THE EFFECTS OF TEMPERATURE AND IRRIGATION ON THE ESTABLISHMENT AND GROWTH OF LUCERNE (Medicago sativa L.) ON MANAWATU SAND COUNTRY.

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SUMMARY

This thesis reports on three experiments carried out in the summer and autumn of 1971/72. The first experiment was on a Himatangi sand (a very well drained soil with about 15 cm of black topsoil, over loose sand (Cowie et al , 1967)). 0.4 ha was sown on November 25 with Wairau lucerne, and areas of this were allocated to irrigated or non-irrigated main plots. Sub-plots had one of six different surface treatments (no mulch; bitumen; straw; straw over bitumen; white paint on bitumen; no mulch but sown with lupin).

Measurements made were plant counts and dry weights at several dates, soil moisture, soil temperature, rainfall, windrun, wind erosion, plant mortality, plant wilting, flowering, net radiation and surface albedo with the various treatments.

The main results observed were that plant mortality was high in the bitumen treatment, and also in the unmulched and lupin treatments and these results were attributed to the high 2 cm depth mean maximum soil temperatures recorded. The 2 cm soil temperatures were highest under the bitumen, followed by the unmulched and lupin treatments. The lowest temperatures recorded were on the two straw treatments. Yield per plant and per unit area were highest on the bitumen treatment, despite the greater plant mortality, and lowest on the straw treatments.

Subsequently, to check on the effects of high soil and soil surface temperatures on plant mortality and growth, two glasshouse experiments were carried out. Equipment was designed and built to independently vary the soil surface temperature from the soil temperature (below approx. 2.5cm). In the first experiment with four surface temperatures (25, 35, 45, 55°C) for 3 - 3¼ hours/day and two soil temperatures (25, 35°C) continuously it was found that plants in a pot with a 45 or 55°C surface temperature died, while there were no significant differences in growth rates between 25 and 35 35°C for either soil or surface temperature.

In the second glasshouse experiment a temperature of 50°C was used for either 3, 6 or 24 hours per day. This increased duration reduced dry matter yield, while increasing the number of days treated (from 1 to 3 or 7 days) had no effect. Seedlings 10 days from planting were affected much more by high temperature than those 13 days old.

It was concluded that the soil temperatures recorded on the sand country in the summer months could be too high for the survival of lucerne seedlings from seedings carried out at that time of the year.

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INTRODUCTION

This research was undertaken to study the establishment of lucerne on one of the drier soils of the Manawatu sand country. Lucerne has often been difficult to establish on these soils, yet once established grows well, possibly due to the large supply of water that is to be found in the water table a metre or so below the surface.

Difficulty in establishing lucerne has often been attributed to shifting of the unconsolidated cultivated sand surface by wind, and also to the low moisture holding capacity of the soil. Lucerne stands are usually sown in the spring, but the available soil moisture may be quickly evaporated by the strong prevailing westerly wind at this time and wind erosion may occur, often burying plants with sand and leaving other young plants with their root systems exposed.

Another possible reason for poor establishment of lucerne could be the high surface temperatures often experienced on the bare surface.

The aim of the field study was to examine the effects of soil temperature, soil moisture and wind erosion on lucerne establishment. Subsequently, glasshouse experiments were conducted to investigate the effects of temperature variations in the soil and on the surface on the growth and survival of lucerne seedlings.

Chapter One REVIEW

1.1 Introduction

The aim of the experiments was to examine the effect on lucerne establishment and survival, of some factors that are characteristic of the Manawatu sand country. It is not intended to review all aspects of germination and establishment of lucerne. Rather, attention will only be paid to the three factors of wind erosion, soil moisture and soil temperature since these were the factors considered in this study. The main emphasis in this review will be on the early growth of the seedling, until it is considered to be established. Since "establishment" appears to have been rarely defined in the literature, it is here defined as the stage at which the plant could be reasonably expected to continue to grow under normal seasonal climatic conditions and management practices.

In this review, use has often been made of information available on other species, in an attempt to present a reasonably complete picture. Most of this information is drawn from work on other legumes, but this is not always the case. Unless otherwise stated the literature quoted refers to lucerne.

1.2 Description of the Sand Country

Soils formed from wind blown sands cover an area of over 110,000 ha on the West coast of the southern part of the North Island of New Zealand. A full description of the soils was given by Cowie, Fitzgerald and Owers (1967). Briefly, the soils in the Manawatu can be divided into 3 age groups, the oldest group furthest inland from the sea. Within each age group the soils are further subdivided into dune and plain soils. The plain soils are further classified into soil types largely on the basis of drainage and the type of humification.

A characteristic of the sand country is a fluctuating water table, which from a maximum level in the winter, may drop 1 to 2 metres in the summer. This water table has a distinct influence both on the soils and on the types of vegetation that can be grown on them. (Cowie _et al_, 1967; Esler, 1969; 1970)

The area is characterised by warm summers and mild winters. Rainfall is reliable and evenly spread throughout the year with about 75 mm a month. Most of the rain is brought by the prevailing westerly and north-westerly winds. Air temperatures are highest in February and lowest in July with mean monthly temperatures of 17.3°C and 8.0°C respectively (Cowie et al, 1967). During spring and early summer strong winds frequently reaching gale force are common. These decrease over the summer with only light winds over the late autumn to early spring period.

1.3 Requirements for establishment of lucerne

Establishment of lucerne can be considered as occurring in 3 related and not well defined phases. The first phase is germination, which does not have a uniform meaning in the literature. Some workers have regarded a seed as germinated when the seed coat is burst, while others only consider a seed germinated after the root or shoot has emerged or after the root or shoot have attained a certain length. Often there is a specification that growth must be "normal" (Shaw, 1952). Mayer and Poljakoff-Mayber (1963) define germination "as that consecutive number of steps which cause a quiescent seed, with a low water content, to show a rise in its general metabolic activity and to initiate the formation of a seedling from the embryo." This definition is desirable in that it differentiates between germination and growth but is not practical, because growth is usually the only way in which germination can be readily identified.

The second phase of establishment is the emergence of the seedling from the ground. In lucerne the unopened cotyledons emerge first, and open as they appear above the ground surface.

The third phase is growth of this seedling until it is considered established. The importance of the micro climate during this phase will be discussed in more detail later. Establishment of lucerne on sand country is considered to be complete when the lucerne covers the surface.

Shaw (1952) points out that fully ripened seed can germinate only when external conditions are favourable. Temperature, moisture, oxygen, carbon dioxide, soil pH, mineral elements and activities of micro-organisms may all affect the speed and completeness of germination. Parle (1967) and McElgunn and Heinrichs (1970) point out that there may also be antagonisms from other plants or micro-organisms. The viability of the seed is of obvious importance (Mayer and Poljakoff-Mayber, 1963). All the above factors also affect emergence and establishment of the seedling, and in addition the seedling must also be able to force its way through the soil. Hence depth of seedling, soil compaction and crusting are important (Williams, 1963; Triplett and Tesar, 1960).

Competition with weeds can affect the establishment of a stand (Allen, 1967). In particular on the sand country there is competition from subterranean clover (Trifolium subterraneum L.) and Indian doab (Cynodon dactylon (L.) Pers.) both of which are difficult to control with selective weedkillers at present available (L.W. Blackmore, pers. comm.).

Further information on requirements for lucerne germination and establishment may be found in several references e.g. Bolton, 1962; Langer, 1967; Bringans, 1971.

Briefly these are a firm, fine and weed free seed bed, with an adequate supply of nutrients and moisture. The soil may need lime to raise the soil pH for successful nodulation and growth.

Sowing is normally done on the Manawatu sand country in early spring or autumn to avoid the winds in the spring months and the hot, dry conditions in the summer months. The rate of seed sown is usually between 10 and 16 $kg.ha^{-1}$. Innoculation of the seed with a suitable strain of Rhizobium meliloti is essential for nodulation. The seed is usually sown 1 to 2 cm deep, without a companion crop.

Selection of sites for lucerne involves finding areas that are far enough above the average water table height not to be flooded during the winter.

Temperature and moisture are particularly important for the germination and establishment of lucerne and will be considered in more detail on the following pages.

1.3.1.1 Influence of temperature on plant growth

Temperatures related to plant growth are usually classified according to the "cardinal temperatures" proposed by Sachs in about 1860. A plant shows three cardinal temperatures; the minimum, the lowest temperature at which growth is exhibited; the optimum, the temperature at which growth is most rapid; and the maximum, the highest temperature at which growth will occur (Shaw, 1952).

These points are now realized not to be definite, but range over at least several degrees celsius, depending on the plant material, the period of exposure and other factors.

The influence of temperature is very complex, possibly affecting most of the growth processes of the plant. Hagan (1967) and Levitt (1972) discuss some of these possible processes, and the possible influences of high temperature on them. There is some evidence that plants can adjust to lower or higher temperatures (Shaw, 1952; Kramer, 1969; Levitt, 1972).

Temperature may also affect the plant growth through the effect on activity of micro-organisms in the rhizophere or nodules, or of pathogens.

1.3.1.2 Soil temperature, germination and emergence

Germination and emergence are intimately related to soil temperature (Shaw, 1952). The cardinal temperatures for germination of lucerne are about 4 - 5°C for the minimum, an optimum of about 25°C and a maximum of about 38°C. Germination is similar within the range 15 - 30°C (Dubetz *et al*, 1962; Williams, 1963; Larsen, 1965; Heinrichs 1967) although there are varietal differences.

Alternating temperatures are found to be more favourable for the germination of many seeds (Shaw, 1952). For lucerne seed germination, the Seed Testing Station of the New Zealand Ministry of Agriculture and Fisheries uses 20°C for 8 hours and 18°C for the remaining 16 hours (M. J. Hill, pers. comm).

The soil temperature is extremely variable and shows both diurnal and seasonal fluctuations. There is also usually a temperature gradient with depth (Chang, 1968). Germination is determined mainly on a suitable combination of temperature and moisture (Mayer and Poljakoff-Mayber, 1963) but these large fluctuations and steep gradients of temperature appear not to have been examined for lucerne. Cohen and Tadmor (1969) found the optimum temperature for seedling root elongation near the surface (2-12 cm) was generally higher than in the 12-22 cm depth.

Generally moderate daily fluctuations in soil temperature are desirable as they aid in soil moisture distribution and soil aeration and may be directly beneficial to plant growth (Kohnke, 1968). Shaw (1952) reported that growth in young pea plants proceeded equally well whether root temperature was constant or fluctuated as much as 22°C within 7 and 29°C as approximate limits. There appears to be little evidence that alternating temperatures favour root growth; rather sudden shifts in temperature may temporarily retard growth (Shaw, 1952).

1.3.1.3 The influence of soil temperature on root and top growth.

It is impossible to cite optimum temperatures for lucerne growth, because of evidence that optimum temperatures are much influenced by other environmental factors.

Brouwer (1962) showed that the influence of soil temperature on shoot growth may be considerable for a number of species. Gist and Mott (1957) found lucerne root growth was decreased as temperatures increased from 15.5 to 32°C at the light intensities used in their experiments. The maximum light intensity used was 1200 foot candles. Root growth was decreased more than top growth by increased temperature and decreased light.

Trevino (1965) found lucerne seedlings up to one month old were favoured by high temperature (30°C or 30°C day/15°C night at the high light intensity in their trial. McElgunn and Heinrichs (1970) found better growth of lucerne roots and tops at 20°C than at 10 or 15°C soil temperature. Heinrichs and Nielson (1966) found a maximum herbage production at 27°C soil temperature, while most root and nodular tissue was produced at 12°C. Leach (1971) with high levels of light found better growth at 27 and 33°C than at 15 and 21°C. Garza et al (1965) found that early in their growth lucerne seedlings were favoured by high temperatures, while later on they were favoured by lower temperatures. They found day and night temperatures of 30° and 15°C respectively gave the best growth. Rogers (1969) found with 3 month old plants a lower D.M. yield with high temperature in pots exposed to the sun than those that were cooled. Robison (1966) found that warm nights reduced growth, although initially there was a growth response to warm nights in seedlings. Henderson (1970) also found better top growth with cool (11 or 15°C) than warm (22°C) night temperatures.

Shaw (1952) gives results of trials with lucerne and red clover growing in pots, with the temperature ranging from 12 to 36°C in 3°C steps. The maximum top growth of lucerne at 9 weeks was at 21°C, with little growth below 15°C but reasonable growth up to 36°C. Red clover had little growth below 18 or above 33°C. As the plants became older and with more light Shaw reported that the dwarfing at 12 and 15°C disappeared. Shaw (1952) reports that with a range of air temperatures and light intensities the optimum temperature for soyabeans was 22 to 27°C. There was a smaller increase in top weight from 7 to 27°C with low light than with higher light intensity. The optimum temperature also increased with higher incident light intensity indicating some care must be used in interpreting experiments under low light intensities. Brouwer (1963) showed that temperature effects were dependent on high light intensity.

As the plants get older there is evidence of a shift to a lower optimum temperature (Shaw, 1952; Hagan, 1967). With cotton Shaw (1952) shows that the optimum temperature for a few days after germination is about 33 to 36°C, while by the seventh day the optimum is 27 to 30°C. In lucerne there has been a shift demonstrated towards a lower optimum temperature with age (Garza et al, 1965; Robison, 1966) over the first few weeks or months.

Shaw (1952) and Hagan (1967) report increasing top growth with temperature in strawberries up to a soil temperature of about 25°C, while root growth reached a maximum at about 10 - 12°C less. The roots were finer and more branched at the higher temperature. Shaw (1952) gives another example with tomatoes where top growth was greatest at 30°C in nutrient solution and root growth was greatest at 20°C. With soyabeans the roots reached a weight plateau from about 18 to 36°C, while top growth had a maximum at 27°C. There was an increase in the top : root ratio as temperatures increased, as in some lucerne trials (Heinrichs and Nielson, 1966).

The maximum temperature at which growth will occur is likewise difficult to cite. A plant can stand for several minutes temperatures which would kill it if the plant was exposed for several hours or days (Shaw, 1952). Lethal temperature effects could be due to disruption of protoplasm, desiccation of tissues, or disturbance of the photosynthesis - respiration balance (Shaw, 1952; Hagan, 1967; Kramer, 1969; Levitt, 1972). Erwin and Kennedy (1957) noted lucerne 'scald' was the result of xylem necrosis and root collapse which was reproducible in the glasshouse at 39°C. The range between the upper figure for the optimum temperature and the maximum temperature may be only several degrees. For example lucerne germination can occur up to about 38 - 39°C (Williams, 1963; Larsen, 1965) with good germination right up to about 35 - 36°C.

Herbel and Sosebee (1969) on some range grasses found that high temperatures were not so detrimental when the soil was kept at field capacity. Shaw (1952) and Kramer (1969) indicate that tops of plants can survive high atmospheric temperatures because of transpirational and convectional cooling provided transpiration can occur. Shaw presents data showing that high relative humidity increases the killing effect of high temperatures on the plant, and that by submerging conifers in heated water it was found that roots died at lower temperatures than did tops. It is usually assumed that roots are at approximately the same temperature as the soil, and that the only place this is not likely to be true is near the soil surface where the flow of transpirational water may cool the roots and the bottom of the stem (Geiger, 1950). However, the temperature of tops of plants may lag considerably behind the atmospheric temperature.

The minimum temperature for growth is not well defined. Growth will continue slowly at low temperatures. Generally soil temperatures lower than the optimum delay maturity of plants, (Shaw, 1952; Hagan, 1967; Smith, 1969; Ueno and Smith, 1970; Evenson and Rumbaugh, 1972).

In general terms, it thus appears from the literature that the optimum soil temperature for lucerne growth and development is 12 to 33°C. Young seedlings appear to grow well at the higher temperatures while older plants and/or those in unfavourable environments make better growth at low temperatures. It may be that only when other growing conditions for roots are suboptimal may the growth rate of the plants be strictly determined by temperature of the root system. Shaw (1952) gives some evidence for this from work on tomatoes, for which root growth was greatest at about 20°C, but shoot growth was high from 16 to 32°C root temperature. Where nutrient solutions used were considered less suitable the growth rates were determined to a greater extent by the soil temperature.

1.3.1.4 Soil temperature and nodulation

In general the temperatures favourable for the growth of the legume rhizobia coincides with the optimum temperature range for the host plant. Freezing in the winter is not believed to have much effect on rhizobia, but the high soil surface temperature during summer may be detrimental. A temperature of 60°C for 2 - 3 minutes will destroy legume bacteria in a water suspension. Rhizobium meliloti requires a temperature of 41°C to stop its growth which is higher than that for red clover (Shaw, 1952). The number of nodules with lucerne was reduced above 33°C and below 18°C.

Gibson (1971) found that lower root temperatures than those optimum for plant growth retarded root hair infection more than they affect nodule initiation, nodule development (including bacteroid tissue development and degeneration) or nitrogen assimilation. Above optimum root temperatures upset the formation of bacteroid tissue and hasten its degeneration. Low and high shoot temperatures affect nodulation and nitrogen fixation, but the effect is less severe than that of similar root temperatures.

With subterranean clover Gibson (1963) found nitrogen fixation was reduced below 22°C and at 5°C was only 10 - 17% of that at 18°C. At 30°C there was a marked reduction in nitrogen fixation by some host-strain combinations. There were significant interaction of varieties and strains on both dry weight and nitrogen fixation throughout the temperature range examined (5°C - 30°C). At higher temperatures nodule production was independent of the amount of nitrogen fixed. Possingham (1964) found that high temperatures increased the number of nodules but reduced the protein and total nitrogen percentage compared with fertiliser nitrogen supplied plants. A high shoot temperature did not affect percentage nitrogen in the tops, but reduced plant yield compared with nitrogen supplied plants.

Rogers (1969) found with lucerne that with high temperatures, both the plant nitrogen yield and the D.M. yield were reduced in the uncooled pots on the soil surface compared with those cooled by a water bath. When the heat stress was removed nitrogen fixation recovered.

1.3.1.5 Extreme temperatures and plant damage

Both high and low temperatures may kill plants, the roots being more susceptible than the shoots (Shaw, 1952).

Temperatures in the soil near the surface can fluctuate between wide limits, from below 0°C to 70°C (Shaw, 1952; Geiger, 1950 and 1965; Herbel and Sosebee, 1969; Levitt, 1972). These temperatures may well be outside the limits for plant survival. At low temperatures, death could be due to ice crystal formation in the tissues or to the effect of frost heave (Shaw, 1952; Langer, 1967; Kohnke, 1968; Kramer, 1969; Levitt, 1972).

High temperatures in soils directly exposed to insolation, as in a recently cultivated soil, may kill plants. Shaw (1952) reports examples of death from heat in flax, buckwheat, wheat, barley, rye, cowpeas, beans, parsley, carrots, cucumber, cotton, ash, beech and several conifers. He also notes that heat damage is more common in saline soils. Young stems near the ground may be killed by high temperatures at the soil surface (Shaw, 1952; Herbel and Sosebee, 1969; Levitt, 1972). A band of discoloured tissue forms around the stem and shrinks. The plant usually dies.

The aerial portion of plants may be injured as a result of root damage at high soil temperatures. Accelerated root maturation may cause water deficits. After heating cotton plant roots to 60°C for 75 minutes the plants showed pale areas in the older leaves within 60 minutes, which disappeared when the roots were cooled but reappeared several days later as yellow or yellow-brown patches. Arndt (1937) suggested a toxic substance was formed in the roots and carried to the tops. These leaves became abnormally rigid and leathery, never recovered and eventually fell from the plant. Levitt (1972) presents similar hypotheses and evidence, and he suggests many possible mechanisms that may be involved.

