DECLARATION

I hereby declare that this thesis has been composed entirely by me and that all the work herein was carried out by me alone, except where otherwise acknowledged.

1989
Dedicated

to my parents
ABSTRACT

The aim was to investigate the water use of *Medicago sativa* L. in an irrigated agricultural system in Saudi Arabia using three different techniques: (i) Bowen ratio method; (ii) a method relying on the energy balance of leaves; and (iii) the use of a laboratory measurement system to provide the physiological parameters that enable a modelling approach to be used. The climate of the nearby desert is characterised by high albedo (0.40), low water vapour pressure (<10% RH) and high temperature (22-45 °C). After the air had flowed 50-100 m over the irrigated crop the temperature decreased by ~6 °C, and the vapour pressure increased by 2.0 kPa. Crop albedo varied diurnally and seasonally and was much lower than the desert. Net radiation over the crop was a near-linear function of short-wave irradiance.

Analysis of the diurnal microclimate of the two irrigation types (surface irrigation and spray) indicates slight differences. The sources of the differences may be related to the scale of the field size and the irrigation frequency.

The Bowen Ratio method was used to estimate water use by the crop. The equipment was placed well in from the leading edge of the field (150 m). The Bowen Ratio was in the range -0.5 to 0.5. An examination of probable errors suggested that the technique is close to the limit of its applicability in this case, but it nevertheless provides an estimate of day time evaporation to within 20%. The daily total of evapotranspiration in the summer months was in the range of 9-15 mm day⁻¹.

Water use by a sample of leaves at the top of the canopy was assessed. It was clear that the leaf energy balance method can be used to track stomatal conductance and thus indicate times of atmospheric stress indicated by stomatal closure. The maximal stomatal conductance was 3.5 cm s⁻¹ and the corresponding maximal leaf surface transpiration rate was 800 Wm⁻². A type of error analysis was devised to explore the effect of making errors in the measurement of the important variables. It was concluded that the technique was most useful between 09.00 and 15.00 h, when the probable error was about ±20%.

Gas exchange in the laboratory provided light response curves of photosynthetic rate and stomatal conductance. Maximal photosynthesis was 22-32 μmol m⁻²s⁻¹, but light-saturation did not always occur even a photon flux density of 1800 μmol m⁻²s⁻¹. The stomatal conductance was only weakly dependent on leaf-air vapour pressure deficit and the maximal value was 600 mmol m⁻²s⁻¹. In the dark, there was a considerable conductance, suggesting a possible importance of nocturnal transpiration.
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CHAPTER ONE

GENERAL INTRODUCTION
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1.1 Climate

The climate of Saudi Arabia is classified as a true desert, which is characterised by low precipitation and a clear cloudless sky with high irradiance, low humidity and scarce water resources except during winter months. Energy exchanges over such an area are characterised by high conversion of solar energy to sensible heat and kinetic energy, giving rise to high air temperatures and air movements which often lift the surface material to cause sand storms.

The energy balance of such a barren and arid area, when put under extensive irrigation, may be expected to undergo profound changes where the actual evapotranspiration (ET) rises from near-zero to more than the potential rate. Latent heat exchange resulting from the high ET is likely to cause considerable changes in the microclimate over the transpiring surfaces, and the new conditions may be favourable to agriculture, as in an oasis.

The high ET, low water supply and water use efficiency are the practical limiting factors to plant productivity and yield (Fischer and Turner, 1978). Irrigation is necessary to maintain high productivity and field yield. Under adequate irrigation, many crops are found to grow successfully in the arid climate including field crops, fruits and vegetables. Local and introduced crops used widely in Saudi Arabia include alfalfa, Sudan grass, Bermuda grass and Zea mays. All these crops are characterised by high water use when grown under similar conditions.

1.2 The need for agricultural production

Over twenty years ago, the agricultural production of Saudi Arabia was comparatively high with a low dependence on imported foods from abroad. At that time more than 60% of the country’s population worked in agriculture, of which 12% were
Bedouin (Hajarah, 1971). According to Hajarah (1971), the contribution of agriculture to the local economy reached 10% in the early seventies. However, social, economic and educational factors have led to the immigration of some people from rural areas to the cities, causing a decline in agricultural production and subsequently higher prices of local agricultural products compared to imported foods (Thorne and Thorne, 1979).

These factors persuaded the government to introduce reforms in agricultural policies to encourage the people to invest in agriculture and develop the rural areas in order to reverse the trend. Such encouragement made agriculture more attractive to both the farmers and the businessmen with the aim of increasing local production and stabilising food prices in order to achieve self-sufficiency for certain crops.

This has led to an increase in the area irrigated to exceed one million hectares for only one crop (wheat), where the production has increased to more than 2.5 million tonnes according to the Ministry of Irrigation and Water. There was also a substantial increase in forage crop production following the same pattern as that of wheat, but in this case the increase was to satisfy the expanding market for forage.

1.3 Irrigation requirements

Of total land area of Saudi Arabia, 200 \( \times 10^6 \) hectares, only about 0.3% is agricultural whilst about 2% is rangeland, most of the rest is absolute desert. Climatic diagrams for four regions of the country are shown in Figure 1.1. Much of the agricultural area in Saudi Arabia is confined to the Wadis and their flood plains, where water resources can support agricultural production and may be expected to meet the needs of future developments. The distribution of cultivated areas is shown in Figure 1.2.

