance' is alternatively referred to as 'moisture availability'.

to be of significance for a lesser period. Each meteorological variable was, however, included for three months such that in the model, for example, X_2 is moisture availability in month t, X_3 is moisture availability in month (t-1), and X_4 is moisture availability in month (t-2).[6]

The model makes no attempt to distinguish between meteorological effects upon butterfat yield arising from physiological effects upon the animal, or direct effect upon fodder availability. It is believed that lagged weather variables are not very important in affecting animal physiology.[7]

The prediction model established is of the form:

$$Y = b_o + \sum_{k=1}^{n} b_k X_k + E$$

where: Kth variable is the kth <u>significant</u> variable

Y and b_o are as above;

The b_k's are estimators of the population parameters;

The X_i's are the significant regressor variables ($p< 0.05$);

and E, with mean zero and variance σ^2, is assumed to define the distribution of error from all sources.

The success of this model as a prediction equation is dependent upon the degree to which the assumptions made regarding its use are met.

Notes:

1 See especially Ezekiel and Fox (1959), Quenouille (1957), and Miller and Kahn (1962).

2 Wallis and Roberts (1956) have warned that sound *a priori* knowledge of any such seasonal effect should be present before its elimination is attempted. Knowledge that a seasonal cycle exists, however, is not lacking if such a decision were to be considered in this case.

3 Most standard climatological and meteorological texts illustrate the importance of solar radiation as by far the major energy source initiating and maintaining global energy processes. Sellers (1965) offers a profound treatment of the major processes in mathematical model form, while more advanced meteorological texts such as Haltiner and Martin (1957) and Humphreys (1964) may be approached for reference to more specific atmospheric processes.

4 Ezekiel and Fox (1959) develop methods whereby joint function relations can be graphically and mathematically derived; the reader is referred to this work for a more extensive discussion of regression techniques and joint regression surfaces in particular.

5 For detailed information about the use of factor analysis as an analytical technique reference should be made to Kendall (1957) and Harman (1960).

6 Dr W.J. Maunder (pers. comm.) endorsed this decision.

7 Literature on this point was discussed under the various meteorological variables in Chapter Three, but for convenience some of the valuable papers are listed as follows: Regan and Richardson (1938), Gaalaas (1945, 1947), Seath and Miller (1946, 1947), Lee and Philips (1948), Hancock (1954) - a particularly good summary of research up to this date -, Brumby (1955), and Quartermain (1962a, 1962b).

Chapter Five

RESULTS OF THE ANALYSIS

Four separate analyses were carried out upon the data collected. The means for butterfat production were regressed on the temporal and meteorological variables recorded at each climatological location in turn, and finally on the averages of recordings made at these stations. The number of observations in each case was thus conditioned by the availability of dairy production figures and the time for which each climatological station had been operating. Details of the period over which the observations were made and the number of observations are provided in Table XII.

TABLE XII: The Four Case Studies Made

Case No.	Climatological station(s)	Period of Regression Dairying Season: October-March (initial and final months of regression bracketed)	No. monthly observations available
1	Palmerston North D.S.I.R.	(Oct.) 1939 - (Jan.) 1970	184
2	Ohakea	(Dec.) 1955 - (Dec.) 1969	96
3	Foxton - Waitarere Forest	(Dec.) 1962 - (Dec.) 1969	47
4	Mean of cases 1, 2, and 3	(Dec.) 1962 - (Dec.) 1969	44

Certain assumptions made in Chapter Four about the statistical model and the nature of the data remained unsatisfied. These assumptions are shown to be valid below.

Poole and O'Farrell (1971:53) claim:

> "It is impossible to test directly, in any specific empirical example, the validity of the four assumptions relating to characteristics of the disturbances, for these characteristics are unknown because the disturbances are unobservable. However, tests may be carried out on the pattern of residuals, using this as an estimate of the pattern of disturbances."

Due to the high number of observations and variables involved in some cases it was deemed desirable only to print out the residuals in one instance. This was done with Case Four in which averaged meteorological variables from all the stations employed were utilised. It is contended that patterns exhibited by the residuals given out in this analysis would be similar to those of the other three analyses.

It is assumed that the residuals are serially independent. Poole and O'Farrell (1971) have indicated that unbiased estimates of the regression coefficients are still obtained with autocorrelated disturbances, but that the coefficients may have large inaccurately-estimated variances and hence statistical inference procedures are unjustified. The residuals delivered in Case Four were employed to test the null hypothesis, $H_o : r_a = 0$, where r_a is the coefficient of autocorrelation.[1]

A negative coefficient of autocorrelation resulted ($r_a = -0.355$) which is significant at the 0.05 level but not the 0.01 level, and the null hypothesis, $H_o : r_a = 0$, is accepted with the acknowledgement that a Type II error may have been committed.[2]

It is manifest that the assumption of multicollinearity is satisfied as far as the regression analysis is reported. The standard errors of the partial regression coefficients (b's) are such that a t-test carried out on the coefficients results in satisfactory probability levels (see below). The partial regression coefficients are therefore, sufficiently identifiable to ignore multicollinearity.

The stepwise multiple regression programme (Appendix F) included each variable on the basis of change in mean square regression over the variance left unexplained at each stage. As indicated in Appendix F this criterion was not used in reporting the results and instead the significance of the added variables was sought by dividing the additional variation accounted for with the inclusion of a new term by the variance left unexplained at each step. These two slightly different techniques meant that, at times, the programme included variables which gave a non-significant (at the 0.05 level) variance reduction. The results presented may have thus contained F-levels greater than 0.05 as long as other variables later entered reached this specified level. Results are not reported after all variables which contribute to an error reduction are included. Variables with $F > 0.05$ may be included in the equations.

If the hypotheses tested are true a random test on the situation prescribed by the statistical model will produce results with probability levels less than, or equal to, the prescribed level of α (0.05) with a probability of α. The statistic of the specific value under test is deemed to be 'significant' if its level of probability (p) is less than, or equal to, α . α thus specifies the probability of observing a result in the rejection region if the hypothesis under test is true. The confidence in the decisions to reject the hypotheses is given by 100 (1-p)%.

The results of the stepwise regression analyses are entered in Tables XV, XIX, XXIII, and XXVII (the notation used in these Tables is defined in Appendix G). Tables XIII, XVII, XXI, and XXV contain summary statistics for the variables used and Tables XIV, XVIII, XXII, and XXVI contain the matrices of simple correlation coefficients for the significant variables.

Tables XV, XIX, XXIII, and XVII display step by step the variables entered in the analyses and includes statistics and coefficients associated with these variables. The constant indicates the level of butterfat production expected when the regressor variables are equal to zero.

The partial regression coefficient (b-coeff.) for any variable takes into account all the variables entered to that stage of the analysis while holding the non-entered variables constant. The b-coefficient thus refers to the particular variable as it affects the dependent variable in combination with the variables already entered. The standard error of this coefficient ($s_{by.x}$) is also given. At the final step the exact level of probability (p(b)) associated with this regression coefficient is presented.

The partial correlation coefficients (partial r) are given with their probability levels (p(r)) also. These partials express the correlation between the dependent variable and the regressor variable concerned while accounting for those variables already in the model and holding the others statistically constant.

The partial regression coefficients depend on the relation between the variables and the units in which each is stated. The β-coefficient (β-coeff.) standardises these units expressing each of the variables in terms of its own standard deviation. The importance of these individual variables can be more appropriately assessed from the β-coefficients. Their standard errors are also given ($s_{\beta y.x}$).

The multiple correlation (R) is a measure of the goodness of fit of the least squares equation at each stage. p (R) is the exact probability level calculated for the last stage of the analysis, on the hypothesis that R equals zero.

The decrease of the residual standard deviation ($s_{zy.x}$) can be noted as the regression analyses proceed. The *F*-level of the added variable, in terms of the variance criterion earlier outlined (page 79), is also presented for each stage.

From this point each case is considered separately.