1.3.1.6 Soil temperature characteristics

The soil temperature zone of importance to the germinating and establishing seedlings is the volume of the soil with which it is in contact. The zone is at first small, but increases in size with the size of the plant. As Geiger (1965) points out, after the plant emerges from the soil it begins to modify its own environment. The main source of heat for the soil is the radiant energy from the sun. The surface of the earth is the layer for exchange of radiant energy. Net radiation, Rn, may be defined as :-

$$Rn = (1-a) K + Li - Lo \qquad \text{eqn } 1.3.1.1$$

or

$$Rn = E + H + G + P + V \qquad \text{eqn } 1.3.1.2$$

where a = albedo of the soil or crop surface
K = incoming short wave radiation
Li = incoming long wave radiation
Lo = outgoing long wave radiation
E = latent heat flux
H = sensible heat flux
G = ground heat flux
P = energy exchange in photosynthesis and respiration
V = energy stored in vegetation

For most agricultural crops P and V are small (less than 2%) and can be ignored for our purposes. Nor is any account made for advection.

The microenvironment in which the plants grow is dominated by the magnitude of Rn, and E, H and G.

The amount of heat going into the soil is therefore dependent on the albedo, moisture content (which influences the latent heat loss) and the thermal conductivity of the soil. The temperature rise of a unit of soil depends on the reciprocal of the units volumetric heat capacity and on the heat input. With higher conductivity there is less rise in the surface temperature but a higher rate of temperature increase in the soil below the surface.

The surface layers of sand soils are characterised by large diurnal fluctuations in temperature (Geiger, 1950; Shaw, 1952; van Wijk, 1963; Nakshabandi and Kohnke, 1965; Rose, 1966; Chang, 1968; Kramer, 1969). It also has been shown by several workers that darker coloured soils tend to be warmer than lighter coloured soils (Geiger, 1950; Daubenmire, 1959; Kohnke, 1968). This is because the albedo is lower. The volumetric heat capacity of a damp soil is higher than a dry soil, and at the surface there is likely to be a greater proportion of heat used in vapourising water, so the soil is not likely to get as warm as a dry soil. Nakshabandi and Kohnke (1965) found that thermal conductivity was closely related to soil moisture tension for a variety of soils. The effect of moisture content on volumetric heat capacity was much less than the effect on thermal conductivity.

It seems likely, then, that on a dry Himatangi sand surface the heat capacity and thermal conductivity are low with a low albedo and low latent heat losses so the surface is prone to rapid and extreme fluctuations in temperature.

van Kraayenoord (pers.comm.) measured temperatures in a black sand and a lighter coloured sand during a period of 10 weeks in the spring, after sowing lupin on some of it on 18th September, 1958. The first weeks measurements began on the 6th October, using samples brought to a common location (Palmerston North) from Himatangi (light sand) and Wanganui (black sand). By the end of the measurement period the lupins were about 50 cm high. Table 1.3.1 shows the weekly mean temperatures on the lighter coloured sand, which only differs slightly from the black sand. The highest temperature recorded on any day was 53°C on the bare sand at the 0.6 cm. depth. On the sand country itself on several occasions in January and February, the maximum temperature exceeded 61°C, the maximum thermometer reading. The black sand was reported to reach a higher maximum temperature than the lighter coloured sand.

Table 1.3.1 Temperatures at varying distances below and above the surface on sand with and without a developing lupin cover.

Mean Weekly Temperatures in Sand

Bare Surface (No lupins)

	Below Surface				Above Surface	
Week	7.5 cm 9 am	2.5 cm 9 am	.6 cm max.	.6 cm min.	2.5 cm max.	2.5 cm min.
1st	15.7	16.5	31.8	12.0	27.5	11.9
2nd	16.3	22.6	29.9	7.9	23.1	7.8
3rd	14.4	16.4	28.9	7.8	24.7	9.0
4th	16.1	29.6	32.1	11.7	30.2	10.8
5th	17.6	21.8	43.6	11.5	33.6	9.3
6th	19.2	22.5	41.6	13.3	33.2	11.1
7th	17.8	27.9	38.8	7.6	29.9	5.2
8th	20.3	26.1	35.6	8.9	28.9	7.8
9th	20.6	26.7	41.9	13.3	32.3	14.4
10th	22.2	26.7	37.8	13.6	32.2	14.4

Table 1.3.1 contd.

Mean Weekly Temperatures in Sand

Lupins growing on surface

	Below Surface				Above Surface	
Week	7.5 cm 9 am	2.5 cm 9 am	.6 cm max.	.6 cm min.	2.5 cm max.	2.5 cm min.
1st	16.3	16.7	30.8	12.8	28.9	16.7
2nd	16.1	19.9	27.4	8.6	20.1	7.5
3rd	13.3	15.4	26.0	8.8	26.3	9.0
4th	15.8	17.6	27.8	12.4	29.1	10.6
5th	16.5	17.6	32.5	12.6	34.8	9.3
6th	16.9	18.5	30.7	14.3	28.4	10.8
7th	13.7	15.6	21.8	8.7	28.3	4.9
8th	15.0	17.5	19.4	9.2	26.9	7.8
9th	17.2	16.7	21.7	13.3	20.8	13.9
10th	17.2	17.2	23.3	13.3	21.1	15.0

1.3.2.1 Properties of water in soils and plants

Water is a constituent of protoplasm, constituting 80-95% of the fresh weight of herbacious plants. Water is a solvent for gases, minerals and other solutes. It is also a reactant or reagent in many processes, and is essential in the maintenance of turgidity in plants (Kramer, 1969). Currier (1967) indicates the importance of water in transport in the plant and soil, how it acts as a buffer against temperature changes because of its high specific heat, and how its high heat of vapourisation allows cooling of plants leaves by transpiration.

Water has a high surface tension and tensile strength because of its high internal cohesive forces. It also is strongly adsorbed to the surface of cellulose, clay micelles, proteins and many other substances.

In the soil, water may exist as a solid, liquid or gas. The forces that keep soil and water together are all based on the attraction between soil and water (adhesion) and among the water molecules themselves (cohesion) (Kohnke, 1968). As water is withdrawn from a saturated soil the force needed to withdraw successive increments increases. This may be due to soil shrinkage and/or capillary attraction which together are referred to as matric forces, or if the water is withdrawn through a semipermeable membrane there may be a mounting solute concentration increasing the osmotic forces on the water. Soil water is also subject to forces originating from the gravitation field and from gas pressure. These forces may be described in thermodynamic terms by assigning potentials to soil water. The total potential of soil water is then the sum of the matric, osmotic, pressure and gravitational potentials. The total potential may be identified with the partial molal Gibbs free energy of the soil water relative to pure free water at the same temperature, and represents the capability of the soil water to do work compared with the pure free water. For a full description of the terms see Rose, (1966); Slatyer, (1967); or Day et al (1967).

As water movement takes place in response to potential gradients, only the differences in potentials are of significance. The potential concept may be applied to water in all parts of the soil-plant-atmosphere continuum, and differences in potential between any two points will be due to osmotic or matric potentials, as the pressure and gravitational potential differences can be assumed negligible.

In addition to this potential concept soil water has been described in other terms. Field capacity is the water content after gravitational forces have drained the water with a high potential from the soil. Generally field capacity is equated to $-\frac{1}{3}$ bars potential (Buckman and Brady, 1968) or -0.1 bars for undisturbed soil samples and -0.3 bars for dried, ground and seived samples (Slatyer, 1967). Field capacity is not a constant, but it does characterise the soil water storage value following soil water recharge (Slatyer, 1967; Kramer, 1969).

Permanent wilting point is the point at which plants remain permanently wilted, unless water is added to the soil. Slatyer (1967) has criticised attempts to relate permanent wilting point to a soil water potential of -15 bars, as wilting occurs because of a lack of turgor in the leaves, and the potential at which this occurs depends on the osmotic characteristics of the cell sap in the leaves. Kramer (1969) indicates for most crop plants the osmotic potentials at wilting range from about -10 to -20 bars, and there is little water content change over this range, so -15 bars is probably a useful term to describe permanent wilting point.

Readily available soil water is taken to be the water content between field capacity and permanent wilting point. The potential concept makes it apparent that soil water is not equally available over this range (Slatyer, 1967; Kramer, 1969).

Soil moisture is a function of income from rain, dew, irrigation and movement from a water table, while soil moisture losses are in evaporation, transpiration, drainage and runoff. From equation 1.3.1.2,

$$Rn = E + H + G + P + V$$

it may be seen Rn provides energy for E, the loss of water in evaporation and transpiration. The magnitude of E depends on the potential difference of the water in the plant or soil from that of the air, and the resistance to its movement. Another source of energy for evaporation and transpiration can be in warm dry winds (advection) which have a low water potential.

Water flow through the plant appears to be principally in response to potential gradients, as there is evidence that active water uptake is absent or of minor importance normally in the plant (Slatyer, 1967; Kramer, 1969). The water passing through the plant encounters the main resistance in the root surface layers, or at the leaf-atmosphere interface where the resistance can be modified by the opening or closure of stomata.

There is a diurnal fluctuation of the potential gradients. During the day there is a steep gradient between the soil and atmosphere. Plant transpiration is rapid and the water content and potential of the plant may drop. With the rapid uptake of moisture from around the root, soil moisture in the vicinity of the roots may drop (at the same time resistance will increase) causing plants to wilt even when the average soil potential is high (Slatyer, 1967; Kramer, 1969). This increased resistance may cause closure of stomata via the effect on leaf water potential (Stanhill and Vaadia, 1967).

The water potential in the plant is, therefore, a function of soil and atmospheric conditions, as well as genetic and adaptive controls.

The response of crops to soil water is mediated via the plants water status. There is data to indicate the maximum growth occurs where plant water potential is high (i.e. low water stress) (Stanhill and Vaadia, 1967; Vaadia and Waisel, 1967;

Slatyer, 1967; Kramer, 1969). Low water potentials result in reduced plant growth by closure of stomata, reduced cell expansion, division and leaf area, as well as reduced photosynthesis, and increased respiration. There may be a change in the structure of proteins, affecting enzyme activity. Translocation of assimilates and growth regulators may be disturbed and there may be an effect on nitrogen metabolism (Slatyer, 1967; Kramer, 1969).

1.3.2.2 Influence of soil moisture on lucerne germination and emergence.

The first change that occurs in the germination of a seed is imbibition of water. Seeds have a low water potential, and water stress per se is not likely to be a factor in the initiation of embryo growth. It does reduce the rate of radicle emergence, and, as a consequence affects the germination percentage because of increased chances for microbial infection (Peters and Runkles, 1967).

Uhvits (1946) used sodium chloride and mannitol to vary the osmotic potentials of petri dish and sand cultures around the lucerne seed. With lower osmotic potentials the rate of water uptake and the germination percentage were reduced. To overcome problems of solute entering the seed and to equate osmotic and matric potentials McWilliam, Clements and Dowling (1970) used high molecular weight (about 20,000) polyethylene glycol. There was no lucerne germination at -12 bars.

Collis-George and Sands (1962) considered the effects of osmotic and matric potential were not the same on lucerne germination. This work was criticised by Sedgley (1963) who pointed out that Collis-George and Sands had assumed the permeability of the soil-seed interface was the same at different matric potentials, while in fact it may be quite different as Sedgley showed.

McWilliam and Phillips (1971) found with perennial ryegrass that there was no difference between the effect of osmotic and matric potential on germination, under conditions where soil moisture diffusivity and seed-soil contact were non-limiting. There was a difference between osmotic and matric potential with phalaris, this difference being attributed to a large resistance of the phalaris seed coat to the absorption of water, and equality of osmotic and matric potential no longer held.

The germination behaviour of lucerne appears to be controlled by two soil moisture properties; the potential and the resistance to moisture movement to the seed (Collis-George and Sands, 1959, 1962).

Seedlings emergence is highly sensitive to soil moisture and other soil conditions at the time of emergence. Both osmotic and matric potential strongly influence the emergence percentage and the rate of emergence (Peters and Runkles, 1967). Triplett and Tesar (1960) showed that compaction of the soil partly overcame the effect of low soil water potential, presumably because of improved contact between the soil and seedling and reduced resistance to water movement.

The strength of the soil can be a large factor in emergence, and water can influence the formation and strength of crusts (Shaw, 1952; Hillel, 1959).

Germination and emergence are both dependent on an oxygen supply. Aeration of the soil is influenced by water content, and a saturated soil may have a low air content (Peters and Runkles, 1967).

Soil moisture stress and temperature appear to interact in germination. Tadmor _et al_ (1969) and Hillel (1972) found germination was increasing affected by moisture stress the more temperature varied from the optimum.

1.3.2.3 _Influence of soil moisture on lucerne root and top growth_.

Water influences the direction of root growth, the extent and depth of rooting and the root : shoot ratio (Peters and Runkles, 1967).

Roots will follow moisture in the soil when they are in contact or in close proximity to moisture. The lateral extent and depth of penetration of roots are under genetic control, but are subject to modification by the environment (Peters and Runkles, 1967).

Under water stress the growth rate of the tops is usually reduced more than that of the roots (Peters and Runkles, 1967; Slatyer, 1967; Kramer, 1969).

When the rate of transpiration exceeds water uptake for any length of time internal water deficits occur, and competition between organs occurs. The priority usually remains with the growing tip (Kramer, 1969) as the growing tip can develop a lower water potential than other parts of the plant. Kramer (1969) considers that the amount of water needed for the functions of the plant is probably less than 5% of the water passing through the plant.

1.3.2.4 Influence of soil moisture on nodulation.

Much of the work in this field has been carried out on legumes other than lucerne. A composite picture is therefore given but exceptions to the general pattern may be expected (Nutman, 1965).

All stages of nodulation including pre-infection and nitrogen fixation are affected by the environment and host (Masterton and Sherwood, 1970; Lie, 1971).

The formation and longevity of root nodules has been shown to be affected by the availability of the water in the soil (Wilson, 1921; Sprent, 1971). Formation of nodules probably depends on adequate moisture in the soil for rhizobial multiplication in the rhizosphere. Reduced root growth because of water stress will reduce the sites for nodule formation. With very low moisture levels the survival of both host and rhizobia may be affected. Once infection has taken place the development and function of the nodules will depend on the plant's water balance, which may directly effect the hydration of enzymes and transport of assimilates to and from the nodule, but which will also influence the plants growth processes and so indirectly influence the nodule development and function.

Lucerne nodules are most likely to be found at depths where soil moisture levels are favourable (personal observation and Stiefel, pers.comm.)

Sprent (1971) found that if the fresh weight of nodules in soybean fell below 80% of the fully turgid value, the nitrogen fixation ceased and irreversible gross structural changes occurred, and she considered that the nodule would be shed. Between 80 and 100% of the fully turgid weight there was a reduced rate of fixation but the effect was reversible.

Submerging nodules in water reduced their rate of nitrogen fixation because of a lack of O_2 (Sprent, 1971). In the soil lack of O_2 (due to high water content) is not likely to limit nodule function according to Dart and Day (1971) but it may inhibit nodule formation (Loveday, 1963). It seems likely, however, that a waterlogged soil would also inhibit function.

McKee (1961) reported decreased nodulation of birdsfoot trefoil (Lotus corniculatus L.) under a low soil moisture regime, but the growth of tops and roots was much less affected. Kawatake et al (1962) found nodulation was depressed with 30% soil moisture compared with 70%. Masefield (1952, 1955, 1957, 1958, 1961 quoted in Chu, 1971) found heavier nodulation of several species under moist conditions irrespective of soil type.

1.3.2.5 Working hypothesis of the plant response to changing soil water potential.

In the lucerne plant, with initially an adequate water and nutrient supply and an otherwise favourable environment for growth, only small diurnal water deficits will occur. These may reduce cell division in the cells experiencing the maximum water deficit, and a reduced rate of shoot apex elongation. Growth of the whole plant should progress virtually unimpeded.

As the soil dries, there will eventually be continued stress, with an imposed daytime lag of absorption behind transpiration. There may be a gradual reduction in the rate of cell division. Initially each day there will be only a short reduction in metabolism, but this period will become longer each day. Stomatal closure at this time will retard transpiration and increase leaf temperature, and may also reduce gross photosynthesis by reducing CO_2 exchange. Net photosynthesis may also be reduced by effects on cell turgor and by increased respiration. Reduced cell expansion and division, which will reduce leaf area, all combined reduce net photosynthesis. This may limit the supply of assimilates to the bacteroids in the nodules and reduce nitrogen fixation.

The soil water will become depleted to successively greater depths, with increasing resistance to water uptake and decreased soil water potential.

As stress becomes more severe with soil water depleted nearly to wilting point the diurnal water deficits will become less marked. Plant potential will become increasingly dominated by soil potential and turgor pressure will approach zero. Cell division will be markedly reduced and cell enlargement cease. The stomata will be closed virtually all day, with marked increases in leaf temperature. There may be a decline in respiration, but net photosynthesis will decline to almost zero because of direct dehydration and reduced CO_2 transport.

Nitrogen fixation will have ceased, and it is likely many nodules will have been shed. Root growth will cease and root hairs may die. Maturation and suberization of the roots proceeds rapidly.

Associated with a breakdown of proteins and carbohydrates there will be a migration of soluble P and N compounds to the stems, and an increase in osmotically active carbohydrate breakdown products.

As dehydration continues it will reach critical levels and individual cells and tissues will die. With a gradually imposed stress the older leaves are shed first.

If water supply is renewed before death, recovery to normal metabolic activity takes several days.

The drought tolerance of lucerne is usually credited to its deep rooting system (Leach, 1967), but in an establishing lucerne stand the roots are neither deep nor extensive. As a result there is a smaller volume of soil to supply the moisture requirements of the young lucerne plants than in an older stand.

1.3.2.6 Moisture characteristics of the sand country.

P.J. Rumball (pers.comm.) has studied in some detail the moisture holding capacity of several soils on the sand country. In the top 18 centimetres of a Himatangi sand he found the field capacity was 31%, and the wilting point was 7%, giving available water as 24%. With a bulk density of 1.22 this meant about 5.2 centimetres of available water. Between 18 and 46 cm the respective figures were 15% and 3% giving an available percentage of 12.

Rumball comments that because of slow water uptake of the sand the water supply in the field is not well related to what may be expected from the above parameters.

1.3.3 The Influence of Wind on Lucerne Establishment

The soils on the Manawatu sand country are prone to wind erosion (Cowie et al, 1967), until the lucerne plants cover the surface.

Wind erosion is initiated when the pressure of wind against the surface grains overcomes the force of gravity holding the grains. The grains of sand move in series of jumps or bounces, (saltation) and this movement is accompanied by surface creep of larger and denser particles and suspension of the smallest and lightest particles. (Chepil and Woodruff, 1963; Williams, 1972).

Chepil and Woodruff (1963) in their extensive review consider saltation is the major component of soil movement, although suspension may appear more spectacular. As the wind erosion on bare or sparsely-covered soil depends mainly on wind velocity at the soil surface, methods of overcoming wind erosion usually involve methods of reducing surface windspeeds or of increased cohesion of the particles on the soil surface. Vegetation covers effectively reduce surface wind speeds (Chepil and Woodruff, 1963) and may bind surface particles. Shelter belts may reduce wind speed (Caborn, 1965; Williams, 1972).