Irrigation is essential in desert areas, since water has a direct or indirect effect on almost all plant functions, including growth. However, there are some regional variations in climate which may influence the amount of irrigation required and timing of irrigation during the plant growth cycle, and which may influence selection of the crop species.
FIGURE 1.1: Climatic diagrams of four different regions of Saudi Arabia.
FIGURE 1.2: Map showing the topography and agricultural area of Saudi Arabia.
Irrigation requirement (IR) can be defined as the amount of water required to meet the need for evapotranspiration by any crop (Jensen, 1974). By definition, those factors which affect the ET will also affect IR. Therefore, IR will vary with plant species, crop physiological parameters, growth conditions, season etc.

The irrigation requirement (IR) for any crop varies widely. IR for alfalfa varies from 500-2000 mm yr$^{-1}$. This big variation in IR is caused by environmental variables (Christian, 1977; Blad, 1983) irrigation management, agronomic practices, plant species, variety etc. There are many methods used to evaluate water requirements for crops growing in the field. These can be classified as direct or indirect methods. The direct method includes inventory of soil water content, but often direct methods are expensive and time consuming. Indirect methods include the calculation of potential evaporation with the estimation of actual ET by using an empirical coefficient, or the use of evaporation from an open pan or other evaporimeters (for details see Chapter 3).

Information regarding the water use of crops in Saudi Arabia is lacking. The available information is mostly for alfalfa but based on very small-sized plots. Extremely high rates of ET have been found (see Chapter 3). This may represent the effect of heat transfer from a nearby barren area (regional advection).

1.4 Existing irrigation systems

In general, there are two types of irrigation system used in Saudi Arabia: (a) surface irrigation; and (b) spray irrigation using sprinklers.

(a) Surface irrigation

This is most extensively used, using furrows, borders or basins, to direct water where it is needed. It is gradually being replaced by more advanced technology, involving spraying water which has been pumped from great depth.
There are various types of spray methods used in irrigation (see Thorne and Thorne, 1979; Addink et al., 1983). The use of overhead sprinklers has significantly increased in recent years. There are mechanical, moveable systems with wheel-mounted sprinkler lines attached to a pump. The sprinkler lines rotate in a circle, the wheels usually being driven by electric motors. Such a system is costly but it has many advantages; it can irrigate a circular field of 40-100 hectares (see Chapter 3). It can be used to spray fertiliser, fungicides, and is normally turned on and off by the farmer according to perceived need. Such technologically advanced systems need a qualified engineer on hand to deal with system failure. Using an advanced system it becomes possible to incorporate information about crop response to the field environment in order to regulate the supply of water to the crop.

1.5 Objectives

The aims of this project were to investigate three techniques of evaluating water use by the crop.

1. The Bowen Ratio method applied to the whole crop, based on the assumptions of the 'big leaf model' (see Chapter 3).

2. The use of energy balances at the scale of individual leaves to characterise the diurnal pattern of stomatal transpiration for a sample of leaves at the top of the canopy; and also to study stomatal response to the environment in two irrigation schemes (see Chapter 4).

3. An open gas exchange system in the laboratory, in order to develop a model of water use efficiency of single leaves (see Chapter 5).

The intention is to evaluate these types of information for the prediction of water use efficiency of the crop.
The three approaches yield different types of information, each shedding light on a different aspect of overall problems. In principle the Bowen Ratio method yields an estimate of water use by the crop, and so is particularly useful in the context of agriculture. The energy balance method based on measurements on individual leaves provides an estimate of the rate of water use only by the (limited) sample of leaves that can be instrumented. It does however provide information on the trends in stomatal conductance which can be used to make deductions about plant water stress. In the extreme, it is expected that stomata would shut if water stress is large. The third approach, measuring gas exchange in the laboratory enables controlled environment study of gas exchange and should resolve some of the difficulties in interpreting field response. This approach also facilitates an examination of the relationship between the $\text{H}_2\text{O}$ and $\text{CO}_2$ flux, and the calculation of water use efficiency. The relationship between these approaches and their general usefulness is considered in the final chapter (Chapter 6).

1.6 The choice of species

Alfalfa or lucerne (*Medicago sativa* L., Leguminosea) is an important forage crop normally cut and used to feed to dairy cattle as fresh or dry matter. It is a deep-rooted, erect perennial growing up to a metre tall. Its leaves are trifoliate with leaflets up to 30 mm long, with purple flowers borne in racemes. In cultivation, the strong tap root penetrates to 0.9 to 2.4 m (Christian, 1977). Life span depends on the susceptibility of the genotype to various diseases. Alfalfa is adapted to a wide range of climate and soil conditions. It has a wide distribution both in the old and new world.

Alfalfa has some advantages over other forage crops, such as grass, by being richer in leaf protein (Heichel, 1983). It is known to tolerate high salinity stress, hot climate, and to avoid water stress by deep rooting. It displays a usefully long life span (3 to 5 years) and high productivity. If well-grown, it can be cut eight to twelve times per year, cutting down from 7 to 5 cm. All these features make this plant attractive to the farmer. However,
the plant has a reputation of being a 'water spender' though it may not be very different in this region from wheat, corn or sorghum grown in the same environments (Christian, 1977).