Case One

With reference to Table XIV, of the meteorological variables X_{13} shows the highest simple correlation with butterfat (+ 0.69). X_7 shows a moderately high correlation with butterfat

TABLE XIII: Case One: Summary Statistics for Sample Butterfat Data and Meteorological Data Recorded at Palmerston North D.S.I.R. (1939 - 1970)

Variable	Low	High	Average	Standard Deviation	Variance
Bfat (t) (Y)	4.15	5.95	5.04	0.36	0.13
Time (t) (X_1)	1.00	31.00	15.84	8.88	78.83
WB (t) (X_2)	0.00	2.90	0.20	0.47	0.22
WB (t-1) (X_3)	0.00	2.90	0.14	0.43	0.19
WB (t-2) (X_4)	0.00	1.99	0.06	0.28	0.08
SR (t) (X_5)	315.70	645.90	467.50	74.24	5511.6
SR (t-1) (X_6)	274.90	645.90	459.90	87.51	7657.7
SR (t-2) (X_7)	179.80	645.90	413.66	127.32	16211.0
MDT (t) (X_8)	51.60	67.60	60.18	3.80	14.46
MDT (t-1) (X_9)	49.70	67.60	58.54	4.87	23.70
MDT (t-2) (X_{10})	45.50	67.00	55.94	5.45	29.66
MAX (t) (X_{11})	58.90	76.50	68.41	4.29	18.41
MAX (t-1) (X_{12})	56.60	76.50	66.60	5.42	29.32
MAX (t-2) (X_{13})	52.50	76.20	63.83	5.94	35.25
MIN (t) (X_{14})	42.50	61.30	52.12	3.62	13.10
MIN (t-1) (X_{15})	41.50	61.30	50.60	4.60	21.13
MIN (t-2) (X_{16})	37.70	60.50	48.24	5.25	27.58
GMT (t) (X_{17})	33.60	55.10	45.63	3.99	15.90
GMT (t-1) (X_{18})	33.50	55.10	44.19	4.94	24.36
GMT (t-2) (X_{19})	28.30	55.10	41.82	5.63	31.67

Bfat = Butterfat
WB = water balance
SR = solar radiation
MDT = mean daily temperature
MAX = mean daily maximum temperature
MIN = mean daily minimum temperature
GMT = mean daily grass minimum temperature

The values (t), (t-1), and (t-2) are as referred to in the text (p. 74).

No. of cases = 184.

TABLE XIV: Case One: Matrix of Simple Correlation Coefficients; Sample Butterfat Data and Meteorological Data for Palmerston North D.S.I.R. (1939 - 1970)

	Y	X_1	X_5	X_7	X_{13}
Y	1.000	0.472	-0.219	0.616	0.692
X_1		1.000	0.007	0.020	0.089
X_5			1.000	0.112	-0.116
X_7				1.000	0.910
X_{13}					1.000

Y = butterfat in time (t),
X_1 = time,
X_5 = solar radiation in time (t),
X_7 = solar radiation in time (t-2),
and X_{13} = mean daily maximum temperature in time (t-2).

TABLE XV

CASE ONE : RESULTS OF REGRESSION ANALYSIS BETWEEN SAMPLE BUTTERFAT DATA AND METEOROLOGICAL DATA RECORDED AT PALMERSTON NORTH D.S.I.R. (1939–1970)

Step	Variable	Constant	Partial b – coeff	$s_{by.x}$	p(b)	Partial r	p(r)	β – coeff	$s_{\beta y.x}$	R	p (R)	$s_{zy.x}$	F–level of added term
1	X_{13}	2.3706	0.0417	0.0032		0.6922		0.6922	0.0534	0.6922		0.2594	$<$ 0.0005
2	X_1		0.0167	0.0017		0.5709		0.4136	0.0442				
	X_{13}	2.2475	0.0395	0.0026		0.7405		0.6555	0.0442	0.8055		0.2135	$<$ 0.0005
3	X_5		–0.0007	0.0002		–0.2482		–0.1480	0.0430				
	X_1		0.0168	0.0017		0.5855		0.4162	0.0429				
	X_{13}	2.6470	0.0385	0.0026		0.7399		0.6382	0.0432	0.8189		0.2074	0.002
4	X_7		0.0010	0.0003	0.0012	0.2199	0.0064	0.3653	0.1211				
	X_5		–0.0011	0.0002	0.001	–0.3241	$<$0.0005	–0.2289	0.0499				
	X_1		0.0177	0.0017	$<$0.0005	0.6097	$<$0.0005	0.4399	0.0427				
	X_{13}	3.7148	0.0177	0.0073	0.016	0.1778	0.030	0.2941	0.1216	0.8285	$<$0.0005	0.2029	0.01

X_1 = time, X_5 = solar radiation in time (t), X_7 = solar radiation in time (t–2), X_{13} = mean daily maximum temperature in time (t–2).

(+ 0.62). X_7 and X_{13}, however, are highly intercorrelated (+ 0.91). Thus, consequently, the partial regression coefficient of X_{13} was reduced as X_7 entered the regression analysis (Table XV).

The stability of the b's can be followed down Table XV. It appears that all but X_{13} have stable regression coefficients, whereas in step four this coefficient tended to reduce markedly as the highly intercorrelated X_7 entered the regression.

According to the β-coefficient in this trial X_1 is the most important variable affecting butterfat production. Although for this analysis the β-coefficient ranks variables X_7 and X_{13} above X_5 the standard errors of these two former variables' β-coefficients are relatively high.

Table XVI indicates the amount of variation in butterfat production explained at each additional step in the analysis.

TABLE XVI: The Variation Explained at Each Step in the Multiple Regression Analysis: Palmerston North D.S.I.R. Case

Step	Variable Entered	Multiple Correlation Coefficient (R)	Coefficient of Determination (R^2)	Percentage Variation Explained	Percentage Additional Variation Explained
1	X_{13}	0.6922	0.4791	47.91%	47.91%
2	X_1	0.8055	0.6488	64.88%	16.97%
3	X_5	0.8189	0.6705	67.05%	2.18%
4	X_7	0.8285	0.6864	68.64%	1.59%

The coefficient of multiple correlation (R) is 0.8285 at the termination of the analysis. Variation in butterfat production is accounted for to the extent of 68.64% by the variation in the meteorological factors and passage of time included in the regression. A 99 per cent confidence interval of 0.8030 to 0.8510 can be set around P, the population parameter.

Case Two

With reference to Table XVIII, the highest simple correlation (+ 0.82) with butterfat is given by variable X_{16}. As in Case One X_7 reveals a reasonable correlation (+0.74), whereas none of the other variables are highly correlated with butterfat. The former two meteorological parameters are, however, relatively highly inter-correlated (+ 0.86).

With respect to the b's of Table XIX only that for variable X_{16} fluctuated markedly, showing a noteable drop in the fourth step as the variable X_7 was entered.

In the results presented in Table XIX the β -coefficients indicate X_7 to be the most important regressor variable in this trial.

Table XX indicates the amount of variation in butterfat production explained at each additional step in the analysis.

TABLE XVII: Case Two: Summary Statistics for Sample Butterfat Data and Meteorological Data Recorded at Ohakea (1955 - 1969)

Variable	Low	High	Average	Standard Deviation	Variance
Bfat (t) (Y)	4.62	5.95	5.20	0.30	0.09
Time (t) (X_1)	15.00	31.00	23.39	4.71	22.16
WB (t) (X_2)	0.00	2.80	0.33	0.66	0.44
WB (t-1) (X_3)	0.00	2.80	0.25	0.63	0.40
WB (t-2) (X_4)	0.00	2.73	0.14	0.51	0.26
SR (t) (X_5)	329.00	712.00	487.20	83.45	6963.10
SR (t-1) (X_6)	277.00	712.00	481.37	94.32	8895.80
SR (t-2) (X_7)	116.00	712.00	439.15	137.43	18889.00
MDT (t) (X_8)	52.30	67.60	61.10	3.89	15.16
MDT (t-1) (X_9)	50.00	67.60	59.33	5.06	25.65
MDT (t-2) (X_{10})	46.10	67.60	56.63	5.57	31.04
MAX (t) (X_{11})	58.90	77.00	69.22	4.33	18.78
MAX (t-1) (X_{12})	56.60	76.30	67.36	5.50	30.24
MAX (t-2) (X_{13})	53.60	76.30	64.51	6.03	36.41
MIN (t) (X_{14})	43.80	59.40	52.91	3.54	12.55
MIN (t-1) (X_{15})	41.00	59.40	51.30	4.72	22.23
MIN (t-2) (X_{16})	38.60	59.40	48.85	5.24	27.48
GMT (t) (X_{17})	39.40	57.00	49.83	3.83	14.68
GMT (t-1) (X_{18})	36.90	57.00	48.00	5.14	26.44
GMT (t-2) (X_{19})	34.40	56.90	45.38	5.65	31.93

Bfat = Butterfat
WB = water balance
SR = solar radiation

MDT = mean daily temperature
MAX = mean daily maximum temperature
MIN = mean daily minimum temperature
GMT = mean daily grass minimum temperature

The values (t), (t-1), and (t-2) are as referred to in the text (p. 74).