The Himatangi sands have little cohesion between sand grains when the surface is dry (Cowie et al 1967; Esler, 1969). Once the vegetation is removed there is little to bind the surface.

Williams (1972) lists 4 known harmful effects of wind on crops and the farming system as : -

(i) The actual removal of surface soil, including seeds, seedlings, fertilisers and herbicides.

(ii) Crop losses, or the failure of the crop to establish satisfactorily. Sand or soil blasting the aerial parts of the plant can be very harmful.

(iii) Wind rocking of plants, causing cracking and twisting of stems.

(iv) In prolonged high velocity wind, transpiration losses can be harmful.

Another effect not specifically mentioned by Williams is burial of seeds and seedlings under blown sand.

Kramer (1969) points out that most of the effect of wind on transpiration occurs at low wind velocity (0 to 3 m.p.h.). Wind acts directly to increase transpiration by reducing the resistance of air to water movement. It acts indirectly to decrease transpiration by cooling leaves and therefore reducing the water potential gradient from leaf to air. Knoerr (1966) pointed out that at low levels of radiation a breeze should increase transpiration, while at high levels (when the leaf is warmer than the air) a breeze should reduce transpiration.

Whitehead (1964-65) and Winter (1964-65) found that plants grown in wind could adapt to the wind, and reduce their transpiration rate per unit leaf area.

The abrassive effect of sand blasting the plant may damage the cuticle causing increased water losses.

1.3.4 Influences of Mulches

Any material spread over and allowed to remain on the ground surface is referred to as a mulch (Chang, 1968). Straw, polyethylene films and bitumen have been among the materials used. The main influence of interest of the mulches in this discussion are those on temperature, moisture and wind.

Van Wijk (1963) points out that there is an extensive literature on the effects of mulches but few articles on the theoretical background. The energy budget approach provides a useful aid to understanding. From the equations 1.3.1.1 and 1.3.1.2

$$Rn = (1 - a) K + Li - Lo = E + H + G + P + V$$

it is apparent a knowledge of the physical properties of a mulch should allow a prediction of the effect on the soil temperature. For example, dyeing a soil black should reduce "a" without substantially influencing the emissivity of the soil for long wave radiation. This would therefore cause an increase in Rn, and in E, H and/or G. As a result the soil temperature would increase particularly during the day, as has been found (Geiger, 1950; Shaw 1952; Jacks, <u>et al</u> 1955; van Wijks, 1963; Chang, 1968), and there is also likely to be an increased moisture loss.

Many mulches achieve their effect by changing the thermal conductivity of the surface by the presence of a layer of still air (Waggoner et al, 1960; Collis-George et al, 1962). They also form a physical barrier at the surface to moisture evaporation. Most evidence shows that a straw mulch conserves soil moisture (Jacks et al, 1955).

A straw mulch may have a higher albedo than the soil, but has a much lower thermal conductivity than the soil. As a result the mulch surface will have warmer temperatures during the day and cooler temperatures at night than adjacent soil (van Wijk, 1963) while the soil below the mulch will be cooler during the day and possibly warmer at night than the adjacent soil (Geiger, 1950; Jacks et al 1955). Generally a straw mulch keeps the average soil temperature lower and more uniform during summer, and warmer in the winter.

Bitumen mulches reduce evaporative moisture losses from the soil (Smith, 1960; Collis-George et al, 1962; Anon, 1962; van Kraayenoord pers. comm.; Bowler pers. comm.). Smith (1960) found that bitumen mulches applied to clay soils may reduce the rate of water infiltration into the soil, but that fast breaking emulsions reduced this tendency. On sand the rate of infiltration with fast breaking emulsions was not impaired.

Temperature increases of the soil under bitumen during the day are marked (Bowler, pers. comm.; van Kraayenoord, pers. comm.) because of the lower albedo of bitumen than most soils (Smith, 1960), and the absence of an insulating air layer (Collis-George et al, 1962).

On a dark soil with low albedo the increase in temperature under bitumen would not be expected to be as great and may depend on differences in evaporation. Collis-George et al (1962) found that a bitumen surface painted white reduced the daytime temperatures of the soil compared with the adjacent unmulched soil.

As the lucerne develops the influence of the plant alters the albedo of the surface and also intercepts the light over a distance of several centimetres. Transpiration from the plant is also important and the influence of the mulch on soil temperature and moisture declines (Geiger, 1950; Collis-George et al, 1962).

Mulches will also alter the effect of wind on the plant. Straw mulches reduce the velocity of the wind at the soil surface, and hence reduce the likelihood of sand blasting (Chepil, 1965; Bagnold, 1946).

The moisture microenvironment under straw is also likely to be more favourable for early seedling development because of a higher relative humidity (Dowling et al, 1971) although temperature during warm times of the year may be too high (Shaw, 1952; Waggoner et al, 1960) and light intensity may be below the optimum for seedling development.

Bitumen and other chemical mulches may increase the cohesion between surface particles (Williams, 1972) or form a protective layer against wind moving the soil particles. The wind velocity at the soil surface may increase slightly as the surface will present less resistance to the wind (Chepil and Woodruff, 1963).

Mulches may have other effects on plant growth. Waggoner et al (1960) found an increased incidence of disease on strawberry roots under plastic mulches. Decaying straw or vegetation mulches may utilise nitrogen (Jacks, 1955) or, alternatively, may supply nutrients to the plant. They may harbour insects and plant diseases.

Bitumen is not toxic to plants, (though bitumen for roading purposes may have toxic chemicals added) nor is it likely to supply appreciable quantities of plant nutrients (Collis-George et al, 1962). Smith (1960) and Collis-George et al (1962) found that rates of 3.8 to 4.5 litres.m^{-2} of emulsion did not appreciably reduce emergence of the grasses and legumes studied except where the bitumen formed pools on uneven ground. The usual rates of application are about 0.5 to 1.1 l.m^{-2} and appeared to have no inhibiting effect on emergence. Smith (1960) did find that emergence was reduced where the bitumen was applied to clay and silt soils on top of seed that was broadcast and not covered with some soil.

Collis-George et al (1962) found that as the rate of application of bitumen increased, the daytime temperature also increased while soil moisture losses decreased.

Chapter 2 MATERIALS AND METHODS

Introduction

Three experiments are reported in this thesis. The methods of each will be described separately under the headings : -

- 2.1 Sand country experiment
- 2.2 Glasshouse equipment
- 2.3 Glasshouse experiment 1
- 2.4 Glasshouse experiment 2
- 2.5 Statistical methods

2.1 Sand Country Experiment

The area selected for this field trial was on a Himatangi sand. The area was limed about 6 years previously, and no fertilizer applied since, although hay cut on alluvial river silt flats had been fed out on the area most winters. Ministry of Agriculture and Fisheries "quick soil test" figures indicated a pH of 5.5, Ca of 5, K of 3, P of 7 and Mg of 5. (The units are described in Appendix 1)

An area of 0.4 ha was rotary hoed in early September to about 3 cm and left fallow until ploughed and disced on November 5. 1800 $kg.ha^{-1}$ of lime, 350 $kg.ha^{-1}$ of 30% potassic superphosphate and 230 $kg.ha^{-1}$ of serpentine superphosphate were applied on November 13. The area was cultivated on November 18 with Dutch harrows and 2.2 $kg.ha^{-1}$ active ingredient benfluralin for weed control was applied and cultivated in with 3 more passes of the Dutch harrows. On each of November 24 and 25 another pass was made.

The area was sown with a Stanhay precision drill on November 25 with pelleted and inoculated seed from "Prillcote". The seed was sown at a rate equivalent to 6 - 7 $kg.ha^{-1}$ uncoated seed in rows 15 cm apart, with about 1 cm between seeds within the row. The experimental treatments were then applied in 5 blocks (see Appendix 2 for layout). Each block was split into 2 main plots with one irrigated regularly until December 24 to keep the soil moist. Each of these main plots were split into 6 subplots each 4.88m x 4.88m which were assigned at random to different surface mulches. These were :

1. Control or unmulched.
2. Bitumen coat (Shell Coalas Mix).
3. Barley straw, in a layer 4-5 cm thick.
4. Bitumen coat with 4-5 cm of barley straw on top.
5. Bitumen painted with white paint (British Paints 100% acrylic).
6. Lupins sown as a companion crop.

Immediately before the lucerne was sown the lupins were drilled with a Stanhay drill at 60 cm spacing between the rows with 7.5 cm between seeds.

On November 26 thermocouples were placed on block 1 at three depths: surface, 2 cm and 10 cm. The next day bitumen was sprayed on plots requiring bitumen. Due to some difficulties with bitumen setting and blocking the nozzle and hose used, blocks 4 and 5 were sprayed with a different nozzle and had a heavier application of bitumen than blocks 1, 2 and 3. The bitumen was mixed with an equivalent volume of water and heated before application.

By evening of November 28 much of the seed had germinated with almost none having emerged. Two rain gauges and a cup anemometer were installed and the temperature recorder was started.

On November 29 white paint was sprayed and straw spread on the appropriate plots. This was the first day the wind was light enough for these operations. Many of the seedlings had emerged, particularly where the seed were close to the surface.

Irrigation was applied by a sprinkler when the soil surface became dry (Appendix 3). No applications were made after December 24.

8 cm diameter tins were set flush into the ground on the side of the plot opposite the direction of the prevailing wind to record sand movement. While the work of Bagnold (1946) has shown this does not record the total movement of sand, it would give the relative magnitude of sand movement with the different treatments.

Temperature recording was with a series of 36 copper-constantan thermocouples switched through an automatic channel changer to record the temperature with a "Honeywell Electronik 19" pen recorder. All electrical joints were sealed with "Araldite" epoxy resin to prevent interference from ground currents, and in addition the thermocouples were enclosed in heat shrink tubing. Melting ice was used as the reference temperature of 0°C. The 2 and 10 cm depth thermocouples were placed after sowing and before the application of surface treatments. The surface thermocouples on the bitumen painted white treatment were sprayed with white paint. On the straw mulch plots the thermocouples were placed near the surface of the straw, and on the bare sand and bitumen coated plots the thermocouples were initially left on the surface. On December 5 the grey coloured thermocouples on the bare sand were dampened with "Araldite" and coated with sand and those on the bitumen plots were covered with bitumen.

On December 22 and 24 net radiation readings were taken on the different surfaces. Limited data were collected on December 22 because of some high haze, but December 24 was suitable for extensive recording on block 1. One net pyrradiometer was sited on the control plot, while the other net pyrradiometer was shifted from plot to plot. Radiation readings were taken both before and after irrigation on the irrigated plots, with both polythene and perspex hemispheres on the moved net pyrradiometer to record total and shortwave radiation components.

Plant information was provided by density counts from 4 quadrants, each 30.5 cm x 30.5 cm, on the 4 occasions December 6, 9, 23 and January 6. Yield data were obtained from the same quadrants on December 9, 23 and January 6. The whole plot, except for a 60 cm margin around the plot, was harvested on January 26 and 27.

2.2 Equipment developed for glasshouse experiments

This equipment was constructed to simulate in the glasshouse the field condition of a soil with a high surface temperature, the soil below the surface being controlled at a lower temperature. This had previously been attempted by Sosebee and Herbel (1969) and Herbel and Sosebee (1969) who used heat lamps for this purpose, which would have meant that temperature differences between treatments were confounded with differences in radiation received by the plants.

Numerous workers (e.g. Tisdale and Jones, 1921; Shaw, 1952; Levitt, 1972), have controlled soil temperature by standing pots in a water bath and insulating the top of the soil to prevent a surface temperature drop. In many cases this has not allowed separation of temperature effects from glasshouse or growth chamber position effects. The water bath, if not sealed off from the aerial environment, may cause localised variations in air temperature and humidity.

To overcome all these problems, and to allow independent control of the soil and surface temperatures, it was decided to build plant pots with individual water jackets and to plant young lucerne seedlings through a surface water jacket to vary surface temperature. Figure 2.2.1 (a) and (b) shows the general construction of the apparatus. The seedlings can be seen in Plate 1.

The side walls of the water-jacketed pot were constructed of 7.5 cm diameter P.V.C. pipe for the inside and 10 cm P.V.C. pipe for the outside and were glued on to flat P.V.C. sheeting (3 mm thickness) for the base. The top was made out of the same material. (See fig. 2.2.1 (b)).

Brief construction details are as follows. The 7.5 and 10 cm diameter P.V.C. pipe was cut into 10 cm lengths and the ends smoothed and squared with a sander. The bases and tops were cut out of P.V.C. sheeting, and after drilling the 7.5 cm hole out of the top and rounding the outside diameter to 11 cm the pot was glued together with "Novacem B". Both a 5/16 inch brass inlet and outlet (0.79 cm diameter with a 0.54 cm inside diameter) were glued (with "Araldite") into each pot for water reticulation and tested for water leaks.

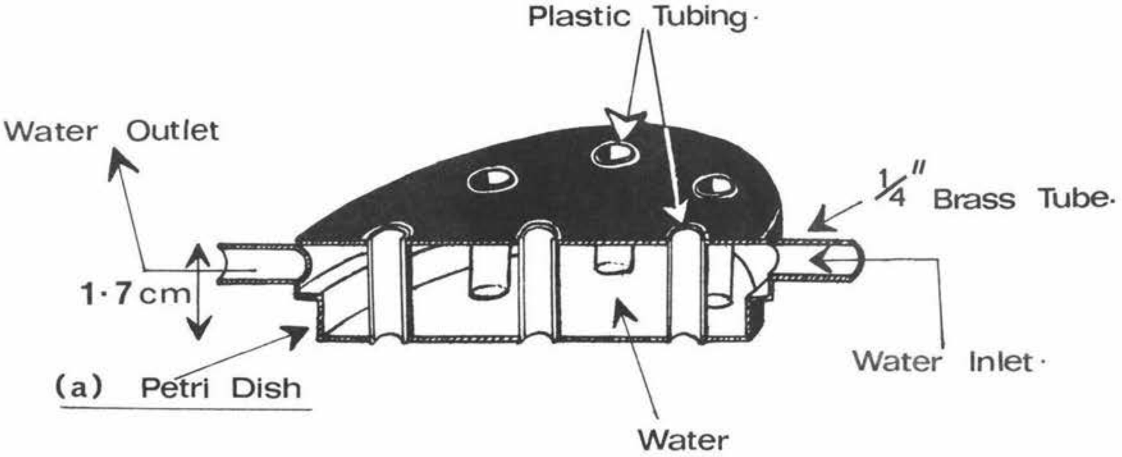
A plastic petri dish (9 cm diameter and 1.7 cm deep) was used to water-jacket the 2 cm long plastic tubing through which the plants grew. (See fig. 2.2.1 (a)). The inside diameter of the plastic tubing was approximately 3 mm.

The petri dish top was made by gluing together the top and base of the petri dish (with "Araldite"), then drilling vertically through the petri dish and fitting and gluing (after considerable experimentation, with "Cyanoacrylate I.S. 12" adhesive) the plastic tubes in position. There were 10 plastic tubes per jacket (or petri dish).

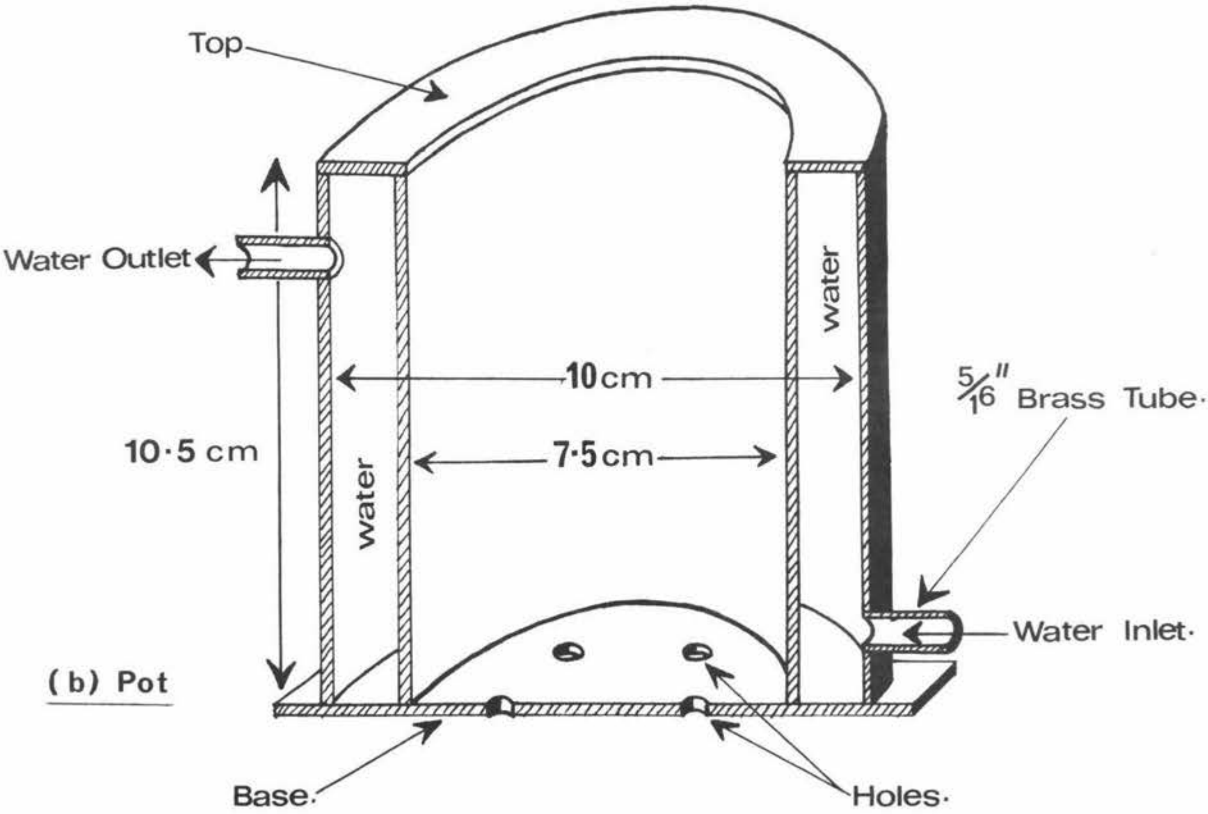
The $\frac{1}{4}$" brass tubing (0.64 cm diameter with 0.42 cm inside diameter) was glued with "Araldite" into position through holes drilled in the vertical walls of the jacket for water circulation.

The top and sides of the petri dish were then painted with black bitumastic paint to prevent light reaching the soil and plant roots.

Figure 2.2.1 Diagram showing the water-jackets to modify surface and soil temperatures



(a) Petri Dish



(b) Pot

The required temperatures were obtained in both the petri dishes and the pots by pumping water from a controlled temperature water bath into a central manifold. Short flexible pipes connected the central manifold with each petri dish or pot, with the water then returning to the water bath through individual pipes, so flow rates and/or temperatures could be checked.