The main imported varieties in Saudi Arabia are Diablo Verde, Maxidor and Cuflol. The common local variety is Hejazi.
CHAPTER TWO

GENERAL CHARACTERISTICS

AND RADIATION BALANCE OF THE SITE
CHAPTER TWO
GENERAL CHARACTERISTICS
AND RADIATION BALANCE OF THE SITE

2.1 INTRODUCTION

The site is at the Alkharj Plain, 88 km south-east of Riyadh (24° 10' N 47° 24' E). The elevation is 430 m above sea level, on a sandy soil. The area can be considered as one of the richest agricultural regions in Saudi Arabia with its supply of underground water. It is owned by the Government, ensuring ready access to the site.

Measurements were made in and above an irrigated field of a three-year old Alfalfa crop (Medicago sativa L. variety Hejazi). The plants grow during the whole year and the crop extends to more than three years without great loss in productivity.

The existence of two types of irrigation, flooding and spraying, and the occurrence of desert plants nearby (which can be used for comparative study) are advantageous. The area has a desert climate with low rainfall (the mean is about 67 mm per year) and high maximum temperature (Table 2.1).

Using the system of central pivot sprinklers, water from deep wells is pumped through pipes under pressure (370 kPa). The system has the advantage that it can cover a large area of land compared with the old surface irrigation by flooding. However, using this system both depletes a finite water resource and incurs a high energy cost. The water level is declining rapidly with this extensive water use to irrigate an expanding acreage (Table 2.2). Typical groups of sprinkler units are sited together on a dairy farm (Figure 2.1). The main two crops are wheat and alfalfa (lucerne). Both crops need large amounts of water and therefore a high irrigation frequency. Application rate is typically about 13 kg m⁻² day⁻¹ (about 13 mm) applied in the months of March to June.
### TABLE 2.1: General climatic data of Alkhari showing monthly means of five years of maximum temperature (TMx), minimum temperature (TMn), mean temperature (T); maximum relative humidity (HMx), minimum humidity (HMn) and mean relative humidity (H); rainfall (mm), pan evaporation rate (mm), sunshine (hrs), total solar energy flux (W m\(^{-2}\)), wind speed (km.hr\(^{-1}\)). (Data source: Ministry of Agriculture and Water, Saudi Arabia).

<table>
<thead>
<tr>
<th>Month (± SD)</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TMx</td>
<td>22.9 ± 1.4</td>
<td>25.5 ± 3.0</td>
<td>30.1 ± 2.2</td>
<td>36.8 ± 1.8</td>
<td>41.5 ± 0.7</td>
<td>44.7 ± 0.7</td>
<td>45.4 ± 0.9</td>
<td>44.4 ± 1.3</td>
<td>42.5 ± 1.0</td>
<td>36.4 ± 1.4</td>
<td>29.9 ± 2.2</td>
</tr>
<tr>
<td></td>
<td>TMn</td>
<td>6.5 ± 0.8</td>
<td>8.8 ± 1.4</td>
<td>13.4 ± 1.6</td>
<td>18.1 ± 0.9</td>
<td>22.3 ± 1.2</td>
<td>23.9 ± 1.2</td>
<td>24.7 ± 1.0</td>
<td>23.8 ± 1.7</td>
<td>20.8 ± 1.3</td>
<td>15.7 ± 2.5</td>
<td>11.5 ± 1.0</td>
</tr>
<tr>
<td></td>
<td>T</td>
<td>14.7 ± 0.9</td>
<td>17.1 ± 1.8</td>
<td>21.8 ± 1.9</td>
<td>27.5 ± 1.3</td>
<td>31.9 ± 0.9</td>
<td>34.3 ± 0.6</td>
<td>35.0 ± 0.9</td>
<td>34.1 ± 1.5</td>
<td>31.7 ± 1.0</td>
<td>26.0 ± 1.7</td>
<td>20.8 ± 1.1</td>
</tr>
<tr>
<td>2</td>
<td>HMx</td>
<td>65.4 ± 6.0</td>
<td>61.4 ± 11.3</td>
<td>63.3 ± 10.3</td>
<td>46.0 ± 17.3</td>
<td>36.5 ± 7.3</td>
<td>22.9 ± 3.9</td>
<td>20.8 ± 2.8</td>
<td>24.1 ± 4.9</td>
<td>29.2 ± 2.9</td>
<td>45.3 ± 1.09</td>
<td>56.7 ± 11.8</td>
</tr>
<tr>
<td></td>
<td>HMn</td>
<td>22.2 ± 2.2</td>
<td>21.0 ± 4.8</td>
<td>22.0 ± 1.03</td>
<td>17.0 ± 3.0</td>
<td>14.0 ± 1.9</td>
<td>10.3 ± 2.2</td>
<td>10.2 ± 1.8</td>
<td>12.3 ± 2.1</td>
<td>13.5 ± 1.4</td>
<td>18.5 ± 2.8</td>
<td>20.0 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>44.0 ± 4.1</td>
<td>41.2 ± 8.1</td>
<td>42.7 ± 6.7</td>
<td>31.5 ± 9.4</td>
<td>25.5 ± 4.4</td>
<td>16.5 ± 2.7</td>
<td>15.7 ± 2.1</td>
<td>18.0 ± 3.4</td>
<td>21.3 ± 2.1</td>
<td>31.8 ± 6.9</td>
<td>38.3 ± 7.7</td>
</tr>
<tr>
<td>3</td>
<td>Rf</td>
<td>4.2 ± 4.3</td>
<td>14.4 ± 18.6</td>
<td>24.2 ± 78.9</td>
<td>6.8 ± 8.6</td>
<td>3.73 ± 2.8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4.5 ± 10.2</td>
<td>3.4 ± 6.1</td>
</tr>
<tr>
<td>4</td>
<td>E_o</td>
<td>136.1±12.3</td>
<td>164.6±20.6</td>
<td>226.7±47.1</td>
<td>333.1±44.7</td>
<td>413.4±28.3</td>
<td>452.6±80.2</td>
<td>498.9±53.0</td>
<td>486.4±53.0</td>
<td>352.1±29.1</td>
<td>277.4±33.4</td>
<td>194.2±45.8</td>
</tr>
<tr>
<td>5</td>
<td>S_s</td>
<td>7.28 ± 0.2</td>
<td>7.5 ± 1.1</td>
<td>7.4 ± 0.7</td>
<td>8.1 ± 0.7</td>
<td>8.1 ± 0.8</td>
<td>9.8 ± 0.7</td>
<td>9.3 ± 0.6</td>
<td>10.1 ± 0.7</td>
<td>9.0 ± 1.5</td>
<td>8.8 ± 0.9</td>
<td>8.5 ± 1.1</td>
</tr>
<tr>
<td>6</td>
<td>EF</td>
<td>181.2±17.6</td>
<td>197.8±25.1</td>
<td>222.0±47.1</td>
<td>241.8±35.3</td>
<td>241.4±19.4</td>
<td>261.4±19.4</td>
<td>260.3±26.6</td>
<td>251.1±25.8</td>
<td>232.4±21.5</td>
<td>198.2±15.3</td>
<td>174.6±15.9</td>
</tr>
<tr>
<td>7</td>
<td>U</td>
<td>3.7 ± 0.3</td>
<td>4.4 ± 0.5</td>
<td>4.9 ± 0.4</td>
<td>4.9 ± 0.5</td>
<td>5.0 ± 0.3</td>
<td>4.9 ± 0.4</td>
<td>5.2 ± 0.7</td>
<td>4.6 ± 0.4</td>
<td>3.7 ± 0.4</td>
<td>3.2 ± 0.3</td>
<td>3.4 ± 0.8</td>
</tr>
</tbody>
</table>