No. of cases = 96.

TABLE XVIII: Case Two: Matrix of Simple Correlation Coefficients; Sample Butterfat Data and Meteorological Data for Ohakea (1955 - 1969)

	Y	X_1	X_5	X_7	X_8	X_{16}
Y	1.000	0.126	-0.313	0.741	0.498	0.822
X_1		1.000	-0.044	-0.102	-0.117	-0.045
X_5			1.000	-0.055	0.186	-0.182
X_7				1.000	0.857	0.858
X_8					1.000	0.740
X_{16}						1.000

Y = butterfat in time (t),
X_1 = time,
X_5 = solar radiation in time (t),
X_7 = solar radiation in time (t-2),
X_8 = mean daily temperature in time (t),
and X_{16} = mean daily minimum temperature in time (t-2).

TABLE XIX

CASE TWO : RESULTS OF REGRESSION ANALYSIS BETWEEN SAMPLE BUTTERFAT DATA AND METEOROLOGICAL DATA RECORDED AT OHAKEA (1955–1969)

Step	Variable	Constant	Partial b – coeff	$s_{by.x}$	p (b)	Partial r	p (r)	β– coeff	$s_{\beta y.x}$	R	p (R)	$s_{zy.x}$	F–level of added term
1	X_{16}	2.8976	0.0469	0.0033		0.8215		0.8215	0.0588	0.8215		0.1715	< 0.0005
2	X_5		–0.0006	0.0002		–0.2913		–0.1689	0.0575				
	X_{16}	3.2788	0.0451	0.0032		0.8186		0.7907	0.0575	0.8381		0.1650	0.01
3	X_1		0.0098	0.0034		0.2836		0.1550	0.5460				
	X_5		–0.0005	0.0001		–0.2885		–0.1605	0.0555				
	X_{16}	3.0095	0.0456	0.0031		0.8321		0.7993	0.0555	0.8523		0.1591	0.002
4	X_7		0.0008	0.0002		0.3309		0.3733	0.1115				
	X_1		0.0111	0.0033		0.3310		0.1746	0.0521				
	X_5		–0.0008	0.0002		–0.3997		–0.2409	0.0579				
	X_{16}	3.6963	0.0265	0.0064		0.3963		0.4651	0.1129	0.8697		0.1509	0.01
5	X_8		–0.0322	0.0074	<0.0005	–0.4161	<0.0005	–0.4199	0.0967				
	X_7		0.0014	0.0002	<0.0005	0.4975	<0.0005	0.6639	0.1220				
	X_1		0.0102	0.0030	0.001	0.3362	0.0021	0.1619	0.0478				
	X_5		–0.0005	0.0001	<0.0005	–0.2990	0.0074	–0.1656	0.0557				
	X_{16}	5.0714	0.0308	0.0059	<0.0005	0.4774	<0.0005	0.5395	0.1046	0.8936	<0.0005	0.1380	< 0.0005

X_1 = time, X_5 = solar radiation in time (t), X_7 = solar radiation in time (t–2), X_8 = mean daily temperature in time (t), X_{16} = mean daily minimum temperature in time (t–2).

TABLE XX: The Variation Explained at Each Step in the Multiple Regression Analysis: Ohakea Case

Step	Variable Entered	Multiple Correlation Coefficient (R)	Coefficient of Determination (R^2)	Percentage Variation Explained	Percentage Additional Variation Explained
1	X_{16}	0.8215	0.6748	67.48%	67.48%
2	X_5	0.8381	0.7024	70.24%	2.76%
3	X_1	0.8523	0.7264	72.64%	2.40%
4	X_7	0.8697	0.7564	75.64%	2.99%
5	X_8	0.8936	0.8034	80.34%	4.70%

The coefficient of multiple correlation (R) is 0.8936 by the fifth step of the analysis. 80.34 per cent variation in butterfat production is accounted for by variation in time and meteorological factors included in the regression. A 99 per cent confidence interval of 0.8220 to 0.9370 can be set around P, the population parameter.

Case Three

Table XXII shows that variables X_7, X_{10}, and X_{16} have moderately high positive correlations with butterfat of +0.76, +0.74, and +0.80 respectively. These three variables, however, are highly intercorrelated.

TABLE XXI: Case Three: Summary Statistics for Sample Butterfat Data and Meteorological Data Recorded at Foxton-Waitarere Forest (1962 - 1969)

Variable	Low	High	Average	Standard Deviation	Variance
Bfat (t) (Y)	4.76	5.95	5.22	0.29	0.09
Time (t) (X_1)	23.00	31.00	27.30	2.37	5.60
WB (t) (X_2)	0.00	2.90	0.35	0.67	0.45
WB (t-1) (X_3)	0.00	2.90	0.27	0.66	0.44
WB (t-2) (X_4)	0.00	2.33	0.11	0.39	0.15
SR (t) (X_5)	333.40	612.80	489.26	76.95	5921.70
SR (t-1) (X_6)	289.70	612.80	480.67	91.10	8298.30
SR (t-2) (X_7)	185.40	612.80	429.60	136.76	18705.00
MDT (t) (X_8)	52.10	67.90	60.07	3.93	15.46
MDT (t-1) (X_9)	49.90	67.90	58.19	5.14	26.46
MDT (t-2) (X_{10})	44.90	67.90	55.84	6.04	36.52
MAX (t) (X_{11})	59.40	75.80	67.96	4.33	18.75
MAX (t-1) (X_{12})	55.30	75.80	65.97	5.42	29.38
MAX (t-2) (X_{13})	54.20	75.80	63.39	5.89	34.69
MIN (t) (X_{14})	43.90	58.40	51.75	3.53	12.45
MIN (t-1) (X_{15})	41.00	58.40	49.98	4.74	22.49
MIN (t-2) (X_{16})	35.60	57.60	47.88	5.84	34.14
GMT (t) (X_{17})	38.00	55.70	48.10	3.97	15.74
GMT (t-1) (X_{18})	35.30	55.70	46.13	5.38	28.93
GMT (t-2) (X_{19})	30.80	54.60	43.85	6.51	42.44

Bfat = Butterfat
WB = water balance
SR = solar radiation
MDT = mean daily temperature
MAX = mean daily maximum temperature
MIN = mean daily minimum temperature
GMT = mean daily grass minimum temperature

The values (t), (t-1), and (t-2) are as referred to in the text (p. 74). No. of cases = 47.

TABLE XXII: Case Three: Matrix of Simple Correlation Coefficients; Sample Butterfat Data and Meteorological Data for Foxton - Waitarere Forest (1962 - 1969)

	Y	X_1	X_5	X_7	X_{10}	X_{16}
Y	1.000	-0.396	-0.344	0.755	0.742	0.795
X_1		1.000	0.078	-0.100	-0.120	-0.070
X_5			1.000	0.034	-0.129	-0.159
X_7				1.000	0.899	0.883
X_{10}					1.000	0.956
X_{16}						1.000

Y = butterfat in time (t),
X_1 = time,
X_5 = solar radiation in time (t),
X_7 = solar radiation in time (t-2),
X_{10} = mean daily temperature in time (t-2),
and X_{16} = mean daily minimum temperature in time (t-2).