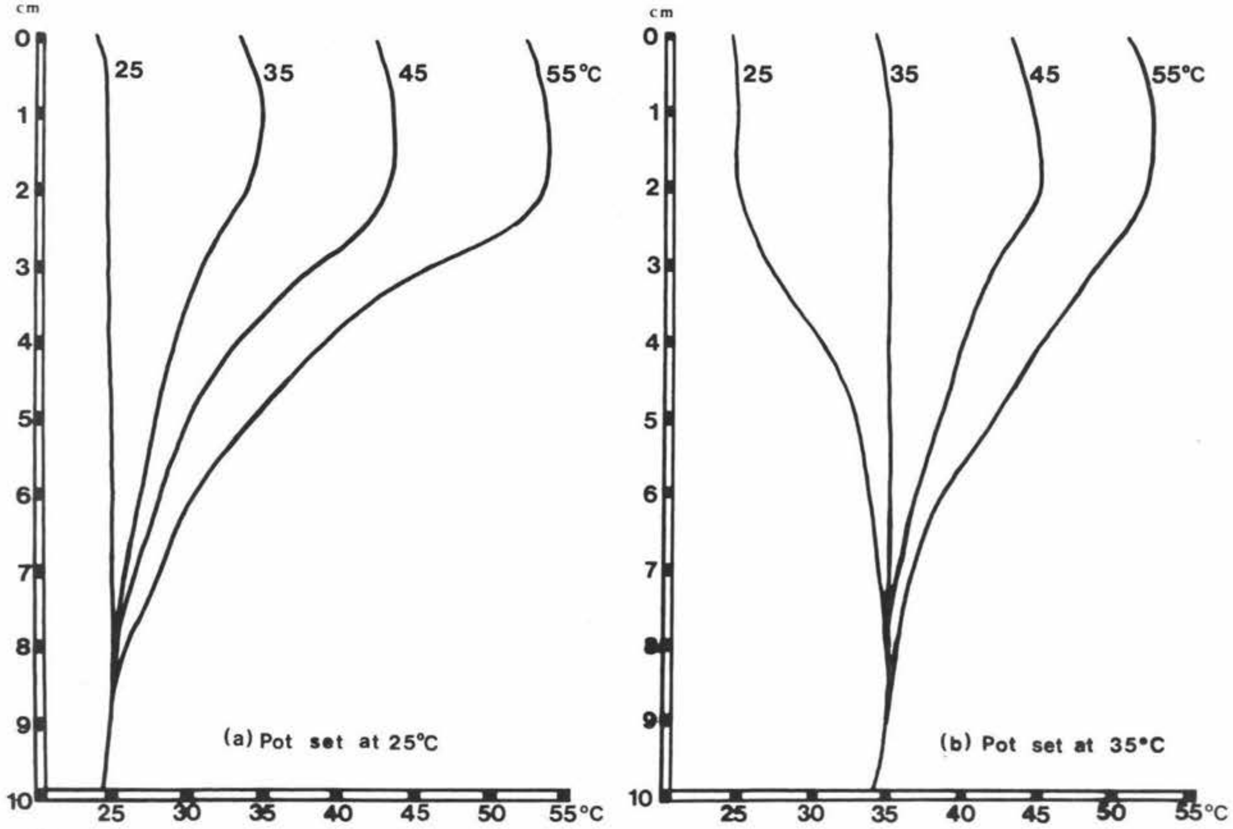
At the flow rates of water used in the experiments (approximately 2 l. min^{-1}) water returning to the water bath had lost 0.5°C at the highest temperature used (55°C) and no temperature losses were detected at 25 or 35°C. The drop in temperature was less than the variation in the water bath temperatures (1° to a maximum of 2°C either above or below the setting).

Centripetal pumps were used for water circulation. The speed of the pumps were controlled so only low water pressures were obtained. When water flow was restricted in part of the system pressures only increased slightly, which was important because of the flimsy nature of the plastic materials used in the petri dishes.

The pots could have been used to contain nutrient solutions for roots, or, as in the experiments reported in this thesis, fine pumice. Pumice was chosen mainly for the ease with which it may be washed off plant roots, and also as it may more closely resemble sand than a nutrient solution. Sand was not used because of previous difficulties found when growing lucerne in sand in the glasshouse (Clements, pers.comm.).

Temperatures at various depths in the pumice were recorded by the use of thermocouples. For temperature measurements within the plastic tubes of the petri dish a fine thermocouple was used, and a slightly more robust thermocouple mounted at the end of a 1.5 mm diameter glass tube was pushed into the pumice in the pot to record soil temperatures at different depths.

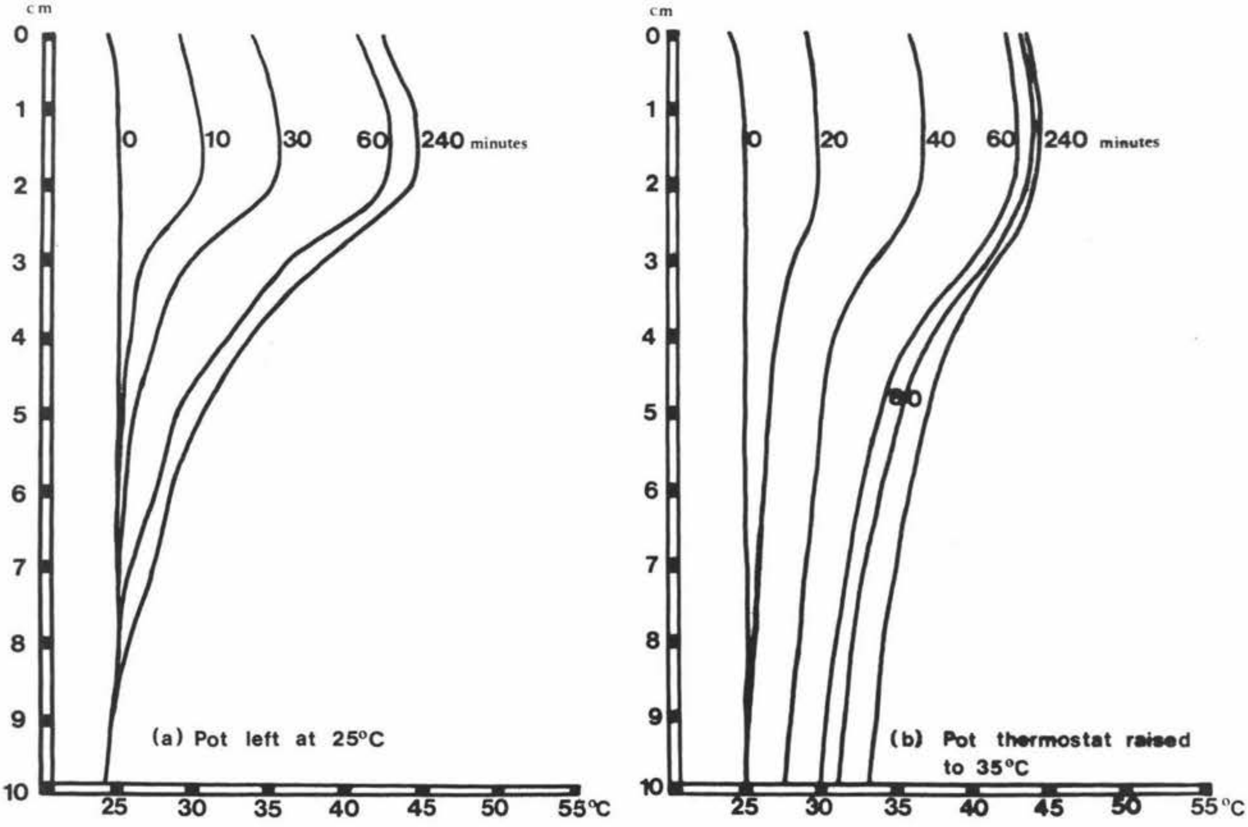
A representative sample of temperatures is shown in fig. 2.2.2 (a) and (b) and fig. 2.2.3 (a) and (b). In fig. 2.2.2 (a) and (b) the equilibrium temperatures at various depths are shown for the 25 and 35° soil temperatures respectively. These readings were taken approximately 4 hours after turning the water baths on. An idea of the speed at which equilibrium was reached is given by fig. 2.2.3 (a) and (b). In fig. 2.2.3 (a) the soil temperature



(a) Pot set at 25°C

(b) Pot set at 35°C

Figure 2.2.2 Equilibrium temperature profiles at indicated depths from the top of the petri dish



(a) Pot left at 25°C

(b) Pot thermostat raised to 35°C

Figure 2.2.3 Temperature profiles at intervals after the surface waterbath was raised from 25 to 45°C on the thermostat setting is maintained at 25°C while the temperature thermostat on the bath is adjusted from 25° to 45°C. Measurements indicated that soil temperature changes quickly followed the change of the water temperature. It took the water bath approximately 60 minutes to reach 45°C. The 35°C, 45°C and 55°C baths were all adjusted to take approximately 1 – 1¼ hours to reach their respective temperatures from 25°C.

Fig. 2.2.3 (b) shows the changes in temperature with depth over a period of time when the soil temperature is increased from 25 to 35°C at the same time as the surface temperature is increased from 25 to 45°C. This shows the slower response of the soil temperature to the temperature of the water in the water jacket than the response to the surface temperature.

The times to respond to both 35 and 55°C surface temperatures were very similar to those for 45°C and are not shown. The rate of response to 35°C from 25°C soil temperature was similar to that in fig. 2.2.3 (b) whether the surface temperature was 25, 35, 45 or 55°C.

The indicated decline in temperature in the top 1 cm is mainly due to the thermocouple conducting heat away from the surface. It was found that very fine thermocouples recorded the maximum temperature almost right to the surface.

In using the equipment, germinated seeds were placed in position on top of the petri dish with their radicles extending downwards through the plastic tubes into the pumice below. After an establishment period, which allowed the development of a root system, various temperature treatments were imposed as described in subsequent sections. Much preliminary experimentation was carried out with the equipment prior to commencing the experiments reported.

2.3 Glasshouse Experiment 1

The aim of this experiment was to simulate and study some of the temperature situations found in the field experiment. The equipment used is described in the previous section.

The layout may be found in Appendix 4. The treatments were :

1. 25°C soil temperature with a 25°C surface temperature
2. 25°C " " " " 35°C " "
3. 25°C " " " " 45°C " "
4. 25°C " " " " 55°C " "
5. 35°C " " " " 25°C " "
6. 35°C " " " " 35°C " "
7. 35°C " " " " 45°C " "
8. 35°C " " " " 55°C " "

There were 9 seedlings in each of 2 pots per treatment within each of 3 blocks, providing a total of 6 replicates. The temperature treatments were only applied for part of each day, with a common temperature of 25/25°C (25°C surface temperature and 25°C soil temperature respectively) for part of the day and at night. Apart from the first few days (see later) before treatments were imposed the water baths were turned up to their respective temperatures at 10.15 a.m. and turned down again at 2.30 p.m. The temperature increased over a period of 60-70 minutes and dropped over a similar period, providing a treatment time at full temperature of approximately 3 - 3¼ hours each day. The water from the water baths was circulated through the system continuously during the day and night.

On April 26 inoculated and pelleted lucerne seed (cv. Wairau) was sown in pumice supplied with nutrient solution (see Appendix 5 for constituents) and after 3 days in a warm situation the seeds were transplanted to the pots, with their root system in contact with the pumice in the pot below. The plastic tubing of the petri dishes surrounded the root/shoot junction and lower shoot. The pumice was supplied with nutrient solution, with additions made at weekly intervals.

The pots were covered for 3 days with a cloth hood which was sprayed with water periodically to maintain a high relative humidity around the seedlings. Seedlings which died during this time were replaced by seedlings of the same age. Pumice and surface temperatures were maintained at 25°C during this period.

10 days from planting (on May 5) temperature treatments were imposed. Treatments continued for 19 days (to May 23) and all seedlings were harvested on May 24 to measure dry weights of the tops and roots.

Once the treatments had started, daily visual scorings of the individual plants were made on a 0 - 5 basis where

0 = dead plant; 1 = plant very weak, expected to die;
2 = weak plant; 3 = moderately healthy plant;
4 = healthy plant; 5 = very healthy plant.

At the conclusion of the trial, counts of nodules were made, heights of shoots recorded and the number of trifoliate leaves counted on each surviving seedling.

2.4 Glasshouse experiment 2

This experiment was designed to complement the previous experiment and in particular to examine several aspects of the timing of high temperature stress. A moderately severe (50°C) surface temperature with a 25°C pumice temperature was chosen on the basis of the first glasshouse experiment. The duration of the 50°C surface temperature was set at 3, 6 or 24 hours per day. In addition the treatments were continued for either 1, 3 or 7 days, commencing either 10 or 13 days after the sowing date (day 1, June 4, 1972). The final comparison was that of the effect of a rapid rise in surface temperature (about 1 minute) with that of a slow rise (about 60 minutes). Day 19 was the last day of treatments, and the plants were harvested for dry matter yields of the tops on day 26.

The experiment was thus an incomplete factorial design with the following treatments (Table 2.4) each replicated 3 times (see Appendix 6 for details of the layout).

Table 2.4 Individual treatments in the second glasshouse experiment. (see text for details).

Treatment Number	Treatment Duration (hours/day)	Number of Days Treatment Continued	Number of Days Treatment Commenced After Sowing	Minutes to Reach Temperature
1.	3	1	10	60
2.	3	3	10	60
3.	3	7	10	60
4.	3	1	13	60
5.	3	3	13	60
6.	3	7	13	60
7.	6	1	10	60

Table 2.4 contd.

Treatment Number	Treatment Duration (hours/day)	Number of Days Treatment Continued	Number of Days Treatment Commenced After Sowing	Minutes to Reach Temperature
8.	6	3	10	60
9.	6	7	10	60
10.	6	1	13	60
11.	6	3	13	60
12.	6	7	13	60
13.	24	3	10	60
14.	24	3	13	60
15.	3	3	10	1
16.	3	3	13	1

The experiment was conducted in a similar manner to the previous trial. Nine lucerne seedlings per pot were transplanted on day 4, and covered for 1½ days with several layers of damp newsprint paper placed directly on top of the plants instead of the cloth canopy over the entire trial which had been used previously. This modification reduced the seedling mortality during the establishment phase (2 – 4% compared with approximately 50% in the earlier trial) and therefore reduced the transplanting required. A continuous fine spray of water was first used to keep the paper moist (day 4 and 5) and later, after the paper was removed, to keep the seedlings moist (days 6 to 9 inclusive).

Treatments commenced on day 10 and daily scores were made on plant vigour on a 0 – 2 scale (0 = dead, 1 = weak, 2 = healthy).

2.5 Statistical Methods

In the sand country experiment because temperature, windrun, rainfall and radiation measurements were not replicated, these were not statistically analysed.

All the other measurements were analysed by the analysis of variance, as in Snedecor and Cochran (1971) on pages 369 - 375. The least significant differences (LSD) for comparisons between treatments and interactions are shown at the foot of each table when the F test indicated the null hypothesis was rejected at the 5% level.

With plant counts at 4 dates, the data were analysed with the count at a date as a split-split plot. The LSD's listed for interactions follow the method of Cochran and Cox (1966) pages 297 - 305.

In the glasshouse experiments individual scores of plant vigour were taken on a daily basis, and the mean and standard error of the treatments were calculated. The final weights were analysed by the analysis of variance, the forms of which may be seen in the appendices and the results sections.

Levels of significance are indicated in the analysis of variance tables with * for significance at the 5% level, and ** for the 1% level.

Chapter Three RESULTS

Introduction

The results are presented separately for the three trials under the headings : -

3.1 Sand Country experiment
3.2 Glasshouse experiment 1
3.3 Glasshouse experiment 2

3.1 Sand Country Experiment

Rainfall and windrun over the period November 29 to December 24, 1971, are shown in Table 3.1.1. On days when no reading was taken, the next days reading is the sum of the 2 days. The figures indicate the high rainfall up until December 8, with negligible rainfall for the rest of the period. Only November 29 was a particularly windy day during the period covered.

The mean maximum, the mean minimum and the daily mean temperatures at the soil surface, at 2 cm and 10 cm are shown in Table 3.1.2 for each of the surface mulch treatments. The figures show the high maximum and mean temperature reached under the black bitumen mulch, particularly at the 2 and 10 cm depths. The two treatments with straw mulches showed much reduced maximum temperatures at 2 and 10 cm while the minimum temperatures were similar to the other treatments at these depths, with a cooler surface temperature.

The bitumen plots painted white showed similar temperatures to the no mulch and lupin plots, although the surface maximum temperatures were lower. Irrigation appeared to have little effect on the temperatures with the exception that it reduced the surface maximum in the straw mulches. At times when the irrigation was going or the surface was still very moist from irrigation a reduction in surface temperature was noticed.

The thermocouples on the soil or mulch surface were treated to make them as similar to the surface as possible. There is doubt that they were measuring the surface temperature accurately, as the thermal properties of the thermocouples plus the outer heat shrink tubing (an overall diameter of 3 - 4 mm) would most likely be different to the surrounding sand or mulch. It is likely that the interface of the sand or mulch with the air would be warmer than the

Table 3.1.1 Record of rainfall and windrun, during the establishment phase of the lucerne.

Date	Rainfall (mm)	Windrun (km)
November 29	0	579
30	0	306
December 1	0	306
2	-	-
3	12.5	193
4	17.5	150
5	-	-
6	0	253
7	0	134
8	11	348
9	.3	161
10	0	122
11	0	137
12	0	151
13	0	148
14	0	51
15	0	201
16	0	175
17	0	106
18	-	-
19	0	491
20	0	249
21	2.3	193
22	0	257
23	0	134
24	0	163

Table 3.1.2 Mean temperatures at 0, 2 and 10 cm depth, December 5 to 23, 1971, on irrigated and non-irrigated plots.

	Mulch					
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin
(a) Mean Maximum Temperature						
Irrigated						
0 cm	44.9	46.0	45.4	38.5	36.1	45.0
2 cm	33.1	40.6	22.4	28.1	33.1	32.9
10 cm	27.1	31.1	22.3	23.4	28.8	27.2
Not Irrigated						
0 cm	48.4	45.1	45.4	47.9	41.2	47.6
2 cm	33.6	39.6	23.0	23.6	33.5	34.0
10 cm	27.7	33.9	21.4	22.4	26.6	28.9
(b) Mean Minimum Temperature						
Irrigated						
0 cm	11.5	12.5	7.6	7.5	11.8	11.4
2 cm	12.5	15.5	15.7	15.7	14.2	14.1
10 cm	15.6	18.5	16.2	18.3	16.7	16.2
Not Irrigated						
0 cm	11.3	13.4	8.2	7.1	10.7	11.6
2 cm	14.2	15.2	15.8	16.9	14.3	14.9
10 cm	17.1	19.1	16.1	17.0	17.3	16.6
(c) Mean Daily Temperature						
Irrigated						
0 cm	28.2	29.3	26.5	23.0	24.0	28.2
2 cm	22.8	28.1	19.1	21.9	23.7	23.5
10 cm	21.4	25.8	19.3	20.9	22.8	21.7
Not Irrigated						
0 cm	29.9	29.3	26.8	27.5	26.0	29.6
2 cm	23.9	27.4	19.4	20.3	23.9	24.5
10 cm	22.4	26.5	18.8	19.7	22.0	22.8

3.1.3 Soil Moisture as an arcsine transformation of % moisture expressed on a dry soil basis.

(a) Samples 0 – 3 cm depth

December 1

	Mulch						Mean	Moisture %
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin		
Irrigated	17.3	23.3	21.0	25.0	25.5	19.9	22.0	14.0
Not Irrigated	18.9	22.1	21.6	23.8	23.4	19.2	21.5	13.4
Mean	18.1	22.7	21.3	24.4	24.4	19.6	21.7	13.7
Moisture %	9.6	14.9	13.2	17.0	17.1	11.2	13.7	

LSD mulch = 2.0

Samples 0 – 3 cm

December 16

Irrigated	20.2	22.3	23.6	24.7	22.4	17.0	21.7	13.7
Not Irrigated	12.3	18.4	18.9	22.9	20.9	14.1	17.9	9.5
Mean	16.3	20.3	21.2	23.8	21.6	15.6	19.8	11.5
Moisture %	7.8	12.0	13.1	16.3	13.6	7.2	11.5	

LSD mulch = 1.8 LSD irrigation = 1.8 LSD interaction = 2.5

Samples 0 – 3 cm

December 24

Irrigated	16.6	21.2	22.9	24.5	23.0	16.7	20.8	12.6
Not Irrigated	8.4	13.4	15.1	19.6	17.8	8.5	13.8	5.7
Mean	12.5	17.3	19.0	22.0	20.4	12.6	17.3	8.8
Moisture %	4.7	8.8	10.6	14.1	12.2	4.8	8.8	

LSD mulch = 2.0 LSD irrigation = 1.6

Table 3.1.3 contd.