Key:
1. Temperature (°C); 2. Relative humidity (H %); 3. Rainfall (Rf) (mm); 4. Pan evaporation (E_o) (mm); 5. Sunshine (S_s) (hrs); 6. Total solar energy flux (EF) (W m\(^{-2}\)); 7. Windspeed (U) (km.hr\(^{-1}\)).
TABLE 2.2: Distance between water level and the surface at a well near the irrigated farmland on the Alkharj Plain. (Source: Ministry of Agriculture and Water).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance (m)</td>
<td>58.6</td>
<td>60.2</td>
<td>65.7</td>
<td>71.5</td>
<td>82.1</td>
<td>23.5</td>
</tr>
</tbody>
</table>

2.2 MATERIALS AND METHODS

2.2.1 Short-wave radiation (0.3-3.0 μm)

Upward and downward components of short-wave radiation were measured using two Moll-Gorczynski Pyranometers, commonly referred to as Kipp solarimeters (Kipp and Zonen Model M11, Holland), mounted back-to-back and exposed 1 m above the alfalfa crop surface. The solarimeters were new and the maker’s calibration was employed. The albedo was found as the upward ($S_u$) divided by downward flux ($S_d$).

2.2.2 All-wave net radiation (0.3-30 μm)

The was measured using a Didcot Funk-type net radiometer type DRN 301 (Didcot Instrument Company Ltd, Station Road, Abingdon, Oxon.) mounted alongside the short-wave sensors. This sensor was also new and the maker’s calibration certificate was used.

2.2.3 Components of long-wave radiation

The upward component ($L_u$) was estimated using this equation:

$$L_u = \varepsilon \times \sigma \times T_s^4$$

where

- $\varepsilon$ = emissivity of the vegetation surface, taken to be 0.98 (according to Fuchs and Tanner, 1966);
- $\sigma$ = Stefan-Boltzmann constant ($5.67 \times 10^8$ W m$^{-2}$K$^{-4}$);
- $T_s$ = surface temperature of the crop in K. For estimation purposes, and in the absence of knowledge of $T_s$, the air temperature at the crop surface was used.
FIGURE 2.1: Map of group of twelve sprinklers, and the location of the masts (○); (A) irrigation with flooding (surface irrigation); and (B) overhead sprinkler, for both field seasons 1985 and 1986. The circles and semi-circle are the areas receiving water from the rotating sprinkler-arms. The X symbols indicate agronomicat station.
The downward radiation \( L_d \) was found as a residual procedure using the values of \( R_n \), \( L_u \) and \( S_d \) taken during the same period.

\[
L_d = R_n + L_u - (S_d - S_u)
\]

2.2.4 Data acquisition

Signals were scanned every ten seconds and averages were computed over thirty minute periods using a Campbell 21x data logger (Campbell Scientific Inc., Logan, Utah 89821).