TABLE XXIII

CASE THREE : RESULTS OF REGRESSION ANALYSIS BETWEEN SAMPLE BUTTERFAT DATA AND METEOROLOGICAL DATA RECORDED AT FOXTON – WAITARERE FOREST (1962–1969)

Step	Variable	Constant	Partial b – coeff	$s_{by.x}$	p (b)	Partial r	p (r)	β–coeff	$s_{\beta y.x}$	R	p (R)	$s_{zy.x}$	F–level of added term
1	X_{16}	3.3140	0.0398	0.0045		0.7951		0.7951	0.0903	0.7951		0.1793	<0.0005
2	X_1		–0.0327	0.0101		–0.4363		–0.2652	0.0824				
	X_{16}	4.2533	0.0388	0.0041		0.8175		0.7766	0.0824	0.8380		0.1632	0.01
3	X_5		–0.0007	0.0002		–0.3719		–0.2060	0.0784				
	X_1		–0.0310	0.0095		–0.4427		–0.2512	0.0776				
	X_{16}	4.6658	0.0373	0.0039		0.8231		0.7448	0.0783	0.8622		0.1532	0.05
4	X_7		0.0009	0.0003		0.3629		0.4265	0.1689				
	X_5		–0.0010	0.0003		–0.4798		–0.2839	0.0801				
	X_1		–0.0283	0.0091		–0.4333		–0.2295	0.0736				
	X_{16}	5.2751	0.0178	0.0085		0.3077		0.3571	0.1704	0.8816		0.1445	0.05
5	X_{10}		–0.0323	0.0124	0.0122	0.3761	0.030	–0.6675	0.2568				
	X_7		0.0012	0.0003	<0.0005	0.4780	0.0023	0.5983	0.1716				
	X_5		–0.0011	0.0002	<0.0005	–0.5245	< 0.0005	–0.2970	0.0753				
	X_1		–0.0318	0.0086	0.0006	–0.4990	0.0014	–0.2578	0.0699				
	X_{16}	5.8861	0.0420	0.0122	0.0014	0.4719	0.0027	0.8393	0.2448	0.8993	<0.0005	0.1355	0.05

X_1 = time, X_5 = solar radiation in time (t), X_7 = solar radiation in time (t–2), X_{10} = mean daily temperature in time (t–2), X_{16} = mean daily minimum temperature in time (t–2).

Variable X_1 retained a relatively constant value of b through the analysis (Table XXIII). The partial regression coefficient for X_5 increased rapidly with respect to its error. That for X_{16} remained stable except at the fourth step when X_7 entered the regression. The b associated with X_{16} increased as X_{10} entered the regression at the fifth step.

In terms of the β-coefficients X_{16} appears to be the most important in this trial although the associated standard error is high. Taking the errors of the coefficients into consideration, X_1 ranks ahead of the other variables when it actually has the lowest absolute β-coefficient.

Table XXIV indicates the amount of variation in butterfat production explained at each step in the analysis.

TABLE XXIV: The Variation Explained at Each Step in the Multiple Regression Analysis: Foxton - Waitarere Forest Case

Step	Variable Entered	Multiple Correlation Coefficient (R)	Coefficient of Determination (R^2)	Percentage Variation Explained	Percentage Additional Variation Explained
1	X_{16}	0.7951	0.6322	63.22%	63.22%
2	X_1	0.8380	0.7022	70.22%	7.00%
3	X_5	0.8622	0.7434	74.34%	4.12%
4	X_7	0.8816	0.7772	77.72%	3.38%
5	X_{10}	0.8993	0.8087	80.87%	3.16%

The coefficient of multiple correlation (R) is 0.8993 by the fifth step of the analysis. Meteorological factor variations and the passage of time account for 80.87 per cent of the observed variation in butterfat production. A 99 per cent confidence interval of 0.7860 to 0.9530 can be set around P, the population parameter.

Case Four

The three variables X_7, X_{16}, and X_{19} reveal moderately high positive correlations of +0.75, +0.80, and +0.77 respectively with the dependent variable (Table XXVI). Again, these three regressor variables are well intercorrelated.

From the point of entry of X_{19} the b associated with X_{16} gained some stability (Table XXVII). Stable b's were maintained for variables X_2 and X_{19} after their inclusion in the regression. The b associated with X_7 increased considerably from the fourth to the fifth steps.

As in the previous case the β-coefficients rank somewhat differently from the b's in this trial. Again, however, the errors of the β-coefficients which are absolutely the most impressive are high.

Table XXVIII indicates the variation in butterfat production explained at each step in the analysis.

TABLE XXV: Case Four: Summary Statistics for Sample Butterfat Data and Meteorological Data Averaged From Cases One, Two, and Three (1962 - 1969)

Variable	Low	High	Average	Standard Deviation	Variance
Bfat (t) (Y)	4.76	5.95	5.24	0.29	0.08
Time (t) (X_1)	23.00	31.00	27.16	2.30	5.30
WB (t) (X_2)	0.00	2.87	0.28	0.61	0.37
WB (t-1) (X_3)	0.00	2.87	0.21	0.58	0.33
WB (t-2) (X_4)	0.00	2.15	0.07	0.33	0.11
SR (t) (X_5)	326.00	602.10	480.39	73.07	5339.10
SR (t-1) (X_6)	283.50	602.10	479.14	84.21	7092.10
SR (t-2) (X_7)	180.50	602.10	433.41	127.03	16138.00
MDT (t) (X_8)	52.20	66.90	60.68	3.76	14.12
MDT (t-1) (X_9)	50.00	66.90	58.81	4.94	24.40
MDT (t-2) (X_{10})	45.70	66.90	56.28	5.83	34.03
MAX (t) (X_{11})	59.20	76.20	60.78	4.34	18.88
MAX (t-1) (X_{12})	53.70	75.40	66.74	5.55	30.80
MAX (t-2) (X_{13})	53.70	75.80	64.02	6.16	37.99
MIN (t) (X_{14})	45.10	59.10	52.51	3.34	11.17
MIN (t-1) (X_{15})	42.20	59.10	50.73	4.54	20.61
MIN (t-2) (X_{16})	37.70	58.10	48.55	5.44	29.64
GMT (t) (X_{17})	41.10	55.40	48.42	3.43	11.73
GMT (t-1) (X_{18})	36.10	55.40	46.38	5.02	25.15
GMT (t-2) (X_{19})	32.00	54.40	44.04	6.02	36.24

Bfat = butterfat
WB = water balance
SR = solar radiation
MDT = mean daily temperature
MAX = mean daily maximum temperature
MIN = mean daily minimum temperature
GMT = mean daily grass minimum temperature

The values (t), (t-1), and (t-2) are as referred to in the text (p. 74). No. of cases = 44.

TABLE XXVI: Case Four: Matrix of Simple Correlation Coefficients; Sample Butterfat Data and Meteorological Data Averaged From Cases One, Two, and Three (1962 - 1969)

	Y	X_2	X_7	X_{14}	X_{16}	X_{19}
Y	1.000	0.111	0.751	0.447	0.798	0.770
X_2		1.000	0.431	0.398	0.431	0.424
X_7			1.000	0.831	0.896	0.894
X_{14}				1.000	0.680	0.684
X_{16}					1.000	0.992
X_{19}						1.000

Y = butterfat data in time (t),
X_2 = water balance in time (t),
X_7 = solar radiation in time (t-2),
X_{14} = mean daily minimum temperature in time (t),
X_{16} = mean daily minimum temperature in time (t-2),
and X_{19} = mean daily grass minimum temperature in time (t-2).