(b) Samples 3 - 20 cm depth
December 1

Irrigated	22.7	24.6	26.8	24.4	25.6	23.1	24.5	17.2
Not Irrigated	22.4	26.1	25.2	26.2	23.5	22.0	24.2	16.9
Mean	22.6	25.4	26.0	25.3	24.5	22.5	24.4	17.0
Moisture %	14.7	18.3	19.2	18.3	17.2	14.7	17.0	

LSD mulch = 2.2

Samples 3 - 15 cm
December 16

Irrigated	26.1	26.1	26.1	25.6	24.5	26.2	25.8	18.9
Not Irrigated	23.1	22.2	24.2	26.1	22.9	22.3	23.5	15.9
Mean	24.6	24.1	25.1	25.8	23.7	24.3	24.6	17.3
Moisture %	17.3	16.8	18.0	19.0	16.2	16.9	17.3	

LSD irrigation = 2.1

Samples 3 - 15 cm
December 24

Irrigated	25.2	26.0	26.5	26.8	27.1	23.4	25.8	19.0
Not Irrigated	20.1	22.7	22.3	23.6	22.0	20.2	21.7	13.7
Mean	22.6	24.4	24.4	25.2	24.6	21.8	23.8	16.3
Moisture %	14.8	17.0	17.1	18.1	17.3	13.8	16.3	

LSD mulch = 1.9 LSD irrigation = 2.4

temperatures recorded. The thermocouples on the sand surface gave very similar readings to a mercury thermometer with the bulb just covered with the sand (i.e. the bulb from about 1 mm to 4 mm below the surface).

The thermocouples at the 2 and 10 cm depths should have measured the soil temperatures accurately at the respective depths.

Soil moisture figures are given in Table 3.1.3 as the arcsine transformation of soil moisture percentages. At each date the corresponding soil moisture percentage is given by reconverting the means to the original scale. The least significant difference (LSD) on the transformed scale at the 5% level is shown where the F test was significant. At December 1 irrigation had not begun, but at the 0 - 3 cm depth the no mulch and lupin treatments had a lower moisture level than the mulched treatments. This trend continued throughout, and is indicated also in the deeper samples except at December 16. As expected irrigation increased the soil moisture.

Table 3.1.4 (a) shows the analysis of variance from the plant counts per m^2, taken on 4 dates. The main results were the highly significant differences in mulch treatments and the highly significant time and mulch interaction. In Table 3.1.4 (b) the means of the different treatments are given together with the appropriate least significant differences (LSD).

There were no significant differences between the no mulch, bitumen and bitumen plus white paint treatment means. The lupin treatment had a higher number of plants than all others, and the two straw covered treatments had a lower number. With an LSD of 26 for comparing mulch means at January 6, there was no significant difference between the no mulch, bitumen, white bitumen and lupin treatments although there were less plants in the two bitumen treatments.

Table 3.1.4 (a) Analysis of variance of the plant counts (number.m^{-2}) at 4 dates (December 6, 9, 23 and January 6).

Source	df	SS	MS	F
Blocks	4	14,808	3,702	1.25
Irrigation (I)	1	12	12	.00
Error (1)	4	11,871	2,968	
Mulch (M)	5	529,375	105,875	66.38 **
I x M	5	2,511	502	.31
Error (2)	40	63,804	1,595	
Times (T)	3	6,393	2,131	3.67 *
T x I	3	6,890	2,297	3.95 **
T x M	15	128,046	8,536	14.69 **
T x M x I	15	6,798	453	.78
Error (3)	144	83,669	581	

Table 3.1.4 (b) Number of plants per m^2 at 4 dates.

	Mulch						Mean
	None	Bitumen	Straw	Bitumen Straw	Bitumen Paint	Lupin	
Irrigated							
December 6	160	210	20	22	177	204	132
December 9	185	174	57	64	156	188	137
December 23	162	167	101	107	154	185	146
January 6	172	132	95	130	133	169	138
Mean	170	171	68	81	155	186	138
Not Irrigated							
December 6	183	191	13	21	171	208	131
December 9	153	194	69	73	166	198	142
December 23	156	156	90	113	176	185	146
January 6	156	149	106	90	154	158	136
Mean	162	173	70	74	167	187	139
Mean of Irrigation Treatments							
December 6	172	201	17	21	174	206	132
December 9	169	184	63	69	161	193	140
December 23	153	161	95	110	165	185	146
January 6	164	140	101	110	143	164	137
Mean	166	172	69	78	161	187	139

LSD Mulch = 18

LSD Time = 9

LSD Times within an irrigation treatment = 8

LSD Times within a mulch = 21

LSD Times within an irrigation and a mulch treatment = 30

LSD Mulch within a time or several times = 26

LSD Mulch within an irrigation and a time = 37

LSD Irrigation within a time or several times = 18

LSD Irrigation within a mulch and a time = 38

Table 3.1.4 (c) Plant counts per m^2 at successive dates combining the control and lupin mulch. Average of the irrigated and not irrigated treatments.

	Mulch				
	None + Lupin	Bitumen	Straw	Bitumen Straw	Bitumen White
Mean of irrigation treatments					
December 6	189	201	17	21	174
December 9	181	184	63	69	161
December 23	172	161	95	110	165
January 6	164	140	101	110	143

There were significantly less plants in the two straw mulch treatments. Comparing times within mulches (LSD = 21) it is apparent there was an increase in the number of plants counted in the straw mulch treatments. At the same time there was a significant decrease in the number of plants in the bitumen, white bitumen and lupin treatments. The largest reduction in plant numbers was on the bitumen treatment. The increase in plant numbers on the straw mulches was mainly due to difficulties in counting all plants among the straw, particularly at the first two dates. The decline in plant numbers is due to plant death. On December 20 a visual assessment of plant deaths was made (Table 3.1.5) of plants dead but still evident on the soil surface. This showed the particularly high death at that time on the bitumen plots, especially in blocks 4 and 5 where the bitumen was more thickly applied.

As there was no apparent reason why the number of lucerne seedlings should have been different between the no mulch and lupin treatments (as the lupins did not germinate well) the two treatments have been combined in Table 3.1.4 (c). This shows even more clearly than Table 3.1.4 (b) the marked reduction in plant numbers under the bitumen mulch. The probable reason for the lower initial plant count under the bitumen painted white treatment compared with the bitumen was that some seedlings were sprayed (and apparently damaged) with white paint when it was applied to the plots on November 29.

Table 3.1.5 Visual assessment of plant mortality on December 20. Scale is 0 – 8 where 0=no deaths to 8= all dead.

	Mulch						Mean
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin	
Irrigated							
Block 1	3	0	0	0	3	5	
2	1	2	0	0	0	3	
3	0	2	0	0	0	1	
4	3	6	0	0	0	1	
5	2	7	0	0	1	1	
Mean	1.8	3.4	0	0	.8	2.2	1.4
Not Irrigated							
Block 1	1	0	0	0	1	1	
2	5	3	0	0	0	5	
3	1	6	0	0	1	4	
4	2	6	0	0	0	3	
5	1	6	0	0	1	1	
Mean	2.0	4.2	0	0	.6	2.8	1.6
Overall Mean	1.9	3.8	0	0	.7	2.5	1.5

LSD mulch = 1.8

Checks were made on the incidence of seedling diseases. On December 13 some plants in the unirrigated main plot of block 3 were found to have an infection of a pathogenic fusarium species, but the other plants studied appeared to have died of heat stress as described in Shaw (1952) and Levitt (1972).

Table 3.1.6 (a) shows the dry matter yields ($g.m^{-2}$) of the tops. Here the bitumen mulch was generally the highest yielding, with the two straw mulch treatments the lowest yielding at the 4 dates shown. Even at the harvest on January 6, it can be seen that the dry matter yield per unit area on the straw covered plots is much lower than the other treatments, in fact proportionately lower than the plant density (Table 3.1.4) would indicate. Table 3.1.6 (b) shows the per plant yield at 4 dates. Throughout the experimental period the plants on the bitumen plots tended to be the heaviest, and significantly so for December 23 and January 6. The plants under the straw mulches were significantly lighter than all other treatments throughout.

Table 3.1.6 (a) Dry matter yield ($g.m^{-2}$) at four dates, showing the influence of surface mulches and irrigation.

	Mulch						Mean
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin	
December 9							
Irrigated	.96	.98	.17	.24	.78	.89	.67
Not Irrigated	.77	1.05	.26	.29	.81	.96	.69
Mean	.87	1.01	.21	.26	.80	.92	.68
LSD mulch 0.13							
December 23							
Irrigated	9.8	14.4	4.1	6.0	7.4	11.5	8.9
Not Irrigated	10.2	11.6	4.1	5.6	10.0	11.4	8.8
Mean	10.0	13.0	4.1	5.8	8.7	11.5	8.8
LSD mulch 2.6							
January 6							
Irrigated	114	111	27	41	97	104	83
Not Irrigated	81	90	33	48	85	77	69
Mean	98	101	30	45	91	91	76
LSD mulch = 13	LSD interaction = 19						
January 26							
Irrigated	104	107	46	58	77	97	82
Not Irrigated	92	115	74	69	84	94	88
Mean	98	111	60	64	81	95	85
LSD mulch = 13	LSD interaction = 19						

Table 3.1.6 (b) Dry matter yield (g x 10^{-2}) per plant at three dates, showing the influence of surface mulches and irrigation.

	Mulch						Mean
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin	
December 9							
Irrigated	.52	.56	.36	.36	.52	.47	.46
Not Irrigated	.50	.55	.37	.40	.49	.48	.46
Mean	.51	.55	.36	.38	.51	.47	.46
LSD mulch = .05							
December 23							
Irrigated	6.1	9.1	4.1	5.5	4.8	6.3	6.0
Not Irrigated	6.1	7.8	4.4	4.8	5.8	6.2	5.9
Mean	6.1	8.5	4.3	5.2	5.3	6.3	5.9
LSD mulch = 1.6							
January 6							
Irrigated	70	91	33	35	79	65	62
Not Irrigated	52	65	32	52	57	49	51
Mean	61	78	32	44	68	57	57

LSD mulch = 12 LSD irrigation = 9 LSD interaction = 16

Visual assessments were made of plant mortality on December 20, and are presented in Table 3.1.5. These are on a scale 0 – 8, with 0 representing no deaths and 8 representing all dead. This assessment was after a number of plants had died. The plants had wilted and collapsed (see plate 2). Individual block assessments are given to show the apparently higher mortality in blocks 4 and 5 where the bitumen was more thickly applied than blocks 1 and 2. As the straw and bitumen plus straw mulches are obviously different to the other mulches, they have been excluded from the statistical analysis, so the LSD refers to the other 4 mulch means. The bitumen mulch tends to have a much higher mortality than the other mulches. In Table 3.1.4 (c) the plant counts per m^2 showed the most decline with time on the bitumen plots.

In this table (3.1.4 (c)) the no mulch and lupin treatments are combined with the rationale that as the lupins germinated to such a limited extent there was no difference in the mulch or surface treatment.

On January 17 at midday assessments were made of plant wilting on a 0 - 8 scale (0 = no wilting to 8 = all plants showing considerable wilting). Table 3.1.7 shows significantly more wilting under no mulch or lupin than under the other mulches. Plants on black bitumen were wilted more than those on white bitumen or the straw mulches.

Table 3.1.7 Assessment of wilting at midday on January 17, 1972. The scale is 0 - 8 with 0 = no wilting and 8 = all plants showing considerable wilting.

	Mulch						Mean
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin	
Irrigated	2.8	2.0	0	0.4	1.2	3.2	1.6
Not Irrigated	6.8	3.0	1.2	2.2	2.0	5.8	3.5
Mean	4.8	2.5	0.6	1.3	1.6	4.5	2.6

Mulch LSD = 0.9 Irrigation LSD = 1.9

On the same day (January 17) an assessment of flowering was made on a 0 - 5 scale (0 = no flowering to 5 = profuse flowering). Table 3.1.8 shows there was much more flowering on the bitumen mulched plots, with the control, lupin and white bitumen plots showing more flowers than the two straw mulched treatments.

Table 3.1.8 Assessment of flowering on January 17, 1972. The scale is 0 - 5 with 0 = no flowering and 5 = profuse flowering.

	Mulch						Mean
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin	
Irrigated	1.0	3.0	0	0.2	0.8	1.0	1.0
Not Irrigated	1.6	2.6	0	0.6	1.4	1.4	1.3
Mean	1.3	2.8	0	0.4	1.1	1.2	1.1

LSD mulch = 0.4 LSD irrigation = 0.2

Net pyrradiometers were used to measure net radiation and net short wave radiation. The basic equation used was -

$$Rn = (1-a)K + Li - Lo \qquad \text{eqn. } 1.3.1.1$$ (see page 11 for definition of terms)

For December 12, 1971, the meteorological base at Ohakea supplied a value of 987 watts. m^{-2} for K at midday. By using a perspex dome on both hemispheres of the net pyrradiometer longwave radiation was excluded, so (1-a)K was measured, meaning that "a" could be calculated. J. Kerr (pers. comm.) suggested a more suitable estimate of K for the experimental site may be provided by assuming Rn = .75K (Kerr and Talbot, 1971). There are many possible values of Rn to use, so an arbitrary value of 850 watts. m^{-2} was chosen, and is used in Table 3.1.9.

The reference net pyrradiometer was read at the same time as the net pyrradiometer that was shifted from plot to plot. In this way variations in K with time could be allowed for by adjusting both readings by a factor to maintain Rn of the reference net pyrradiometer at an arbitrary value of 600 W. m^{-2}.

In Table 3.1.9 measurements are presented for unirrigated plots, and for irrigated plots both before and after irrigation (Irrigation was applied from 1.35 pm to 2 pm and the readings were taken first with a dry surface and then with a wet surface). From readings on the same area with both the net pyrradiometers for calibration purposes, it was decided to multiply all the readings from the moved net pyrradiometer by 1.026 so both pyrradiometers recorded the same Rn.

In Appendix 7 the approximate time of each reading, the unadjusted Rn and (1-a)K readings and the reference reading are shown. The surface temperature at approximately the same time is shown.

The main features of Table 3.1.9 are the low albedo of the bitumen plots compared with the straw covered and white painted plots on the unirrigated main plots. The lower albedo on the straw covered plots in the irrigated, dry surface, main plots compared with the unirrigated plots may be due to water impurities staining the straw a darker colour. When the surface of the plots was wet the albedo was much lower due to the higher absorption with the darker colour. The albedo on the white painted bitumen and bitumen seemed relatively unaffected.

Table 3.1.9 Net radiation (Rn) and net short wave radiation ((1-a)K) over the different mulches and irrigation treatments on December 24, 1971. Albedo (a) is calculated with K assumed equal to 850 $W.m^{-2}$.

	Mulch					
	None	Bitumen	Straw	Bitumen Straw	Bitumen White	Lupin
Not Irrigated						
Rn ($W.m^{-2}$)	594	660	578	561	553	606
(1-a)K ($W.m^{-2}$)	730	805	660	653	654	748
a 850	.14	.05	.22	.23	.23	.12
Li-Lo ($W.m^{-2}$)	-136	-145	-82	-92	-101	-142
Irrigated treatments with dry surface						
Rn ($W.m^{-2}$)	668	731	670	649	593	638
(1-a)K ($W.m^{-2}$)	735	797	737	733	637	738
a 850	.14	.06	.13	.14	.25	.13
Li-Lo ($W.m^{-2}$)	-67	-66	-67	-84	-44	-100
Irrigated treatments with a wet surface						
Rn ($W.m^{-2}$)	785	780	735	749	629	764
(1-a)K ($W.m^{-2}$)	819	830	788	774	685	813
a 850	.04	.02	.07	.09	.19	.04
Li-Lo ($W.m^{-2}$)	-34	-50	-53	-25	-56	-49

Because these figures are adjusted for changes in K, it is not possible to compare them with the surface temperature recorded in the appendix. However, it is possible from the column Li-Lo to gain some information on the relative surface temperatures. As the Li was likely to be constant over all plots and assuming the emmissivity of longwave radiation of all the surfaces to be 1 or nearly one, the magnitude of the figure is related to the surface temperature. On the non-irrigated main plot the bare sand, lupin and bitumen mulches would have much higher surface temperatures at midday than the white painted bitumen or straw covered plots. On the irrigated plots, wet or dry, the differences were not apparent. In the appendix with the wet surface there was little difference in temperatures between treatments, while there was a difference on the non-irrigated and irrigated with a dry surface. The bitumen, bare sand and lupin treatments were the warmest.

3.2 Glasshouse Experiment 1

The daily scores on plant vigour on a 0 (plant dead) to 5 (very vigorous healthy plant) scale are shown in Figure 3.2.1. The 55°C surface temperature killed the plants, the effect becoming apparent after the second day. During the first and second day of treatment it was apparent the seedlings were wilting when the 55°C surface temperature treatment was applied. On about the 8th day of treatment the plants at 45°C surface temperature were beginning to have reduced vigour compared with the 25 and 35° surface treatment. The plants with a 25° surface and 35° soil temperature seemed more vigorous than the other treatments.

Table 3.2.1 shows the dry matter yield of the whole plant (tops plus roots) at the conclusion of the trial. The difference in weight between 25° - 35° and 45° - 55°C surface temperature is obvious with the surface temperatures above 35°C having killed the plants. In an analysis of variance based on the data for surface temperatures of 25° and 35°C, the F ratio for soil temperature and the interaction of soil and surface temperatures reached significance at the 10% level. The difference between 25° and 35°C surface temperature was not significant. For the tops alone (Table 3.2.2) the F ratio was also significant at the 10% level for soil temperature and the interaction of soil and surface temperature, with the plants being heavier at the 35°C soil temperature. The interaction shows the higher yield with a 35° C soil, and 25°C surface temperature.