The equipment was operated on 45 days in 1986, covering all stages of the irrigated crop and encompassing a range of maximum solar elevation. Data from eight representative days were presented here (Table 2.3). The radiation data were collected simultaneously with the temperature and humidity data that were used in a later chapter to compute water use.

**TABLE 2.3:** Number and distribution of experimental days in the 1986 season with corresponding crop height. The nine days used for analysis in this chapter was selected according to these criteria: (i) crop was fully covering the ground; (ii) sunny, predominantly cloudless days; (iii) all the equipment was in full working order. These nine days were 14 and 15 March, 3 and 13 April, 13 and 23 May, 22 and 24 June, 10 October.

<table>
<thead>
<tr>
<th>Period of measurement</th>
<th>Crop height (m)</th>
<th>No. of days</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 - 15/03/86</td>
<td>0.50</td>
<td>4</td>
</tr>
<tr>
<td>16 - 30/03/86</td>
<td>0.07 - 0.15</td>
<td>15</td>
</tr>
<tr>
<td>1 - 03/04/86</td>
<td>0.15 - 0.20</td>
<td>3</td>
</tr>
<tr>
<td>16 - 17/04/86</td>
<td>0.25 - 0.38</td>
<td>2</td>
</tr>
<tr>
<td>12 - 15/05/86</td>
<td>0.23 - 0.25</td>
<td>4</td>
</tr>
<tr>
<td>22 - 25/05/86</td>
<td>0.45 - 0.50</td>
<td>4</td>
</tr>
<tr>
<td>20 - 24/06/86</td>
<td>0.35 - 0.45</td>
<td>4</td>
</tr>
<tr>
<td>5 - 13/10/86</td>
<td>0.25 - 0.35</td>
<td>8</td>
</tr>
</tbody>
</table>
2.3 RESULTS

Half-hourly average values of all radiation components above alfalfa during a representative day (23 May 1986) are presented in Figure 2.2. The crop was fully covering the ground with leaf area index (LAI) of more than three (Table 2.3). All days were sunny, although there was a variable amount of haze. There was always an increase in short-wave irradiance \( S_d \) during the morning, with a peak at noon and an afternoon decline, corresponding to the diurnal change in solar elevation.

The maximum value varied with season, being highest in June when solar elevation reaches 87°. The net radiation balance is dominated by \( S_d \) and statistically correlated with it. This is illustrated in Figure 2.3. The correlation was produced by pooling eight days of day-time data only from the 1986 field season. The correlation is strong \( (r^2 = 0.98) \), and enables \( R_n \) to be estimated from \( S_d \) using the following relationship, estimated from least square regression:

\[
R_n = -46.19 (±11.53) + 0.777 (±0.065) S_d - 0.0001678 S_d^2 (±0.0000082)
\]

\[ r^2 = 0.98 \] (the ± figure denotes the standard error).

Where data from different months were analysed separately by regression, the slopes \( b \) of the relationship between \( S_d \) and \( R_n \) were similar except for the April data which had a slightly higher slope. Intercepts \( a \) varied with time of year and were negative in sign (Table 2.4).
FIGURE 2.2: Diurnal variations in the radiation components measured above the alfalfa crop on a representative day (23 May 1986).
FIGURE 2.3: The relation between net radiation flux and incoming solar radiation measured above alfalfa crop surface (data for all eight days). Each point represents a half hour mean. Outlines are believed to have been caused by the slow passage of the irrigation arm over the sensor and by shadows from the mast itself (see Plates 3.1 and 3.2).
FIGURE 2.4: Diurnal and seasonal variations in surface albedo of alfalfa crop (1986 season). (a) - and -- are 14th and 15th March; (b) - and -- are 1st and 15th April; (c) - and -- are 13th and 23rd May; (d) - and -- are 22nd and 23rd June; (e) - 10th October; (f) - bare soil 11th October.
FIGURE 2.5: The relation of albedo to the solar angle over alfalfa crop surface. (a) - and -- are 14th and 15th March; (b) - and -- are 1st and 15th April; (c) - and -- are 13th and 23rd May; (d) - and -- are 22nd and 23rd June; (e) - 10th October; (f) o = all the data grouped together.
TABLE 2.4: Regression analysis of Alkhari radiation data on (1986 season). The regression has the form $y = ax + bx^2 + c$, where $y$ is $R_n$ or $R_u$, $S_d$ is $x$, and the coefficients are $a$, $b$ and $c$. ($r^2$) is the square of the correlation coefficient. Data are from two days in each month. The leaf area index (LAI) and plant height were measured as described in Section 3.2.1.