TABLE XXVII

CASE FOUR : RESULTS OF REGRESSION ANALYSIS BETWEEN SAMPLE BUTTERFAT DATA AND METEOROLOGICAL DATA AVERAGED FROM DATA RECORDED IN CASES ONE, TWO, AND THREE (1962–1969)

Step	Variable	Constant	Partial b – coeff	$s_{by.x}$	p (b)	Partial r	p (r)	β–coeff	$s_{\beta y.x}$	R	p (R)	$s_{zy.x}$	F–level of added term
1	X_{16}	3.1698	0.0426	0.0049		0.7981		0.7981	0.0929	0.6370		0.1773	< 0.0005
2	X_2		–0.1373	0.0452		–0.4280		–0.2857	0.0942				
	X_{16}	2.8896	0.0492	0.0050		0.8365		0.9212	0.0942	0.8387		0.1622	0.01
3	X_{19}		–0.0664	0.0312		–0.3185		–1.3743	0.6465				
	X_2		–0.1397	0.0434		–0.4531		–0.2907	0.0904				
	X_{16}	2.2718	0.1222	0.0346		0.4868		2.2867	0.6487	0.8565		0.1556	0.10
4	X_7		0.0006	0.0004		0.2479		0.2916	0.1824				
	X_{19}		–0.0710	0.0307		–0.3466		–1.4708	0.6372				
	X_2		–0.1477	0.0429		–0.4824		–0.3072	0.0893				
	X_{16}	2.6015	0.1137	0.0344		0.4675		2.1280	0.6442	0.8660		0.1527	0.50
5	X_{14}		–0.0351	0.0119	0.0066	–0.4290	0.0098	–0.4036	0.1378				
	X_7		0.0016	0.0005	0.0030	0.4680	0.0042	0.7385	0.2262				
	X_{19}		–0.0663	0.0282	0.0230	–0.3563	0.040	–1.3731	0.5840				
	X_2		–0.1342	0.0395	0.0016	–0.4822	0.0029	–0.2792	0.0822				
	X_{16}	4.4011	0.1011	0.0317	0.0044	0.4586	0.0053	1.8930	0.5949	0.8922	<0.0005	0.1397	0.01

X_2 = water balance in time (t), X_7 = solar radiation in time (t–2), X_{14} = mean daily minimum temperature in time (t), X_{16} = mean daily minimum temperature in time (t–2), X_{19} = mean daily grass minimum temperature in time (t–2).

TABLE XXVIII: The Variation Explained at Each Step in the Multiple Regression Analysis: Averaged Meteorological Data Case

Step	Variable Entered	Multiple Correlation Coefficient (R)	Coefficient of Determination (R^2)	Percentage Variation Explained	Percentage Additional Variation Explained
1	X_{16}	0.6370	0.4058	40.58%	40.58%
2	X_2	0.8387	0.7034	70.34%	29.76%
3	X_{19}	0.8565	0.7336	73.36%	3.02%
4	X_7	0.8660	0.7500	75.00%	1.64%
5	X_{14}	0.8922	0.7960	79.60%	4.60%

By the fifth step of the analysis the multiple correlation coefficient (R) reaches 0.8922 and 79.60 per cent of the observed variation in butterfat production is explained by the meteorological parameters included. A 99 per cent confidence interval of 0.8530 to 0.9210 can be set around P, the population parameter.

Notes:

1 The coefficient of autocorrelation is given by Ezekiel and Fox (1959:337) as:

$$r_a = \frac{\Sigma z_t \; z_{t+1}}{\Sigma z_t^2}$$

where the z_t's are the residuals and the z_{t+1}'s lagged residuals.

2 Tables could not be located for the calculation of the power associated with the decision to accept this hypothesis.

Chapter Six

CONCLUSIONS

Overall 10 of the original 19 regressor variables found their way into the final equations. Four of these appear in three of the final analyses and the other six in one only.

Solar radiation recorded two months in advance of the butterfat test (X_7) is important in all four cases. In each analysis the sign of the partial regression coefficient associated with this variable is positive. This coefficient, however, was not stable from step to step through any of the analyses, but tended to increase with their progress. Solar radiation two months prior to the butterfat test shows a greater impact upon butterfat as some of the temperature variables are included in the equations. These temperature variables show simple correlations with this solar radiation variable ranging from +0.831 to +0.899 (Tables XVIII, XXII, and XXVI). This point is referred to again below.

In each analysis, except that where the meteorological data from all stations were averaged, solar radiation recorded in the same month as the butterfat test (X_5) is significant. The partial regression coefficients are negative. Although shown to be gradually increasing in the analyses using data from Palmerston North D.S.I.R. and Foxton-Waitarere Forest, while fluctuating in the case of Ohakea, the b's here appear to be more stable than those for X_7.

Time (X_1) is significant in the same analyses as X_5. Strangely, its coefficients are negative in the Foxton-Waitarere case. Only in this case did the b fluctuate greatly. Elsewhere it showed a slight increase as the regression proceeded.

One further variable was incorporated in three analyses. Mean daily minimum temperature two months in advance of the butterfat test (X_{16}) is significant and prefixed with positive coefficients in all but the Palmerston North D.S.I.R. case. The stability of the partial regression coefficients tended to fluctuate, particularly as the solar radiation variable for the same month (X_7) was entered. The coefficient for X_{16} was reduced when X_7 was considered in combination with it, but was increased again as mean daily temperature in the same month as the test (X_8) and mean daily temperature two months prior to the test (X_{10}) were entered (Tables XIX and XXIII).

The other variables which are significant are incorporated in one case only, and on the basis of the β-coefficients generated in these trials, are never the most important variables. They are: water balance in the month of the test (X_2), mean daily temperature in the month of the test (X_8), mean daily temperature two months prior to the test (X_{10}), mean daily maximum temperature two months in advance of the butterfat test (X_{13}), mean daily minimum temperature in the month of the test (X_{14}), and mean daily grass minimum temperature two months in advance of the test (X_{19}).

The highest estimated multiple correlation coefficient (R) was obtained in the analysis which used meteorological data from the Foxton and Waitarere Forest stations combined. For the respective periods analysed the coefficient of determination (R^2) indicates the meteorological data recorded at these stations to best explain the variation in butterfat production in the study region.

It is interesting to note that the period for which this highest statistical relationship was obtained (i.e. 1962 to 1970) was that when climatic factors might have been expected to show a lesser impact because of improving farm management practices. These should theoretically, in an 'unchanged' climatological situation, have reduced the impact of physical factors.

From the Foxton-Waitarere Forest analysis it appears that the most desirable condition for butterfat production was cool, sunny weather two months prior to the butterfat test. Cloudy conditions in the same month as the test, however, appear to be suited to dairy production. It has already been shown above that mean daily temperature, mean daily minimum temperature, and solar radiation two months earlier than the butterfat test are significant positive factors.

It is suggested that these findings are not contradictory and can be explained by examining the avenues of meteorological influence upon the butterfat test. Cloudy conditions in the month of the test probably best suit the dairy cow's physiological functioning. This is broadly supported in the literature reviewed by Hancock (1954). Furthermore, the works cited earlier on climate-plant growth relationships indicate that weather factors acting two months in advance of the butterfat test do so through their effects upon pasturage and not animal physiology (Sprague, 1943; Blackman and Wilson, 1951; Mitchell, 1954, 1955, 1956a, 1956b; Mitchell and Coles, 1955; Mitchell and Lucanus, 1962; Brougham, 1956, 1959; Blackman and Black, 1959a, 1959b; Bean, 1964; Ivory, 1964). It is conjectured that solar radiation in the month of the test is less important through its negative effects, as it adversely affects animal physiology, than its positive effects, two months removed, upon pasturage. The meteorological variables prevailing earlier are highly inter-correlated in the same direction and the magnitude of these joint-effects cannot be ignored.

Maunder (1965) was able to predict the effects of above, or below, average climatic conditions upon the branches of the agricultural industry he investigated. Accordingly, he estimated the probable influence of fluctuations of one standard deviation in his climatic parameters. The same idea is used here.

It follows, *ceteris paribus*, that the effects of a variation of one standard deviation above, or below, average meteorological conditions will be as illustrated in Table XXIX.

The second most successful analysis in accounting for butterfat variations was that where meteorological data from Ohakea were used (Case Two). Here R^2 is 0.7985.

Once again cool, but sunny weather two months in advance of the butterfat test is required for high levels of butterfat production. Cool conditions in the month of the test also appear to be important whereas sunny conditions are not, probably for the physiological reasons suggested above.