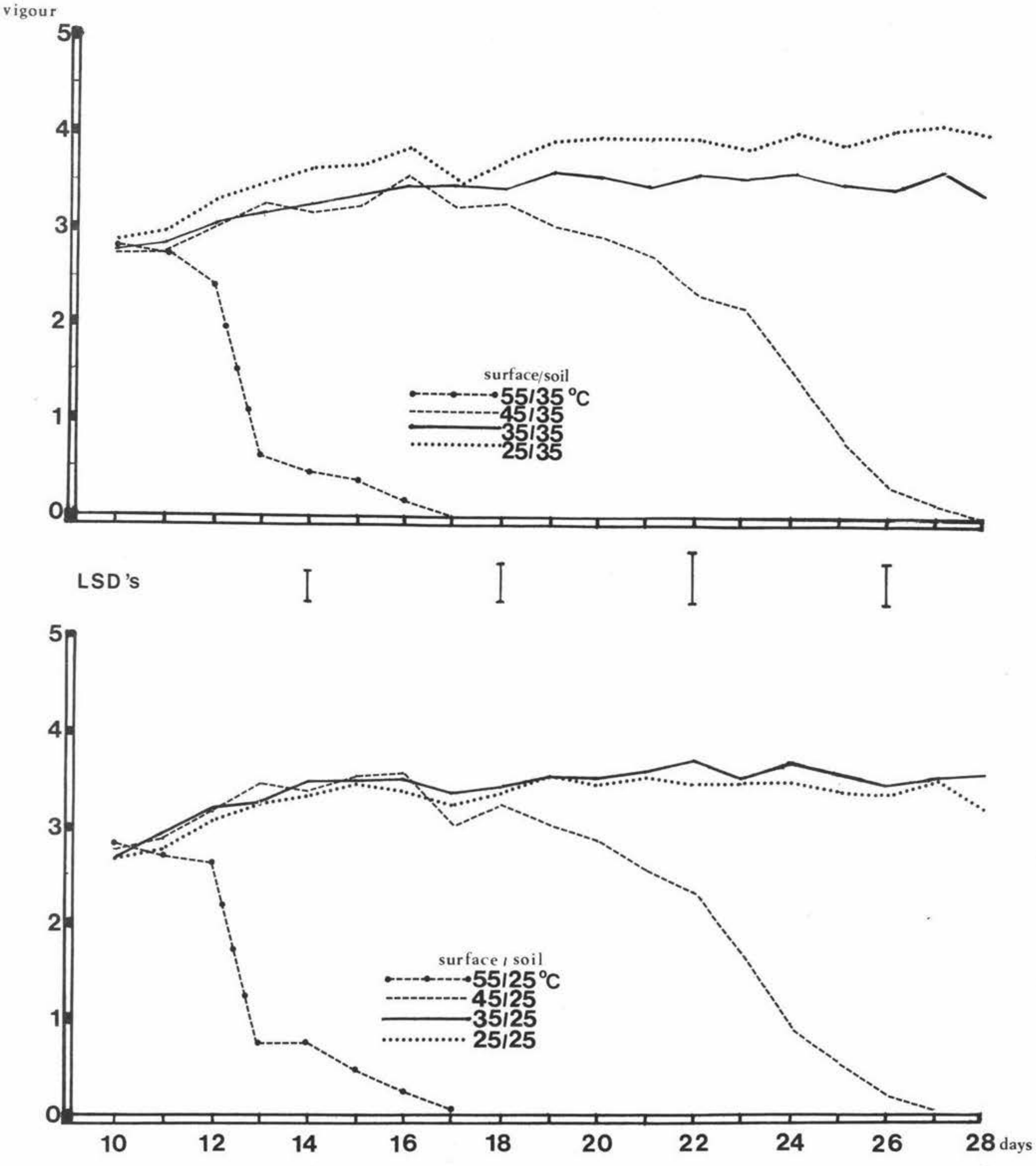


Figure 3.2.1 Mean daily scores of seedling vigour on a 0-5 scale (0 = plant dead ; 5 = very vigourous) showing the influence of soil and surface temperature. Treatments began 10 days after sowing.

Table 3.2.1 Dry matter yield per plant (g x 10^{-4}) at conclusion of the first glasshouse experiment.

	Surface temperature (°C)				
	25	35	45	55	Mean
Soil temperature (°C)					
25	79.2	87.4	0	0	41.7
35	108.2	87.8	0	0	49.0
Mean	93.7	97.6	0	0	45.3

Table 3.2.2 Dry matter yield of tops per plant (g x 10^{-4}) at the conclusion of the first glasshouse experiment.

	Surface temperature (°C)				
	25	35	45	55	
Soil temperature (°C)					
25	54.0	60.6	0	0	28.6
35	82.1	60.6	0	0	35.7
Mean	68.1	60.6	0	0	32.2

Inspection of nodulation on the plants showed only a small number of nodules present, with no apparent differences between 25° and 35°C soil and surface temperatures.

The heights of the plants were closely related to their dry matter yield.

3.3 Glasshouse Experiment 2

For convenience, the layout of this experiment is repeated in Table 3.3.1, together with the dry matter yield of tops per plant at the conclusion of the experiment.

As the layout was a factorial design only up to and including treatment 12, the complete design was not orthogonal. From inspection of the layout, however, it is apparent that treatments 13 and 14, may be compared with 2 and 5 to estimate the effect of 24 hours duration of treatment. Likewise treatments 15 and 16 may be compared with 2 and 5 to see the effect of a sudden application of the treatment temperatures compared with that of a slow temperature increase.

Figures 3.3.1 to 3.3.3 show the influence of temperature treatments on the mean of daily visual assessments of plant vigour. 0 represented a dead plant while 2 represented a vigorous plant. Figure 3.3.1 shows the influence of 3 hours duration per day (treatments 1 to 6) versus 6 hours (treatment 7 to 12) versus 24 hours (treatments 13 and 14).

There is an obvious reduction in vigour with the 24 hour treatment compared with 3 and 6 hours. Generally the 6 hour treatment appears a little less vigorous than the 3 hour.

Figure 3.3.2 shows the vigour of plants when treatment started either 10 or 13 days after planting. The earlier start reduced the vigour of the plants considerably.

Figure 3.3.3 compares the vigour of plants with 1, 3 or 7 days treatment. There is little difference except for an apparent reduction in vigour late in the period with the one day treatment, compared with the 3 and 7 day treatment.

Table 3.3.2 shows the analysis of variance of the 16 treatments with an estimate of the error mean square of 11.26. Treatments gave a highly significant F value. In Table 3.3.3 the analysis of variance of the orthogonal design (treatments 1 to 12) is shown. Effects of the length of time from transplanting to the start of temperature treatments, and of the duration of the temperature treatment each day were highly significant, but there were no significant interactions. Table 3.3.4 shows the main effects of the various treatments in the analysis of variance in Table 3.3.3. The earlier start (Day 10 compared with Day 13) reduced significantly the DM yield, indicating the younger plants were more susceptible to the temperature treatment. 6 hours of treatment each day also reduced DM yield significantly compared with 3 hours. The number of days the treatments were continued did not significantly affect yields.

Table 3.3.5 shows the highly significant decrease in yield of plants subjected to 24 hours duration of treatment, compared with either 3 or 6 hours. The mean yield of dry matter per plant is shown in Table 3.3.6, taken from treatment numbers 2,5,8,11,13 and 14. Not all treatments with 3 or 6 hours are included, but only those comparable with treatments 13 and 14.

Table 3.3.1 Treatments and dry matter yields of tops from the second glasshouse experiment.

Treatment Number	Treatment				Mean Yield/plant
	Duration (hours/day)	Time to reach full temp. (minutes)	No.of days Treatment commenced after sowing	Total No. days treated	($g \times 10^{-4}$)
1	3	60	10	1	22.1
2	3	60	10	3	21.6
3	3	60	10	7	25.1
4	3	60	13	1	34.3
5	3	60	13	3	35.7
6	3	60	13	7	36.7
7	6	60	10	1	22.4
8	6	60	10	3	20.7
9	6	60	10	7	18.2
10	6	60	13	1	26.0
11	6	60	13	3	34.1
12	6	60	13	7	31.1
13	24	60	10	3	15.7
14	24	60	13	3	17.6
15	3	1	10	3	24.4
16	3	1	13	3	30.1

Table 3.3.2 Analysis of variance on the 16 treatments in the second glasshouse experiment.

Source	df	SS	MS	F
Blocks	2	96.01	48.00	4.26 *
Treatments	15	2109.27	140.62	12.48 **
Error	30	337.90	11.26	
Total	47	2543.18		

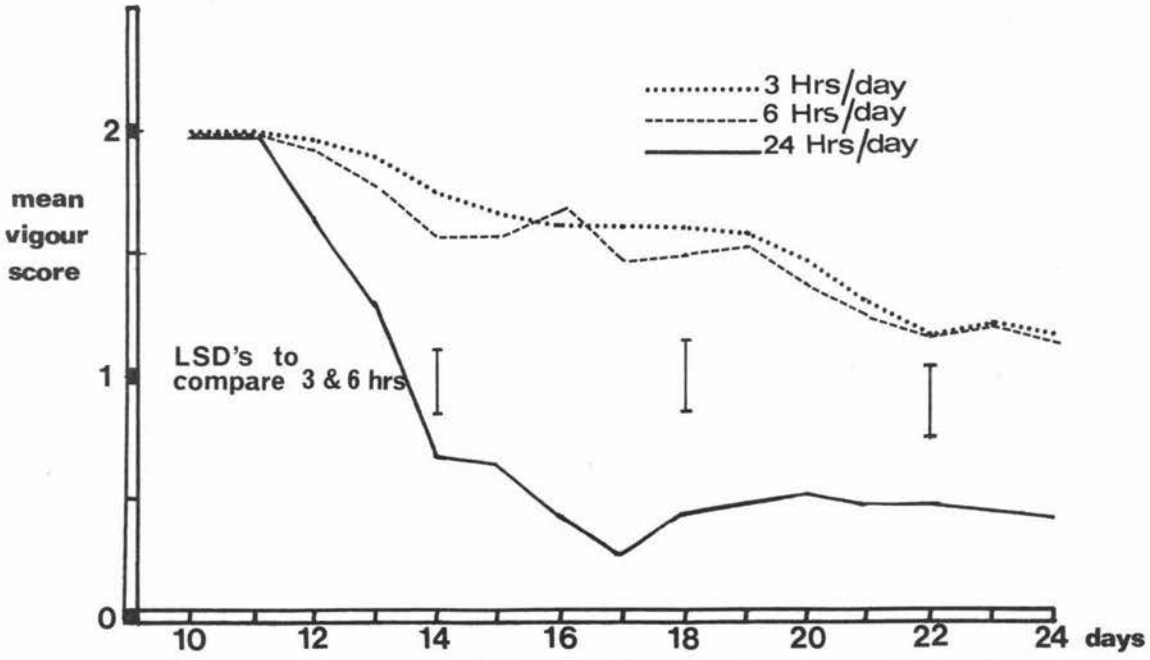


Figure 3.3.1

Mean daily visual scores of seedling vigour on a 0 – 2 scale
(0 = Plant dead 2 = vigourous Plant)
showing the influence of temperature duration per day

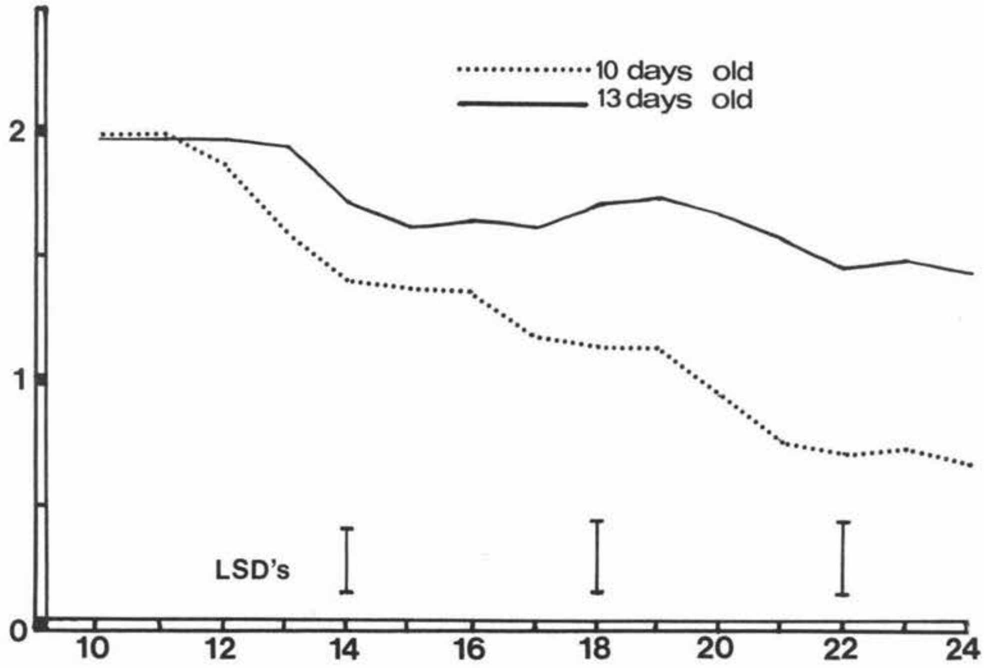


Figure 3.3.2

Mean daily visual scores showing the influence of temperature on different age seedlings

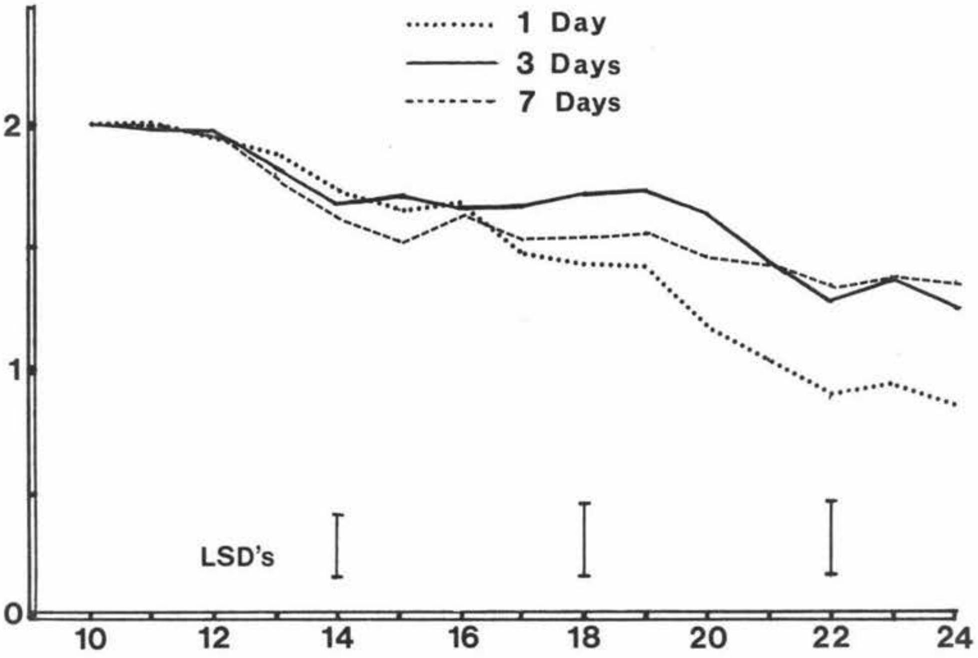


Figure 3.3.3 Mean daily visual score on a 0-2 scale showing the influence of the number of days temperature treatments were applied

Table 3.3.5 also shows that a slow temperature increase does not affect yield differently to a rapid rise. The yields per plant are shown in Table 3.3.7 from treatments 2, 5, 15 and 16.

Table 3.3.3 Analysis of variance on orthogonal treatments 1 to 12 in second glasshouse experiment.

Source	df	SS	MS	F
Blocks	2	85.25	42.63	2.89
Treatments	11	1457.32	132.48	8.99**
Age at Start (S)	1	1150.34	1150.34	78.05**
Duration per day (D)	1	133.40	133.40	9.05
Days Treated (T)	2	23.58	11.79	.80
S x D	1	15.87	15.87	1.08
S x T	2	55.49	27.75	1.88
D x T	2	37.90	18.95	1.29
S x D x T	2	40.74	20.37	1.38
Error	22	324.27	14.74	
Total	35	1866.84		

Table 3.3.4 Mean dry matter yield of tops per plant ($g \times 10^{-4}$) in second glasshouse experiment.

Days treated	1		3		7		Mean
Duration (hours)	3	6	3	6	3	6	
Start 10 days	22.1	22.4	21.6	20.7	25.1	18.2	21.7
13 days	34.3	26.0	35.7	34.1	36.7	31.1	33.0
	28.2	24.2	28.7	27.4	30.9	24.7	27.3
	26.2		28.0		27.8		

Duration 3 hours = 29.3 6 hours = 25.4

Table 3.3.5 Comparison of mean squares from non-orthogonal comparisons in Tables 3.3.6 and 3.3.7. F with 1 and 30 d.f.

Duration 3 hours versus 24 hours	M.S. = 1296.0	F = 115.10 **
Duration 6 hours versus 24 hours	M.S. = 1040.0	F = 92.36 **
Time to reach treatment temperature	M.S. = 17.6	F = 1.56 n.s.
From table 3.3.2	Error M.S. = 11.26	

Table 3.3.6 Comparison of the mean effects of 3, 6 or 24 hours duration of treatment temperatures each day on the dry matter yield per plant (g x 10^{-4})

3 hours	6 hours	24 hours
28.7	27.4	16.7

Table 3.3.7 Comparison of the mean effect of 60 minutes and 1 minute to reach the surface treatment temperature. Dry matter yield per plant (g x 10^{-4})

60 minutes	1 minute
28.7	27.3

Chapter Four DISCUSSION

Introduction

In the following section (4.1) the main results from the 3 experiments are listed. Then in section 4.2 these results are discussed.

4.1 Summary of Main Results

1. In the sand country trial the soil remained moist up until about December 12 during emergence and early growth. The sand dried rapidly on the unmulched and lupin treatments, particularly in the surface layers. Those treatments incorporating bitumen and/or straw mulches had a higher soil moisture percentage than the unmulched treatments, particularly in the 0 - 3 cm depth.

2. The mean maximum soil temperatures at 2 and 10 cm were much higher under the black bitumen than any of the other treatments, while the straw covered treatments were cooler at these depths. The mean temperatures followed a similar pattern.

3. Early establishment counts showed the high initial emergence of the seedlings in the bitumen treatment. With subsequent counts on the bitumen there was a greater decline in the seedling numbers than on the other treatments. This was more evident on blocks 4 and 5 where the bitumen was more thickly applied.

4. Scores of plant death after a period of hot weather showed substantial mortality at this time with the bitumen mulch particularly, but also on the unmulched and lupin treatments.

5. Dry matter yields per unit area were highest throughout on the bitumen treatment, followed by the unmulched and lupin treatments. The white painted bitumen was lower yielding, with the two straw mulches the lowest yielding.

6. Per plant dry matter yields were highest throughout on the bitumen treatment, while in the unmulched, white bitumen and lupin plots the plants were generally heavier than in the two straw-mulched treatments.

7. Irrigation had no effect on plant establishment, plant yield, plant mortality, mean soil temperature or yield per unit area up until and including December 23. There were some responses to (and treatment interactions with) irrigation in January (although irrigation had ceased).

8. Net radiation measurements on a sunny day showed the low albedo of the bitumen. The unmulched and lupin treatments had an intermediate value between the bitumen and the two straw and white bitumen mulched treatments.