<table>
<thead>
<tr>
<th>$y$</th>
<th>Months</th>
<th>Parameter for prediction of $R_n$ and $S_u$ from $S_d$</th>
<th>LAI</th>
<th>Plant height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$a$</td>
<td>$b$</td>
<td>$c$</td>
</tr>
<tr>
<td>$R_n$</td>
<td>March</td>
<td>-54.50</td>
<td>0.81</td>
<td>-0.00028890</td>
</tr>
<tr>
<td></td>
<td>April</td>
<td>-42.63</td>
<td>0.75</td>
<td>-0.00012115</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>-31.4</td>
<td>0.72</td>
<td>-0.00005121</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>-36.21</td>
<td>0.83</td>
<td>-0.00021009</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>-46.19</td>
<td>0.777</td>
<td>-0.00016780</td>
</tr>
<tr>
<td>$S_u$</td>
<td>March</td>
<td>2.87</td>
<td>0.269</td>
<td>0.00006200</td>
</tr>
<tr>
<td></td>
<td>April</td>
<td>6.32</td>
<td>0.263</td>
<td>-0.00005533</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>8.83</td>
<td>0.251</td>
<td>-0.00005168</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>9.32</td>
<td>0.266</td>
<td>-0.00006899</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>6.84</td>
<td>0.263</td>
<td>-0.00005950</td>
</tr>
</tbody>
</table>
The estimated downward long-wave component \( L_d \) varied a little during the day with minimum values occurring near solar noon (Figure 2.2). The upward long-wave component \( L_u \) followed the changes in surface temperatures, with a minimum value in the morning, rising to a higher value at the solar noon, then falling again during the afternoon. The early morning value was about 80 W m\(^{-2}\) while the afternoon value was more than double that figure (Figure 2.2).

Results in Table 2.4 represent a group of regressions between the incoming short-wave \( S_d \) and the other components of radiation. Such regressions may be useful in the future for energy balance studies.

Diurnal and seasonal changes in crop albedo are shown in Figure 2.4. The value of albedo fell from 0.3-0.40 in the morning to about 0.20 at solar noon, then started to increase again during the rest of the day (Figure 2.4). Much of the total variation in the albedo is presumed to be caused by the diurnal change in solar angle. At low solar angles, surfaces display high specular reflectance. When all the data are placed on the same graph (Figure 2.5f) we see more clearly how solar angle is the main determinant of albedo, though some seasonal variation is caused by variation in crop cover and phenological development (Table 2.4).

The albedo of uncultivated desert soil, which was litter-free, is shown in Figure 2.4f. Diurnal trends are similar but the albedo is very much higher.

2.4 DISCUSSION

The overall mean value of the crop albedo was 0.26. This value agrees with the daily mean albedo of alfalfa reported in the literature (Monteith, 1959; Gates and Hanks, 1967; Brown and Rosenberg, 1970; Weiss, 1982). This value was computed as the slope of the regression line between \( S_u \) and \( S_d \), a method recommended by Stanhill et al. (1966), because it gives weight to the data according to the magnitude of the fluxes and it differs from the computed average of hourly values where equal weight is given to hours
of low and high radiation. Others have used the 11.00 hr value of albedo as recommended by Rijks (1967).

Diurnal variations in crop albedo have been ascribed to exposure of the leaves and the crop surface as a whole to different solar angles (Monteith, 1959; Stanhill et al., 1966; Grace, 1983). In alfalfa higher albedo in the early morning and late day is caused by an increased component of specular reflection as opposed to diffuse reflection at low solar angle (Brown, Rosenberg and Doraiswamy, 1970). Lower albedo with higher solar angle is also caused by penetration of some of the radiation further down inside the canopy, allowing more trapping by the canopy. Thus, tall crops with vertical elements have low albedo (Grace, 1983). Leaf arrangement in the canopy also contributes to the diurnal trend in the albedo. Alfalfa leaves track the solar rays (Travis and Reed, 1983), and this tracking mechanism may decrease the albedo and therefore increase the radiation load on the crop surface. There is also an indication that diurnal pattern of crop albedo is asymmetrical in some of the days represented in Figure 2.5. Afternoon albedo values are higher than the morning values at the same solar angle. A similar case was reported in maize crop by Stanhill (1968). Leaf wetness was ascribed in that case, but is not likely here. Diurnal changes in leaf angle, resulting from solar tracking, might cause some of the variation, but this requires more investigation.

As the crop grows up during the season, the plant canopy increases till it fully covers the ground. Albedo usually increases as LAI increases, at least over the lower ranges of LAI (0-2.0). Observed seasonal variation attributable to changes in LAI have been reported in the literature (Rijks, 1967; Kalma and Badham, 1972). Albedo of alfalfa was reported by Weiss (1982) to change from 0.18 to 0.26 corresponding to changes in plant height from 0.15 to 0.60 m. Crop albedo stabilized after LAI reached 3.0 (Graham and King, 1961). Thereafter little change in crop albedo was observed. In this study, albedo shows similar results to Graham and King's but there was only a small variation in plant height and LAI.
In conclusion, the measurements reported in this chapter enable the net radiation to be established from data on short-wave irradiance.

In the next chapter, the partitioning of the net energy supply between evaporation and sensible heat will be considered.
CHAPTER THREE

THE BOWEN RATIO

DETERMINATION OF WATER USE
3.1 INTRODUCTION

Alfalfa has been reported to use water wastefully in comparison with the other crops (Sonmor, 1963). This has been ascribed to the year-round growth duration (Krogman and Lutwick, 1961), depth of rooting (Chamblee, 1958; Van Riper, 1964), high and persistent leaf area index (Krogman and Lutwick, 1961; Krogman and Hobbs, 1965; Carter and Sheaffer, 1983), and plant height (Hafeez and Hudson, 1965). Frequently-irrigated alfalfa, with complete ground cover is reported to exert negligible stomatal resistance for water loss until soil water has been depleted to -4.0 bars (Van Bavel, 1967). This lack of stomatal control was inferred from lysimetric measurement of evapotranspiration. Rosenberg (1969b) also reported high rates of water use by alfalfa and gave support to Van Bavel’s idea of lack of stomatal control.