TABLE XXIX: The Effect of a Meteorological Variation One Standard Deviation From Average Upon Butterfat Production: Foxton-Waitarere Forest Case

Variable	Regression Results			
	X_5	X_7	X_{10}	X_{16}
Average	489.260	429.600	55.842	47.876
Std Dev.	76.950	136.760	6.043	5.843
Coeff. Regr.	-0.0011	0.0012	-0.0323	0.0420
Std Error	0.0002	0.0003	0.0124	0.0122
	Effect Upon Butterfat Percentage			
Effect of ± 1 S.D.	±0.085%	±0.164%	±0.195%	±0.245%
Std Error	0.014%	0.041%	0.075%	0.073%

The predicted effects on butterfat of fluctuations from average meteorological conditions are presented in Table XXX.

When the meteorological data from all stations were averaged over the years 1962 to 1970 the variation in butterfat percentage accounted for by the weather factors is 79.6 per cent (R^2 = 0.7960).

Evidently cool, sunny conditions two months prior to the butterfat test are again important. Warm, dry conditions are not desirable in the month of the test. It is considered that such dry conditions are not favourable as far as pasture growth is concerned, for a lack of precipitation would not directly affect the animal. The cooling benefit of rain in this region, ' . .

TABLE XXX: The Effect of a Meteorological Variation One Standard Deviation From Average Upon Butterfat Production: Ohakea Case

Variable	Regression Results			
	X_5	X_7	X_8	X_{16}
Average	487.200	439.150	61.102	48.851
Std Dev.	83.445	137.430	3.893	5.242
Coeff. Regr.	-0.0005	0.0014	-0.0322	0.0308
Std Error	0.0001	0.0002	0.0074	0.0059
	Effect Upon Butterfat Percentage			
Effect of ± 1 S.D.	±0.042%	±0.192%	±0.125%	±0.612%
Std Error	0.008%	0.028%	0.029%	0.031%

considering the above reviewed literature and the air temperatures involved, is probably minimal. As the correlation between water balance and mean daily minimum temperature in the month of the butterfat test is low (+0.40) it is suggested that the cool temperatures that are indicated as favourable have their greater effect upon the dairy cow's physiological functioning. Substantive reasoning as to the time lag involved over the direct effect of temperature conditions upon pasture growth strengthens this assumption.

The importance of variations in these meteorological factors was predicted and is depicted below (Table XXXI).

Of the four cases analysed that for which the longest time period is involved (Palmerston North D.S.I.R.: Case One)

TABLE XXXI: The Effect of a Meteorological Variation One Standard Deviation From Average Upon Butterfat Production: Averaged Meteorological Data Case

Variable	Regression Results				
	X_2	X_7	X_{14}	X_{16}	X_{19}
Average	0.285	433.210	52.506	48.554	44.038
Std Dev.	0.605	127.030	3.342	5.444	6.020
Coeff. Regr.	-0.1342	0.0016	-0.0351	0.1011	-0.0663
Std Error	0.0395	0.0005	0.0119	0.0317	0.0282
	Effect Upon Butterfat Percentage				
Effect of ± 1 S.D.	±0.081%	±0.203%	±0.117%	±0.550%	±0.399%
Std Error	0.024%	0.064%	0.040%	0.173%	0.170%

shows the weakest statistical link between meteorological factors and dairy production (R^2 = 0.6864). Even so, this is considered to show a reasonably strong cause-and-effect relationship.

In this case time played the major part in accounting for butterfat variations. Of the meteorological variables, however, warm and sunny conditions appear favourable two months prior to the butterfat test. It may be that warm conditions here were not severe enough to create an unfavourable water balance, thereby restricting plant growth (the correlation between water balance and mean daily maximum temperature, both recorded two months before the herd testing, for this case is +0.34549). Cloudy conditions in the month of the test are again required for high butterfat production.

The estimated effects upon butterfat of variations in the weather factors concerned are shown in Table XXXII.

TABLE XXXII: The Effect of a Meteorological Variation One Standard Deviation From Average Upon Butterfat Production: Palmerston North D.S.I.R. Case

Variable	Regression Results		
	X_5	X_7	X_{13}
Average	467.50	413.66	68.830
Std Dev.	74.240	127.32	5.937
Coeff. Regr.	-0.0011	0.0010	0.0177
Std Error	0.0002	0.0003	0.0073
	Effect Upon Butterfat Percentage		
Effect of ± 1 S.D.	±0.082%	±0.127%	±0.105%
Std Error	0.015%	0.038%	0.043%

It is now evident that the results obtained can be considered very satisfactory in respect of the low variability of the dependent variable in the first place. The variation to be accounted for is slight and that as many meteorological variables are significant in accounting for this variation supports the original hypothesis.

The inclusion of a time variable proved satisfactory as it is significant ($\alpha = 0.05$) in three of the four analyses. The linear nature of this variable is apparently justified although no attempt was made to investigate whether, as in the case of Maunder (1965), a second order time variable would have yielded better results. If this variable can be envisaged as one attempting to account for all non-meteorological factors it might well be expected to take other than first order form in which case its effectiveness might be greater.

Despite expectations to the contrary, no water balance variable is significant in three of the four analyses. Three explanations are offered for this. Firstly, a moisture factor is genuinely not as important as originally thought. This appears to be the best explanation. Secondly, the effects of water deficit are largely accounted for by other significant variables, but in no case is the water balance highly correlated with any other single variable. Thirdly, the type of moisture parameter used and the adjustments carried out upon it (Chapter Three) were such as to render it ineffective as a measure of moisture availability. This is not thought likely.

The matrices of correlation coefficients presented in Chapter Five indicate solar radiation to be highly intercorrelated with other meteorological variables, particularly the temperature variables. These weather factors are probably joint in their effect upon both pasturage and animal physiological conditions. The time, solar radiation, and temperature variables are the most consistently significant in the analyses performed. It is interesting to note the indicated significance of the various temperature variables in combination with solar radiation although they showed high intercorrelations with this variable.

Provided the assumptions regarding the use of the model are met and the situation in which the climate-dairy production relationship investigated can be assumed to remain constant into the future, the following prediction equations are valid. The prediction model suggested above (page 75) was:

$$Y = b_o + \sum_{k=1}^{n} b_k X_k + E$$

This is applied to the four cases as:

1) Palmerston North D.S.I.R.

$$\bar{Y} = b_o + b_1 X_1 - b_5 X_5 + b_7 X_7 + b_{13} X_{13}$$

which takes the specific values:

$$Y = 3.7148 + 0.0177X_1 - 0.0011 X_5 + 0.0010X_7 + 0.0177X_{13};$$

2) Ohakea

$$Y = b_o + b_1 X_1 - b_5 X_5 + b_7 X_7 - b_8 X_8 + b_{16} X_{16}$$

which takes the specific values:

$$Y = 5.0714 + 0.0102X_1 - 0.0005X_5 + 0.0014X_7 - 0.0322X_8 + 0.0308X_{16};$$

3) Foxton-Waitarere Forest

$$Y = b_o - b_1 X_1 - b_5 X_5 + b_7 X_7 - b_{10} X_{10} + b_{16} X_{16}$$

which takes the specific values:

$$Y = 5.8861 - 0.0318X_1 - 0.0011X_5 + 0.0012X_7 - 0.0323X_{10} + 0.0420X_{16};$$

and 4) Average of Stations 1, 2, and 3

$$Y = b_o - b_2 X_2 + b_7 X_7 - b_{14} X_{14} + b_{16} X_{16} - b_{19} X_{19}$$

which takes the specific values:

$$Y = 4.4011 - 0.1342X_2 + 0.0016X_7 - 0.0351X_{14} + 0.1011X_{16} - 0.0663X_{19}.$$

Maunder (1968) reported on an analysis of butterfat production in the Puketaha Herd Testing Group and climatic data for Ruakura climatological station for the seasons 1936/37 to 1959/60. Maunder used the model:

$$Y = a_o + a_1 x_1 + a_1' x_1^2 + a_2 x_2 + , \ldots, + a_{15} x_{15}$$

where specifically:

Y = seasonal butterfat production;

x_1 = season (1936/37 = 1, 1937/38 = 2, etc.);

$x_2 \ldots x_6$ = rainfall October ... rainfall February;

$x_7 \ldots x_{11}$ = mean temperature October ... mean temperature February;

and $x_{12} \ldots x_{15}$ = sunshine November ... sunshine February.

Significant (α = 0.05) climatic factors are shown in Table XXXIII.