9. The first glasshouse experiment showed that a soil surface temperature of 55°C for 3 - $3\frac{1}{4}$ hours per day rapidly killed the lucerne seedlings. Initially 45°C did not affect seedling growth differently to 25 or 35°C, but subsequently killed all seedlings.

10. The second glasshouse experiment showed a decline in seedling vigour and final yield with increased treatment time per day at 50°C.

11. Increasing the number of days on which treatments were applied had no effect on final yield.

12. A rapid application of heat (the temperature increased over a period of about 1 minute) and a gradual application (increased over about 1 hour) had similar effects on plant vigour and yield.

13. The age of the plant at the time of treatment application had a marked effect, with the younger seedlings (10 days old) being much more susceptible to damage from high temperature treatments than the older seedlings (13 days old).

4.2 Discussion

The results of these experiments provide strong evidence that high soil temperatures near the soil surface may kill lucerne seedlings. In the field experiment substantial plant mortality occurred on the bitumen treatment, where maximum soil temperatures at a depth of 2 cm frequently exceeded 40°C during the day, and reached 46°C on one day during the period of continuous measurement in December (up to and including December 24). Temperatures in the soil closer to the surface, and particularly right at the surface, would have been considerably higher than those at 2 cm. The problems of measuring soil surface temperatures with the available equipment were noted in an earlier section (see section 3.1) and the surface temperatures in Table 3.1.2 and Appendix 13 should be accepted with caution. However, maximum surface temperatures in excess of 50°C were recorded on several occasions. Because of the high 2 cm soil temperature and the low albedo of the bitumen, its surface temperatures would be expected to be the highest, followed by the control and lupin treatments, then the white painted bitumen. The high surface temperatures recorded on the straw mulches were to be expected. The thermocouples were placed high in the straw layer, where they would have received direct sunlight at times during the day. Because of trapped or still air in the straw the air in this layer would also become warm (Waggoner _et al_, 1960). The soil surface itself would have a lower temperature than the other treatments without a straw mulch. So even if the temperatures were relatively high in the straw, this would have been around the aerial part of the plant, possibly 2 - 3 cm above the ground surface, rather than around the root or lower stem or their junction.

A temperature of 45°C was shown to be lethal in a subsequent glasshouse experiment, whereas a soil or surface temperature of 35°C was not significantly different to 25°C in its effect on seedling growth and survival. The critical temperature for seedling survival was apparently between 35 and 45°C under the conditions in the glasshouse. Seedling mortality in the field occurred to the greatest extent on the bitumen mulch, which had the highest soil temperatures. The unmulched and lupin treatments had the next highest 2 cm soil temperatures, and they had the next highest mortality. Where soil temperatures were lower seedling mortality was negligible. The association between mean maximum soil temperatures (at 2 cm) and seedling mortality in the field trial is shown in figure 4.2.1 which, though its limitations are acknowledged, demonstrates a relationship in reasonable agreement with that observed in the glasshouse. That high temperatures damage seedlings of many species as well as lucerne was noted in Chapter one (e.g. Carroll, 1943; Shaw, 1952; Levitt, 1972).

Low soil moisture was not a factor affecting survival. The plant counts and weights showed little or no effect from irrigation during the time period in which deaths were recorded. After irrigation ceased (December 24) there were signs of moisture stress in both irrigated and non-irrigated treatments in January, although initially the stress showed in the non-irrigated treatments first. The high moisture content of the seedbed at sowing was due to early seedbed preparation and ample rain.

The low initial establishment and growth rate of the lucerne under the straw and bitumen plus straw was thought to be due to the low light intensity for the emerging seedlings under the straw, as the seedlings were noticeably etiolated. At December 9 the seedlings were lighter than the average of the control and lupin treatments

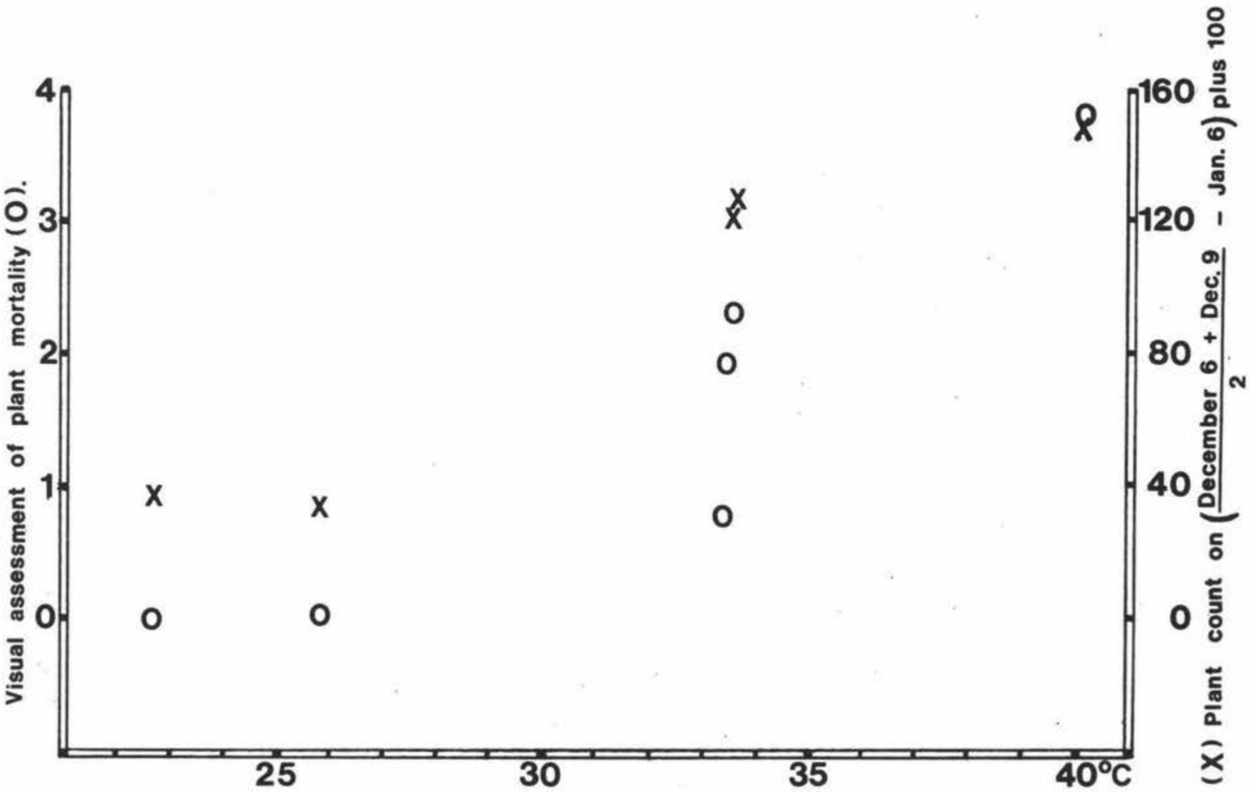


Figure 4.2.1 Visual assessments and counts of plant deaths plotted against the 2cm mean maximum temperatures of the mulches.

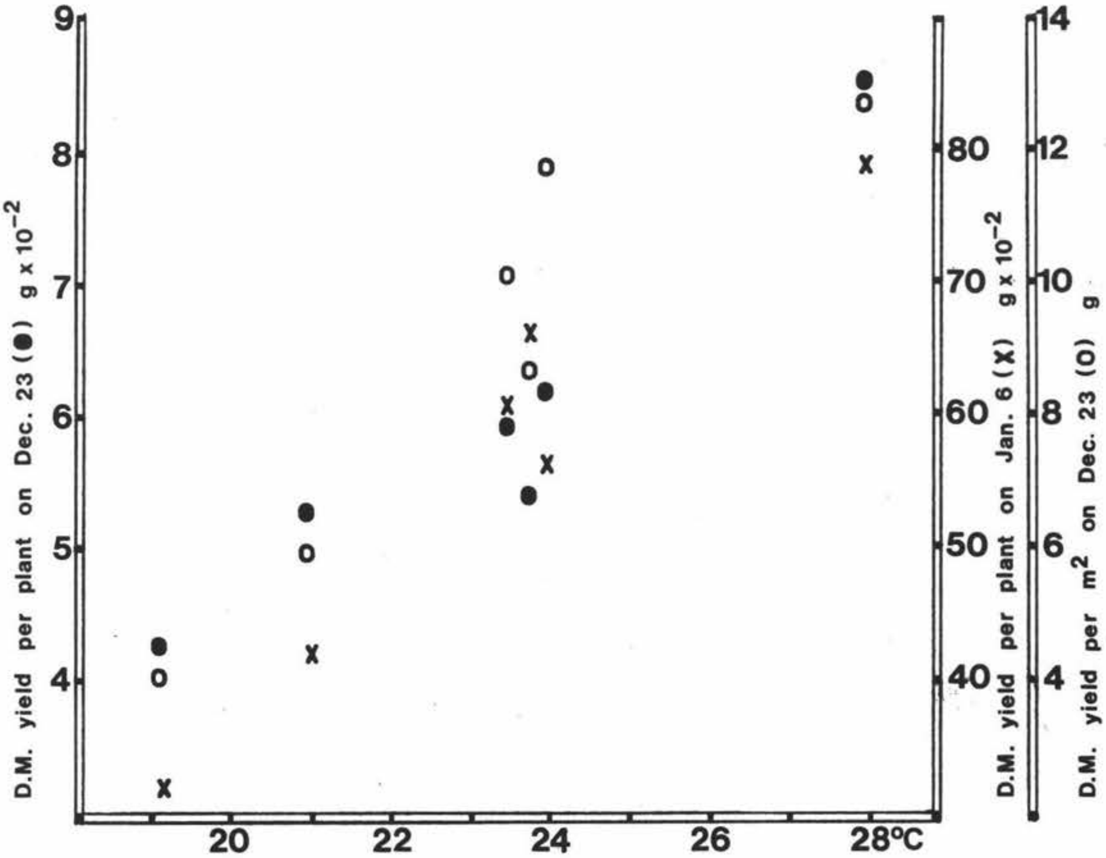


Figure 4.2.2 Dry matter (D.M.) yields plotted against the mean 2cm soil temperatures.

by about 24% (from Table 3.1.6(b)). At December 23 they were 23% lighter, and at January 6, 36%. This increased difference was in spite of a higher soil moisture level under the straw. At the same dates the bitumen treatment had plants 12, 37 and 32% respectively, heavier than the average of the control and lupin treatments. The moisture level was also higher under the bitumen. When the white-painted bitumen treatment was compared with the control and lupin treatments, the plant weights were about the same, while the moisture levels were higher with the white-painted bitumen. On January 6 irrigation had significantly increased the yield on a per plant and per unit area basis on the bitumen in particular, and non-significantly at December 23 (Table 3.1.6 (a) and (b)). The reason for this is not clear from the data presented, yet it may be that surface temperatures were reduced slightly by evaporation at critical times.

Most other physical and nutritional features of the environment seem unlikely to have been responsible for seedling mortality. It is unlikely there were any nutritional limitations in view of the basal fertilizer application, and as mentioned in Chapter three disease was not responsible for seedling mortality.

Although high temperatures are believed to have caused the seedling mortality observed, a positive relationship between soil temperature and herbage yield per plant and unit area was observed and is shown in figure 4.2.2. This shows the plant yield plotted against the mean temperature. This indicates that the plants grew better at the higher mean temperatures, although the limitations of using such data are again acknowledged. It seems likely that the deleterious effects of the high maximum temperatures were offset by a more favourable temperature for growth during much of the time. The optimum temperature for growth appears to be in the range 15 - 30°C, as discussed in Chapter one (e.g. Shaw, 1952; Gist and Mott, 1957; Jensen, Massengale and Chilcote, 1967; Smith, 1969; Nelson and Smith, 1969; Ueno and Smith, 1970; Vough and Marten, 1971; Wolf and Blaser, 1971; Evenson and Rumbaugh, 1972) and temperatures above 30°C appear to be supra-optimal for plant growth.

In the first glasshouse experiment, about 3 hours per day at 55°C surface temperature killed the seedlings within a few days. At 45°C the seedlings were initially healthy looking but they eventually died. This suggests that seedlings can survive 45°C for short periods at least. The glasshouse experiments were under conditions of much lower light intensity (due to light interception by the glass and framing, as well as being in the autumn months) than the field experiment. Plants generally survive higher temperatures under higher light conditions (Shaw, 1952; Gist and Mott, 1957; Levitt, 1972) so the temperatures in the field may not be strictly comparable with those in the glasshouse. The data showed that there were little or no differences between 25°C and 35°C soil or surface temperature on the growth of the seedlings, suggesting that for the seedlings the optimum temperature range may be as high as 35°C.

In the second glasshouse experiment 50°C was used for 3, 6 or 24 hours per day. The longer the period the temperature was applied, the greater the reduction in plant growth. Yet when treatments were compared applying 50°C for 1, 3 or 7 days there were no differences. This suggests the plants may be able to withstand short periods of high temperature each day, and recover by the next day. This phenomenon has been recorded for both heat and water stress (Levitt, 1972) possibly due to retention or reforming of the protein bonds.

These results have indicated that for the season studied moisture was not a limiting factor to successful lucerne establishment. Neither did wind prove to be a limiting factor. Previous observations have indicated that at least on some occassions moisture shortages and wind erosion could be limiting. The results have shown that soil temperatures during the month of December may be so high as to damage or kill lucerne seedlings. It is possible to state on the results of these experiments that lucerne stands sown in the summer months on Manawatu sand country are liable to high seedling mortality because of high soil temperatures.

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Appendix 1. Soil test figures. (units)

Truog Phosphorus - parts of P per 50 million parts of extract. Soil volume to extractant volume ratio = 2.2 to 400.

Calcium - parts of Ca per 40,000 parts of extract.

Potassium - parts of K per 250,000 parts of extract.

Magnesium - parts Mg per million parts of extract.

Soil volume to extractant volume for cations ratio = 4.4 to 20

Appendix 2. Field experiment layout, see next page.

Appendix 3. Dates of irrigation

December 7	irrigated block 2.
14	irrigated all blocks.
16	irrigated all blocks
21	irrigated all blocks
24	irrigated block 1.

Appendix 4. Glasshouse experiment 1 layout, see 2 pages over.

Appendix 5. Nutrient solution used for glasshouse experiments.

The solution was prepared as described below:

Salt	Molar stock solution (g salt/l water)	Volume of stock solution ml/l of nutrient solution
$CaCl_2$	110.99	1.5
KH_2PO_4	136.08	1.5
$MgSO_4.7H_2O$	246.50	2.2
$NaNO_3$	85.00	7.1
"Minors"	+	1.0
"Fe chelate"	++	1.0

\+ Minor elements

2.86 g H_3BO_3
1.18 g $MnCl_2$
0.11 g $ZnSO_4$
0.05 g $CuSO_4$
0.02 g $NaMoO_4$
0.05 g $CoCl_2$

Dissolved in 1 litre of water.

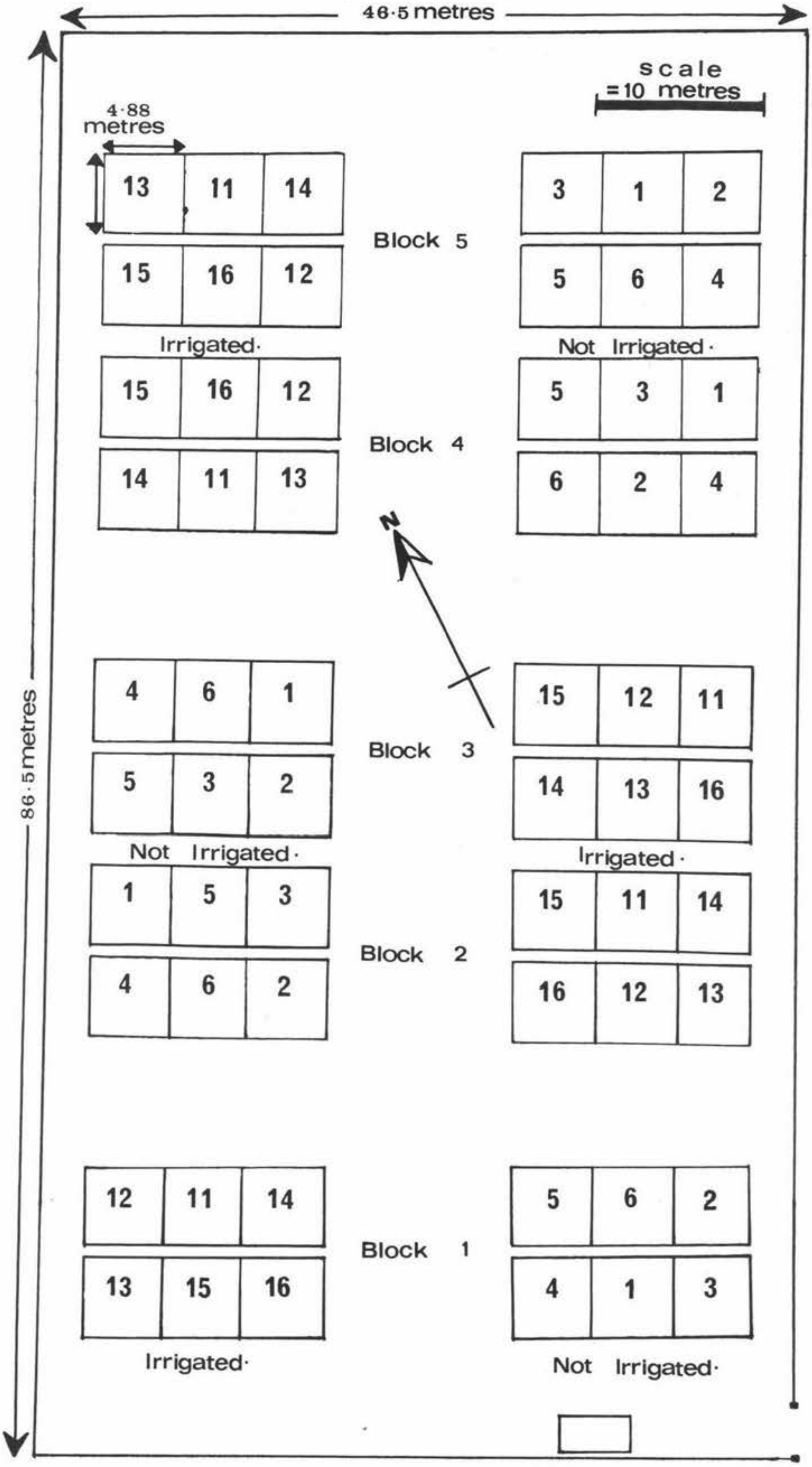
++ Iron chelate

5.0 g NaOH in 800 ml water
33.2 g EDTA
24.9 g $FeSO_4.7H_2O$

Diluted to 1 litre with water

Appendix 6. Glasshouse experiment 2 layout, see 3 pages over.

Appendix 2. Sand country experiment layout



KEY

Mulch·	Not Irrigated·	Irrigated·
None	1	11
Bitumin	2	12
Straw	3	13
Bitumin covered with Straw	4	14
Bitumin painted white	5	15
None with a lupin cover crop	6	16

Appendix 4. Glasshouse experiment 1 layout.