High water use was also reported by Hudson (1965b) for the case of alfalfa growing in Sudan, where the crop was found to use as much as 23 mm day$^{-1}$ for several days. Kerr et al. (1973) observed a diurnal variation in evapotranspiration and reported the high rates of alfalfa compared with paspalum and maize. Water loss was found to vary seasonally with the highest rate exceeding 6 mm day$^{-1}$. In England, lower values were reported by Szeicz and Long (1969) and Tajchman (1971): rates of evapotranspiration in spring were around 1.8 mm day$^{-1}$, while in summer values were higher, about 2.3 mm day$^{-1}$. Recently Carter and Sheaffer (1983) using volumetric determinations of soil water in the USA reported a wider range of values from 1 mm to 10 mm day$^{-1}$ depending on water stress. They reported other work by Jungkull (1982), using a lysimeter and obtaining 3.1-10 mm day$^{-1}$ in Minnesota (USA), while Tanner and Pelton (1960), also in the United States of America, obtained 1-9 mm day$^{-1}$. 
Evapotranspiration has been evaluated using the Bowen ratio technique over alfalfa (Rosenberg, 1969b; Bland and Rosenberg, 1974; Kerr et al., 1973; Verma et al., 1978) and in other plant species (Miranda, 1982; Brun et al., 1985; Heilman and Brittin, 1989). With the higher rates of evapotranspiration mentioned above, the energy needed to evaporate water vapour from the leaves as available energy may be insufficient to maintain such a high rate. Indeed, the ratio LE/R may considerably exceed unity, sometimes being as high as 1.8 (Fritschen, 1965; Rosenberg, 1969b; Bland and Rosenberg, 1974; Brakke et al., 1978). Such high rates can occur only because an additional source of sensible heat comes from the surrounding atmosphere. The rapid transpiration rate achieved in arid climates cools the leaves and the crop surface as a whole, creating the temperature gradient which causes the downward flux of sensible heat.

This effect, which is essentially a feature of arid zone agriculture, is likely to be most pronounced in desert irrigation schemes, and helps to explain the high rates of water use recorded in Saudi Arabia. In this country, evapotranspiration has been routinely estimated using pan evaporation and multiplying the rate by an empirically determined crop coefficient ($K_c$). This coefficient is obtained by comparing the rate of evaporation from open water in a pan with that of a nearby test crop, found by measuring the depletion of water in the soil over a period of a week or so. Estimates for alfalfa based on the ($K_c$) coefficient obtained for a particular locality but extrapolated more widely, suggest that crops reach a peak value of 13.6 mm day$^{-1}$ in the month of June, while lower values of 4.3 are expected in the winter months (Ministry of Agriculture and Water, 1973; Asseed et al., 1981). Recent lysimetric measurements (Deaver et al., 1981; Saeed and Abdulaziz, 1985; Saeed, 1987) showed the Penman formula often underestimated evapotranspiration by more than 10% when used under conditions of low wind speed. They used a drainage lysimeter to ‘calibrate’ this formula which has traditionally been used as an indicator for water loss (Hudson, 1965b). The use of such lysimeter requires certain precautions to be met in order to get a representative estimate of evapotranspiration. In particular, plants in the field and the lysimeter need to be indistinguishable in height, density and colour.
Field size is also important in relation to using the lysimeter. In a small field plot it is
difficult to obtain a representative estimate because the field will be exposed to sensible
heat advection from the surrounding areas and may evaporate more water than a site in
a big field in the same region.

**3.1.1 Determination of evapotranspiration rate**

Different definitions of evapotranspiration occur in the literature. There is the
reference evapotranspiration \( (ET_o) \) which is defined as "the rate of ET from an extensive
surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing,
completely shading the ground and not short of water". Another concept widely used
in the study of evaporation and evapotranspiration is the potential evapotranspiration
\( (ET_p) \), defined by Rosenberg et al. (1983) as "the evaporation from an extended surface
of a short green crop which fully shades the ground, exerts little or negligible resistance
to the flow of water, and is always well supplied with water". In practice, these definitions
are nearly the same.

There are three main approaches used for measuring evaporation from natural
vegetation surface which involve:

1. determination of water balance by sensing water in the soil or by use of a
   lysimeter;
2. energy balance; and
3. water vapour measurement near the vegetation surface.

There are also methods which involve the combination of the second and the third
approaches in addition to a number of methods which involve empirical and semi-
empirical formulae developed to calculate evaporation using readily-measured
meteorological variables. For reviews of the methods used in ET measurement see
Shuttleworth, 1979; Blad, 1983; Rosenberg et al., 1983.

Under desert conditions and with an irrigated crop, evapotranspiration can be
determined either by gravimetric methods or by sensing water using a neutron probe
(Shuttleworth, 1979). This approach has been used to estimate water use in alfalfa (Christian, 1977).