Generally, Maunder (1965) was able to show in his nationwide analysis that favourable monthly conditions for butterfat yields above average levels are a wet October, a wet and cool November, a wet and cloudy December, a wet and warm January, and a wet, cool, and cloudy February. The multiple regression analyses show coefficients significant at the five per cent level for 21 out of his 25 county analyses.

Although seasonally based, Maunder's (1965) results are not inconsistent with those found in this analysis, for cool and cloudy conditions appear to be favourable for butterfat production measured at the monthly level.

TABLE XXXIII: Significant (α = 0.05) Variables According to Maunder (1968)

Variable	Probability Level (%)
October rainfall	0.5
December rainfall	2.5
January rainfall	1.0
February rainfall	0.05
November temperature	2.0
January sunshine	1.0

Maunder used a multiple regression analysis which did not involve stepwise computation. Accordingly, his regression coefficients showed the importance of each variable with all the others held statistically constant. This is not the case in the stepwise analysis where the dependent variable is regressed on combinations of the variables entered with the remaining variables held constant. Although the water balance parameters are not often significant in combination with the variables already entered in these analyses, this is not to say that they would not be in a simple multiple regression analysis. The correlation coefficients between the water balance factors and butterfat are moderate to low. Nevertheless, these water balance parameters might still have been entered in a simple multiple regression analysis where all variables other than the one under consideration are held constant in computing the regression coefficients. Thus, it is not possible to tell directly from the simple correlation matrices which variables are those accounting for most of the variation in butterfat production. When taken in combination with other variables, or when the others are held statistically constant, patterns not suggested in the initial matrices may emerge.

On reflection the mode of analysis would seem to be suited to the type of problem investigated. Many of the variables originally suggested were subsequently found to be not significant, but they may still have been important and accounted for by virtue of their high intercorrelation with other variables. It is thus emphasised that the variables indicated as significant are not necessarily those alone accounting for the variation shown. The effects of other intercorrelated variables may be involved with them.

Within the limits of the prediction model (i.e. that non-meteorological conditions remain unaltered into the future) the meteorological variables used in the final regression equations can be used to predict butterfat levels. This is particularly so since it is apparent that the most important variables can be measured at least two months prior to the butterfat assessment. The model may have been partially unsatisfactory in that lagged effects beyond two months were not ascertained, yet it is now evident that longer lags might well be present.

It is upheld that the working hypothesis initially stated has been substantiated in this research. Further refinements of the mathematical model, to include higher than first order terms and other meteorological and non-meteorological variables, could well add to the explanation given here. When precise measurement of less tangible variables becomes possible more sophisticated techniques might be applied appropriately to similar problems. The use of such techniques and the empirical satisfaction of some of the assumptions made about the data and the model above will produce results which can be interpreted more confidently.

Nevertheless, for the time period concerned it has been shown that meteorological variations account for at least 68.64% and as much as 80.87% of variation in butterfat yield. These figures may be regarded as a minimum explanation for the failure to satisfy any assumptions in the model would have lowered its effectiveness. The prediction case must be treated more carefully for the assumptions involved here are wider than statistical and require the continuance of present conditions in the dairy industry unchanged into the future.

The statistical relationships found can be applied to the physical situation only on substantive grounds, but it is contended that this has been shown to be a valid extension. Finally, it is hoped that the analysis has helped to show, in however limited a way, that further agroclimatological studies of this kind are not unwarranted in an economy so intrinsically bound to primary production.

Appendix A

NOTES ON SITE CHANGES OF THE PALMERSTON NORTH D.S.I.R. AND OHAKEA CLIMATOLOGICAL STATIONS

Palmerston North D.S.I.R.

From the end of 1940 D.S.I.R. staff temporarily took over observations from Massey Agricultural College, and from March 1941 observations were made at the old site by Plant Research Bureau staff.

In November 1942 a new site 400 yards southwest of the previous one was established.

A slight site change was effected on 11 November 1969.

Ohakea

On 12 September 1969 the sunshine recorder was moved to a site approximately 1,400 yards westnorthwest of the previous site.

All synoptic and climatological observations were transferred from the old headquarters site to the Meteorological Radar Office, the new sunshine recording site, at 0915 hours on 1 November 1969.

On 30 October 1969 between 0840 and 0926 hours the Epply solarimeter was shifted to this new site.

Appendix B

THE COMPUTATION OF A WATER BALANCE PARAMETER

In the computation of water balance figures the average daily value of potential evapotranspiration (PE) is compared with the available water for each day (i.e. the day's rainfall (r) plus the available soil moisture). the difference (R-PE) is added algebraically to the soil moisture to get the amount of soil moisture to carry forward to the following day. This, however, is limited to a maximum value - the assumed soil moisture capacity (S). Evapotranspiration is assumed to continue at the potential rate so long as soil moisture has not reached wilting point.

PE is the Thornthwaite average for the month and is calculated from the monthly normal temperature for the station in question (daily or yearly variations in evaporative demand are ignored for they are slight compared with rainfall variations).

Thornthwaite's 1948 formula is readily obtained in climatological texts and the relevant evaluation tables may be found in:

Thornthwaite, C.W. and Mather, J.R. (1957) Instructions and Tables for Potential Evapotranspiration and the Water Balance, Drexel Institute of Technology. Publications in Climatology, 10(3).

For each month the print-out gives:

a b

c d

where, a is the runoff or surplus rainfall summed over the month when rainfall exceeds PE and the restoration of soil moisture to field capacity;

b is the number of such days per month;

c is the sum of daily deficits of calculated evapotranspiration with respect to PE (i.e. the sum of (PE-R) for days when soil moisture is calculated as zero). This is the actual parameter utilised;

d is the number of such days. (The number of days of 'Agricultural Drought' as defined by Rickard (1960 : 432), "Agricultural drought exists when the soil moisture in the root zone is at, or below, the permanent wilting percentage. The condition continues until rain falls in excess of the daily evapotranspiration.")

In addition various summary figures are given. Interruptions of data cause longer interruptions in the printed results.

Appendix C

CALCULATION OF THE SOLAR RADIATION PARAMETER

The parameters involved in the De Lisle equation,

$$Q/Q_o = a + b\ (n/N)$$

were obtained as follows:

Q_o, the radiation per unit time on a horizontal surface 'outside' the atmosphere was obtained from List (1951). The values given therein are for specific dates spaced at irregular intervals. The sigmoid function of solar radiation incident at the top of the atmosphere was plotted from these values to yield values of solar radiation (in langleys) received over the total year. The solar radiation on the fifteenth day of each month (except February, for which the fourteenth day was selected) was interpolated from the resultant graph, and the value obtained adjusted to suit a solar constant of 1.98 ly day^{-1}. List's values were calculated using a solar constant of 1.94 ly day^{-1} and this is now generally believed to be too low (Sellers, 1965; De Lisle, 1966).

N, the astronomically possible sunshine per unit time was calculated for each month using the tables of Thornthwaite and Mather (1957) which give the mean possible duration of sunlight by latitude and month, expressed in units of 12 hours. The 40^{o}S latitude figures were accepted, no attempt being made to interpolate between this and the 41^{o}S line. Again, no adjustment was formulated to account for the inability of the sunshine recorders to record at very low solar elevations (c.f. De Lisle, 1966, who reasoned that the parameter N should be reduced by one-half hour per day), but this failure is not expected to be of profound importance considering the nature of the model developed.

The constants, a and b, are taken from De Lisle (1966) who derived them by least squares from a series of simultaneous radiation and sunshine measurements. The constants are for Ohakea and are legitimately used over a wider area (De Lisle, 1966:997).

n is the bright sunshine per unit time recorded by the New Zealand Meteorological Service at the respective stations.

Appendix D

THE ASSUMPTIONS MADE IN THE USE OF THE LINEAR MODEL

Before stating the assumptions of the linear model, some terminology should be clarified. It is customary to refer to the term on the left hand side of a regression equation as the 'dependent' variable, while those terms on the right hand side are referred to as the 'independent' variables. Kendall and Stuart (1967) suggest that the so-called 'independent' variables need not be random and that it is confusing to designate them 'independent' when the purpose of the model is to investigate the dependence of one other variable upon them. They are thus referred to as the 'regressor' variables, or the 'regressors'.