Block 3

25°c surface soil 35°c	35 35	45 35	45 25
25 35	35 35	55 35	55 25
35 25	45 25	55 25	25 25
25 25	45 35	55 35	35 25

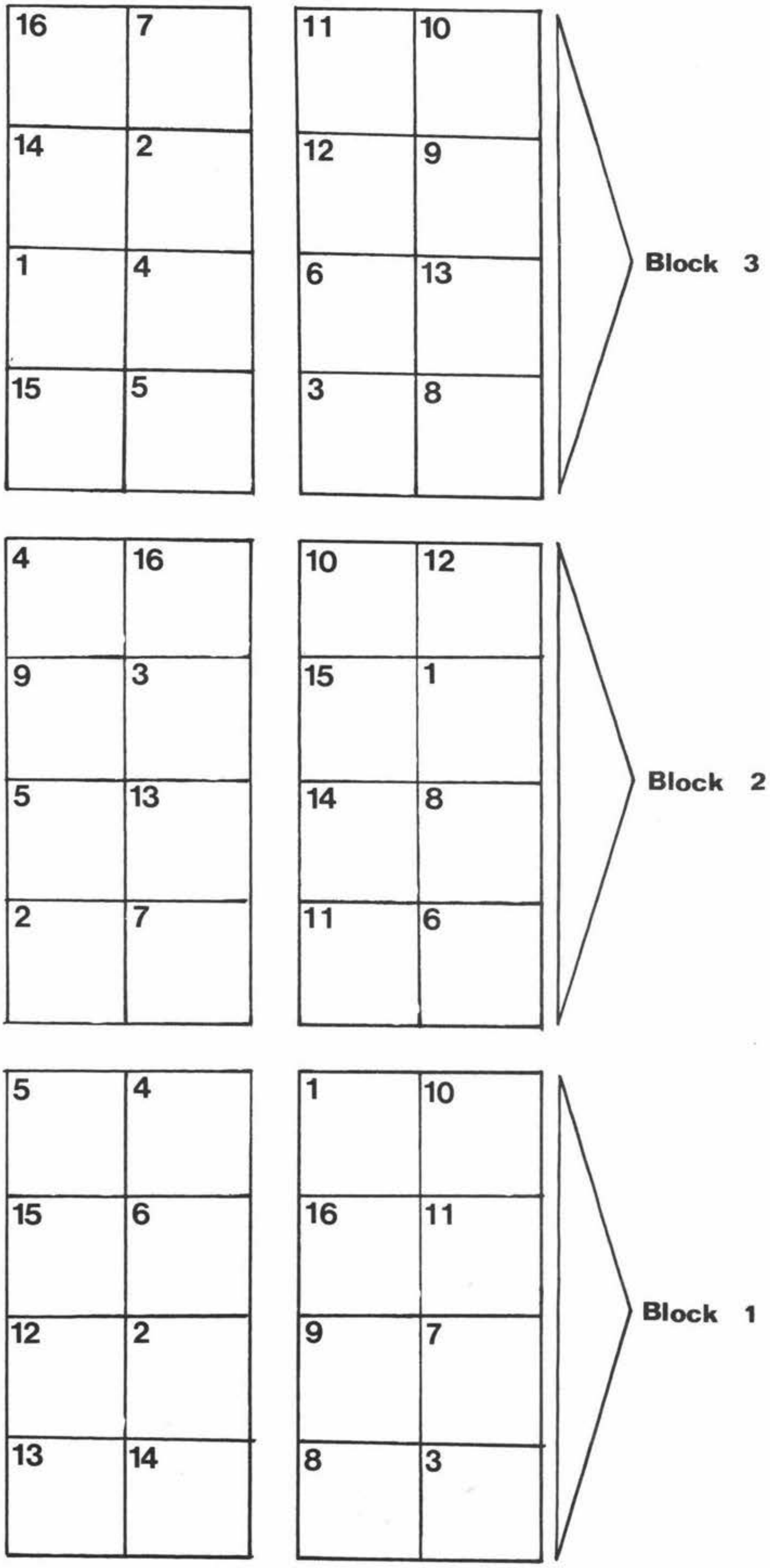
Block 2

45 25	25 25	45 35	55 35
55 25	55 35	25 35	35 25
45 35	25 35	25 25	35 25
35 35	35 35	45 25	55 25

Block 1

45 25	45 35	35 35	45 25
25 35	55 25	25 25	45 35
55 35	35 25	55 25	35 35
25 25	25 35	35 25	55 35

Appendix 6. Glasshouse experiment 2 layout. Key pp. 32-33



Block 3

16	7	11	10
14	2	12	9
1	4	6	13
15	5	3	8

Block 2

4	16	10	12
9	3	15	1
5	13	14	8
2	7	11	6

Block 1

5	4	1	10
15	6	16	11
12	2	9	7
13	14	8	3

Appendix 7. Analysis of variance of soil moisture.

		Mean Squares					
Source	df	December 1		December 16		December 24	
		0 – 3	3 – 20	0 – 3	3 – 15	0 – 3	3 – 15 cm depth
Blocks	4	31.97*	11.93	5.48	36.17	33.92*	10.57
Irrigation	1	3.89	1.20	215.58**	78.66**	744.13**	243.94**
Error (1)	4	3.26	2.99	6.18	8.30	5.05	10.91
Mulch	5	66.64**	22.47**	104.53**	5.86	160.19**	16.98**
Mulch x irrigation	5	4.40	6.55	13.55**	7.23	5.96	1.98
Error (2)	40	4.76	5.72	3.82	6.91	4.79	4.35

Appendix 8. Analysis of variance of plant mortality on December 20.

Source	df	Mean square
Blocks	4	1.21
Irrigation	1	1.23
Error (1)	4	5.91
Mulch	3	16.63*
Mulch x irrigation	3	.49
Error (2)	24	3.66

Analysis made without including the 2 straw mulches.

Appendix 9. Analysis of variance of dry matter yield per unit area at several dates.

		Mean Squares			
Source	df	December 9	December 23	January 6	January 26
Blocks	4	43	220	3705	546
Irrigation	1	6	1	2756	545
Error (1)	4	46	293	929	820
Mulch	5	1215**	1153**	929**	3570**
Mulch x irrigation	5	27	75	692*	387
Error (2)	40	19	81	221	187

Appendix 10. Analysis of variance of matter yield per plant at several dates.

Source	df	Mean Square December 9	 December 23	 January 6
Blocks	4	3509*	1860	5397 **
Irrigation	1	1	33	1691 *
Error (1)	4	456	410	158
Mulch	5	5940**	2078**	2705 **
Mulch x irrigation	5	187	156	650 **
Error (2)	40	306	300	163

Appendix 11. Analysis of variance of visual assessment of plant wilting at midday on January 17.

Source	df	Mean Square
Blocks	4	2.11
Irrigation	1	54.15 *
Error (1)	4	6.69
Mulch	5	30.27 **
Mulch x irrigation	5	3.71 **
Error (2)	40	.94

Appendix 12. Analysis of variance of visual assessment of flowering on January 17.

Source	df	Mean Square
Blocks	4	0.317
Irrigation	1	1.066 *
Error (1)	4	0.067
Mulch	5	9.267 **
Mulch x irrigation	5	0.387
Error	40	0.252

Appendix 13.

Net pyrradiometer readings (W.m^{-2})for the moved* and the reference net pyrradiometer over various surfaces. The time of each reading is shown, and the surface temperature recorded at approximately the same time.

(* the original reading multiplied by 1.026 for calibration)

Mulch	Time (pm)	Polythene	Reference	T°C	Time (pm)	Perspex	Reference	T°C
Not irrigated								
Sand	12.18	599	605	64	13.52	690	567	59
Bitumin	12.25	685	623	61	13.57	752	561	56
Straw	12.23	608	631	52	13.55	623	567	49
Bit/Straw	12.10	561	600	56	13.45	628	577	38
Bit/White	12.15	555	602	49	13.48	618	567	45
Lupin	12.20	629	623	60	14.00	693	555	55
Plots previously irrigated with dry surface								
Sand	11.57	646	581	55	13.28	731	597	50
Bitumin	11.49	700	575	57	13.23	795	599	56
Straw	11.46	624	559	45	13.20	735	599	47
Bit/Straw	12.05	648	599	46	13.36	714	585	40
Bit/White	11.53	585	592	44	13.25	634	597	43
Lupin	12.01	645	607	56	13.31	727	591	56
Wet surface on the irrigated plots								
Sand	14.44	664	507	32	14.17	753	552	33
Bitumin	14.37	673	518	43	14.20	760	550	43
Straw	14.35	633	517	32	14.23	714	544	37
Bit/Straw	14.50	629	504	30	14.05	713	553	32
Bit/White	14.40	537	512	38	14.15	636	557	39
Lupin	14.47	646	507	36	14.10	755	558	38

Appendix 14. The Mean and Standard Error (SE) of the daily visual scores of plant vigour on a 0 – 5 scale for the first glasshouse experiment.

	Soil temperature 25°C								Soil temperature 35°C							
	Surface 25°C		35°C		45°C		55°C		25°C		35°C		45°C		55°C	
Day	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
10	2.67	.07	2.70	.08	2.76	.07	2.85	.07	2.88	.07	2.76	.06	2.75	.09	2.80	.08
11	2.78	.08	2.93	.07	2.88	.06	2.70	.09	2.95	.08	2.84	.05	2.73	.09	2.76	.16
12	3.08	.12	3.20	.08	3.20	.09	2.61	.15	3.30	.09	3.02	.08	3.05	.13	2.41	.19
13	3.22	.12	3.25	.09	3.47	.09	.74	.12	3.49	.10	3.18	.09	3.25	.12	.63	.13
14	3.31	.12	3.48	.09	3.35	.12	.74	.15	3.63	.09	3.28	.09	3.18	.13	.46	.11
15	3.43	.12	3.48	.09	3.51	.11	.48	.12	3.67	.10	3.34	.10	3.25	.14	.39	.10
16	3.39	.13	3.50	.11	3.55	.13	.26	.09	3.84	.12	3.46	.12	3.52	.15	.17	.08
17	3.22	.12	3.35	.10	3.06	.13	.07	.04	3.51	.12	3.46	.09	3.23	.13	0	0
18	3.35	.13	3.40	.13	3.24	.16	0	0	3.70	.13	3.42	.12	3.27	.15		
19	3.53	.16	3.50	.16	3.04	.19			3.91	.14	3.60	.13	3.05	.18		
20	3.43	.15	3.50	.16	2.86	.21			3.98	.15	3.56	.14	2.93	.20		
21	3.51	.16	3.58	.17	2.86	.22			3.95	.14	3.48	.15	2.75	.22		
22	3.43	.17	3.70	.17	2.55	.23			3.98	.14	3.60	.15	2.36	.24		
23	3.43	.16	3.50	.19	2.31	.24			3.88	.16	3.58	.15	2.20	.23		
24	3.47	.17	3.68	.17	1.69	.23			4.02	.18	3.62	.15	1.52	.22		
25	3.39	.16	3.55	.18	.92	.18			3.91	.17	3.50	.16	.86	.19		
26	3.33	.18	3.43	.20	.57	.13			4.07	.17	3.48	.15	.39	.10		
27	3.49	.17	3.48	.21	.20	.07			4.12	.18	3.62	.15	.14	.05		
28	3.22	.18	3.53	.23	.04	.03			4.05	.18	3.38	.18	.02	.02		

Appendix 15. Dry weight of whole plant (g x 10^{-4}) per plant present when treatments were applied and their analysis of variance.

		Block 1	Block 2	Block 3
25°C surface	25°C soil	88.3	82.1	73.5
		76.7	41.2	113.3
35	25	81.8	112.3	61.3
		125.2	73.3	70.6
25	35	98.0	84.3	134.6
		111.1	95.7	125.6
35	35	71.9	93.3	97.5
		98.0	74.4	91.4

Analysis of variance

Source	df	Mean square	F
Blocks	2	449.15	1.29
Treatments	3	917.87	2.64
Surface temperature	1	224.48	0.65
Soil temperature	1	1293.60	3.72
Interaction	1	1235.54	3.56
Residual	18	421.90	1.21
Treatments x Blocks	6	570.66	1.64
Error	12	347.50	
Total	23		

F with 12 and 1 df has a value of 3.18 at the 10% level of probability. Soil temperature and its interaction with surface temperature reach significance at this level.

Appendix 16. Dry weights of tops (g x 10^{-4}) per plant present when treatments were applied and their analysis of variance.

		Block 1	Block 2	Block 3
25°C surface	25°C soil	68.1	53.0	44.0
		46.3	23.9	88.9
35°	25	51.3	87.7	34.0
		95.7	44.0	50.6
25° surface	35°C soil	70.5	64.7	104.0
		91.6	62.1	99.5
35	35	47.2	71.7	63.6
		68.9	52.1	60.1

Analysis of variance

Source	df	Mean square	F
Blocks	2	288.65	0.78
Treatments	3	901.18	2.45
Surface temperature	1	337.50	0.92
Soil temperature	1	1187.23	3.22
Interaction	1	1178.80	3.20
Residual	18	401.01	1.09
Treatments x Blocks	6	466.61	1.27
Error	12	368.21	
Total	23		

F with 12 and 1 df has a value of 3.18 at the 10% level, and soil temperature and the interaction with surface temperature just reach significance at this level.

Appendix 17. Mean and Standard Error (SE) of daily visual scores of plant vigour on a 0 - 2 scale for the second glasshouse experiment.

		Day 10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Treatment																
1.	Mean	2.00	2.00	1.96	1.88	1.80	1.52	1.32	1.08	.88	.80	.52	.32	.20	.36	.28
	S.E.			.04	.07	.08	.13	.16	.13	.16	.13	.14	.10	.08	.10	.09
2.	Mean	2.00	2.00	2.00	1.81	1.65	1.65	1.62	1.50	1.50	1.42	1.31	.88	.77	.85	.77
	S.E.				.10	.11	.11	.13	.13	.13	.13	.13	.10	.10	.11	.10
3.	Mean	2.00	2.00	2.00	1.78	1.59	1.44	1.41	1.44	1.44	1.44	1.26	1.22	1.15	1.07	1.07
	S.E.				.10	.10	.11	.12	.12	.12	.15	.14	.12	.10	.12	.12
4.	Mean	2.00	2.00	2.00	2.00	1.93	1.93	1.96	1.96	2.00	1.93	1.74	1.56	1.37	1.44	1.37
	S.E.					.05	.05	.04	.04	0	.05	.09	.10	.12	.11	.12
5.	Mean	2.00	2.00	2.00	1.96	1.80	1.72	1.60	1.80	1.88	1.96	1.96	1.92	1.72	1.72	1.64
	S.E.				.04	.08	.09	.10	.08	.07	.04	.04	.06	.09	.09	.10
6.	Mean	2.00	2.00	2.00	1.96	1.81	1.81	1.85	1.93	1.96	1.96	2.00	1.96	1.81	1.89	1.89
	S.E.				.04	.08	.08	.07	.05	.04	.04	0	.04	.08	.06	.06
7.	Mean	2.00	2.00	1.96	1.88	1.54	1.54	1.58	1.19	1.15	1.12	.77	.58	.54	.61	.50
	S.E.			.04	.06	.10	.11	.11	.14	.12	.14	.14	.11	.11	.13	.10
8.	Mean	2.00	2.00	1.93	1.59	1.41	1.59	1.52	1.48	1.44	1.48	1.19	.93	.96	.96	.89
	S.E.			.05	.10	.10	.10	.10	.10	.10	.10	.08	.05	.06	.06	.06
9.	Mean	2.00	2.00	1.80	1.52	1.28	1.24	1.28	.96	.88	1.00	.80	.84	.72	.76	.68
	S.E.			.08	.10	.11	.10	.12	.14	.13	.12	.13	.09	.11	.10	.11

Appendix 17 contd.

		Day 10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Treatment																
10.	Mean	2.00	2.00	1.89	1.81	1.70	1.59	1.81	1.63	1.70	1.78	1.67	1.48	1.44	1.33	1.26
	S.E.			.08	.09	.10	.11	.09	.11	.10	.11	.12	.12	.12	.12	.11
11.	Mean	2.00	2.00	2.00	1.96	1.81	1.85	1.89	1.89	2.00	2.00	2.00	1.96	1.67	1.85	1.67
	S.E.				.04	.08	.07	.06	.06	0	0	0	.04	.09	.07	.09
12.	Mean	2.00	2.00	2.00	1.92	1.79	1.58	1.88	1.75	1.83	1.79	1.75	1.71	1.67	1.71	1.75
	S.E.				.06	.08	.10	.07	.09	.10	.10	.12	.13	.13	.11	.09
13.	Mean	2.00	2.00	1.33	.63	.29	.33	.25	.25	.29	.38	.42	.38	.38	.33	.29
	S.E.			.10	.16	.09	.12	.09	.09	.09	.12	.12	.10	.10	.10	.09
14.	Mean	2.00	2.00	1.96	1.96	1.07	.96	.63	.33	.56	.59	.59	.56	.59	.56	.56
	S.E.			.04	.04	.11	.15	.13	.11	.13	.12	.12	.11	.11	.11	.10
15.	Mean	2.00	2.00	2.00	1.85	1.70	1.74	1.89	1.70	1.63	1.59	1.33	1.04	1.00	1.00	.96
	S.E.				.07	.09	.10	.08	.10	.10	.11	.11	.08	.08	.08	.10
16.	Mean	2.00	2.00	2.00	2.00	1.92	1.69	1.62	1.77	1.85	1.96	1.77	1.54	1.46	1.46	1.42
	S.E.					.05	.09	.10	.08	.07	.04	.08	.14	.10	.10	.11

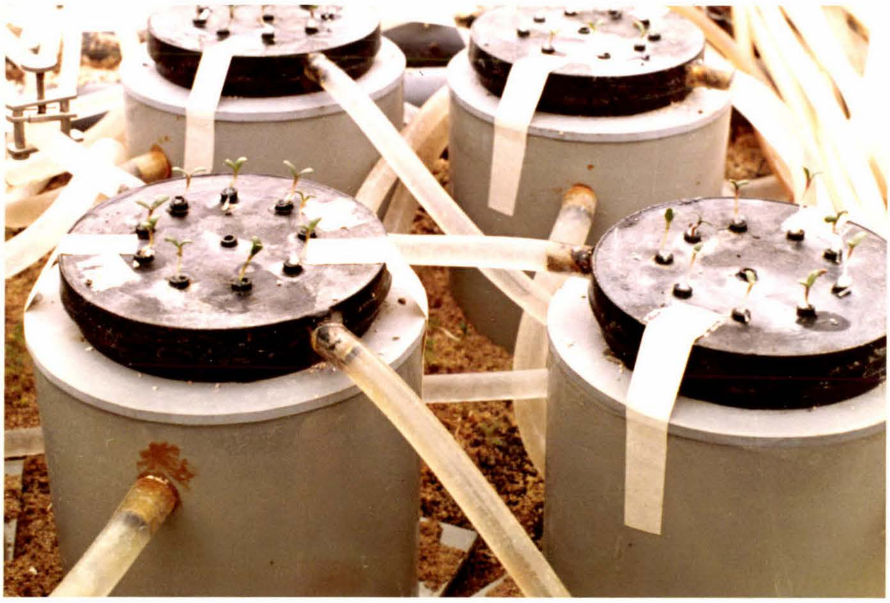


Plate 1. Glasshouse equipment showing the 10 day old lucerne seedlings growing through the plastic tubes in the modified petri dishes. Water at controlled temperatures can be pumped through the petri dishes or the pots.

Plate 2. Lucerne mortality due to high temperature stress on the unmulched sand.