Poole and O'Farrell (1971) comment at some length on the assumptions of the linear regression model, stating seven assumptions commonly involved. Depending on the purpose of the model, not all of these assumptions are relevant in every case, but as the model employed is essentially seen as one of both explanation and prediction the following assumptions are considered paramount.

The presence of measurement error in the data is not serious. This error is assumed to be small because the meteorological recordings used have been instrumentally measured and dairy production figures have been scientifically established. In many instances the unknown amount of measurement error is assumed to be less significant than the errors arising out of the inaccuracy of equation specification (Poole and O'Farrell, 1971) and the measurement errors are not considered to be of a scale granduer enough to be troublesome. They further claim that measurement error may be ignored if the regression's objective is singularly to predict the dependent variable from a given set of regressor variables.

The use of the linear model assumed that for this analysis there is no effect of diminishing dairy returns associated with successive increments of meteorological input. This may well be true over much of the range of meteorological data examined in this work and the assumption of linearity was hereby made. If a curvilinear form fits the relationship more accurately, it might still not fully satisfy the prediction requirements about the disturbance term E (normally distributed, with mean zero and variance σ^2 not depending upon the equation parameters or variables) in the equation (page 75). For purposes of simplification, higher than first order polynomials were not considered. Removing the assumption of linearity would mean that the best-fit linear equation is calculated for the data used, and in this event some of the residual error is due to the linear function's failure to describe the true relationship. For this analysis the assumptions made below about linearity and the error term are deemed to hold, and so the use of the linear model for prediction purposes follows.

Linearity in the parameters of the chosen functional form is essential for the use of the least-squares technique. Kendall and Stuart (1967) emphasise that this is more relevant than linearity in the actual variables. This linearity in the parameters is assumed to exist and so the disturbance is likewise assumed not to be partially a reflection of the model's failure to describe the prevailing relationship.

Poole and O'Farrell (1971) allude to three tests for linearity of a relationship. A high-order polynomial is fitted and the regression coefficients of terms higher than first order are tested for significant departures from zero, or, the data for the regressor variables is stratified and a regression equation computed for each stratum after which the significance of the differences between each of the slope coefficients is tested. Alternatively, the sequence of residuals, arranged in order of increasing value of the regressor variables, is tested for randomness.

An indication of linearity was sought by graphically plotting some of the meteorological variables singularly against butterfat production, but the scatter of points showed little except that several meteorological variables could be jointly important in determining butterfat levels. At this level it was not intended to mathematically test the assumption of linearity but, if it were and the data found to be non-linear in the relationship, transformations of the data could be attempted which, if successful, would grant validity to the use of the classical regression model.

If the variables X_i are not linearly independent of each other multicollinearity is said to be present and the individual regression coefficients for each variable are not identifiable. This imprecision in the estimate of the regression coefficients is generally shown by high standard errors. Multicollinearity may be reduced by incorporating more data or removing certain variables in which case greater care must be taken in interpreting the resultant coefficients. In terms of an estimation of butterfat production by using meteorological data, or describing the relationship between these two sets of phenomena, the fact that the regressor variables are not necessarily independent of each other is not a serious problem. When attempting to place importance upon one meteorological variable on the basis of its regression and correlation coefficients, however, this drawback of interdependence becomes more severe and special attention must be granted to the partial correlation coefficients.

With reference to the variable E of the prediction equation, each conditional distribution of the error associated with each variate has a mean of zero and a variance which is assumed constant. There is also a requirement that the errors associated with these variates are serially independent. Time series data may show correlation between successive measurements and the residuals can hence be serially, or autocorrelated. When autocorrelation is shown to be present the usual error formulae applicable to the regression and correlation coefficients as estimators of the population parameters are invalidated.

For inferential purposes, but not point estimation, it is also necessary, in a model using random variables, for the distribution of each variable to approximate normality if the sample is small. Large samples mean the demand for normality can be waived.

On the validity about the assumptions about the disturbance term, E, Poole and O'Farrell (1971) comment that examination of patterns of residuals indicates patterns of disturbances. The mean of E should be zero and thus independent of the regressor variables, but if the residual variance is small this is not important. Homoscedasticity is difficult to test for, the available tests being highly sensitive to non-normality even though it is apparently not dangerous to ignore non-normality in statistical inference related to disturbance distributions. Autocorrelation of the residuals can be tested for and this is attempted by the method indicated in Chapter Five.

Appendix E

REQUIREMENTS FOR THE USE OF PARAMETRIC TESTS

Parametric tests such as Snedecor's *F*-test and Student's *t*-test were employed in this analysis. The use of parametric tests presupposes certain prerequisites in the population data and the tests are relevant only if the assumptions made about the population conditions are accurate.

Two such conditions are immediately present. The variables are available on the interval scale in that order and degree of magnitude are known. Also, the observations are regarded as being independent in the sense that the selection of one variate in no way alters the chance of selection of another variate. The method of random sample selection (Chapter Three) assured independence in the dairy production variable, while climatologists and meteorologists generally accept that meteorological recordings are distributed as random variables.

In the case of regression the tests require that the errors be normally distributed. In the case of correlation the tests require that the population from which the sample is drawn be normally distributed if the sample is small. The sample taken is considered large but, even so, trial plottings of some meteorological variables on normal probability paper indicated that near-normality exists and this was accepted as satisfactory.

Because of the magnitude of the task of testing for variance homogeneity in the meteorological populations and errors no attempt was made to establish homoscedasticity. The tests are valid so long as this is not considered to be an essential requirement for their use.

Only after fulfilling these requirements could the parametric tests indicated be employed in evaluating the significance of the various coefficients generated in the analysis.

Appendix F

THE STEPWISE LINEAR REGRESSION PROGRAMME

The analysis was effected using the 1130 Statistical System IBM Application Program, Number 1130 - CA - 06X. This stepwise regression programme determined the coefficients of a linear equation of the form:

$$Y = b_o + b_1X_1 + b_2X_2 +, \ldots, + b_nX_n$$

which best approximated the observations in a least-squares sense.

The coefficients b_o, b_1, ..., b_n are obtained as follows. First, the correlation matrix is computed from the source data. This matrix contains all the correlations between all pairs of variables. Variables were then entered into the regression equation on the basis of their contribution to the regression's 'goodness-of-fit'. In this analysis variables were entered into, or removed from, the equation on the basis of change in the mean square regression over the variance left unexplained at each step. The process was terminated when the F-level computed for this variance reduction failed to attain the level of significance desired.

In practice several entry and removal levels were tried, but none resulted in the termination of the regression at an early enough stage. In some cases all the regressor variables reached significance. This variance criterion was, then, too coarse for the desired purpose and a subsequent analysis of the results was used to determine what stage the results were reported to. Chapter Five contains a discussion of this decision.

For full details of this programme the reader may consult:

IBM Application Program: 1130 Statistical System User's Manual, Program Number 1130 - CA - 06X. (3rd edn, Oct. 1969).

Appendix G

SYMBOLS AND NOTATION

σ^2	variance of a population which has been sampled
partial r	estimate of the partial correlation coefficient
r	estimate of the correlation coefficient
R	estimate of the multiple correlation coefficient
R^2	coefficient of determination
ρ	the population correlation coefficient
P	the multiple correlation coefficient
r_a	estimate of the coefficient of autocorrelation
b (b-coeff.)	estimate of the partial (net) regression coefficient
$s_{by.x}$	standard error of b
β-coeff.	estimate of the beta coefficient; standardised regression coefficient
$s_{\beta y.x}$	standard error the beta coefficient
$s_{zy.x}$	residual standard deviation
Y	the dependent variable
X	general symbol for the independent (regressor) variables (X_i's)
E	an unobservable random variable
z	general symbol for a residual
p	the level of probability of any specific statistic
t	Student's *t*-statistic
F	*F*-statistic

α	probability of a Type I error
H_o	Hypothesis under test; usually the null hypothesis
:	such that
Σ	the sum of
$=$	is equal to
$<$	less than
$>$	greater than

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