The energy balance approach concerns the partitioning of the net energy absorbed by the vegetation and soil surface into latent heat and sensible heat (usually assuming that other terms are negligible). This heat exchange can be written as follows:

\[ R_n + LE + C + G + S = 0 \]  

(3.1)

where \( L \) is the latent heat of vaporisation of water (2545 J kg\(^{-1}\)), \( E \) water loss (kg m\(^{-2}\) s\(^{-1}\)), \( C \) is the sensible heat loss, \( G \) is the flux of sensible heat to the soil and \( S \) is the storage term. \( S \) includes heat storage in the mass of plant material and in chemical bonds that are produced by the photosynthesis of the crop. Heat stored in plant mass is very small for short vegetation, and the rate of energy conversion to chemical bonds is also very small, typically less than 5% (Thom, 1975), so the major important terms are \( R_n \), \( LE \), \( C \) and \( G \). \( R_n \) can be measured above the vegetation, while the soil sensible heat flux can also be measured, for example with heat flux plates buried in the soil.

The remaining terms of the energy balance \( LE \) and \( C \) can be obtained using the Bowen ratio technique discussed at length in this chapter.

The third approach involves the determination of water vapour concentration over the vegetation. The traditional (aerodynamic) method is to determine profiles of wind speed and water vapour, then to use the wind speed profile to find the eddy diffusivity of momentum. This value is assumed to apply to water vapour as well, so that the flux of water vapour can be found from the profile gradient and the appropriate transfer coefficient. The technique works best for short vegetation and considerable fetch is required.

Many workers are now beginning to use the eddy correlation principle, in which rapid vertical movements of air are sensed at the same time as the fluctuations in water vapour. This method is reviewed elsewhere (Rosenberg et al., 1983; Angus and Watts, 1984).
There are also other methods based on a number of semi-empirical formulae used to provide an estimate of evapotranspiration from open water (Shuttleworth, 1979). In arid and semi-arid areas, there are a number of formulae recommended for estimation of ET provided certain precautions are taken (Doorenbos and Pruitt, 1977). These include formulae attributable to Thornthwaite, Priestly and Taylor.

Direct measurements of evaporation have often been made from an open water surface such as a Piche evaporimeter or a pan. The evaporation from a standard pan has been used for scheduling irrigation (Halfield, 1979; Donovan and Meek, 1983). Lysimetric devices have frequently been used to assess evapotranspiration (Hudson, 1965). None of these devices which are used to measure evaporation is wholly satisfactory for measuring ET as the surface resistance of the crop itself varies with the stage and condition of growth.

3.1.2 Bowen ratio estimate of LE

3.1.2.1 Background

The Bowen ratio estimate of water use is widely used as a standard method for crops and natural vegetation. It involves computation of sensible and latent heat fluxes from knowledge of net radiation, the soil sensible heat flux, and the temperature and water vapour gradients close to the crop surface. The Bowen ratio is defined as the ratio of sensible heat to latent heat, \( C/LE \).

The derivation of the Bowen ratio can be found in recent reviews (Tanner, 1968; Jarvis and Stewart, 1975; Rosenberg et al., 1983; Angus and Watts, 1984; Garratt, 1984). The derivation begins by the statement of the energy budget (equation 3.1).

The Bowen ratio method of determining LE can be derived by considering the vertical fluxes and diffusion conductances of both \( H_2O \) and heat, and may be presented as follows:

\[
E = \rho L((M_w/M_a)/P) K_w(\Delta e/\Delta z) \tag{3.2}
\]
where $M_w$ is the molecular weight of water, $M_a$ is the molecular weight of air, $p$ is the atmospheric pressure (kPa), $K_w$ (m$^2$s$^{-1}$) is the transfer coefficient for water vapour, $e$ is the vapour pressure (kPa), $Z$ is the height, $\rho$ is the density* of the air (kg m$^{-3}$), and $L$ is the latent heat of evaporation (J kg$^{-1}$).

$$C = \rho c_p K_h \frac{\Delta T}{\Delta Z}$$

(3.3)

where $c_p$ is the specific heat of air at constant pressure (J kg$^{-1}$ C$^{-1}$), $K_h$ is the transfer coefficient for heat and $T$ is the potential temperature. If $K_w = K_h$ (an assumption), then the Bowen ratio, defined as $C/LE$, can be written in this form:

$$\beta = \frac{c_p p}{(LM_w/M_a)} \frac{\Delta T}{\Delta e}$$

(3.4)

where $\Delta T$ and $\Delta e$ are changes in temperature and vapour pressure over the same vertical distance and $c_p p/(LM_w/M_a)$ is the psychrometric constant. Using the Bowen ratio equation (3.2) becomes

$$LE = -\frac{(R_n - G)}{(1 + \beta)}$$

(3.5)

The Bowen ratio was originally used in temperate climates to obtain an estimate of water loss from free water surfaces (Bowen, 1926). Later it was used to estimate $LE$ from a crop (Tanner, 1968; Hellman and Brittin, 1989).

For successful determination of $LE$, the criteria are as follows.

1. The temperature and humidity at two heights over the vegetation must be measured with adequate precision so that $\Delta T/\Delta e$ is accurately known.
2. These measurement points must be within the fully developed boundary layer of the crop. Thus, adequate fetch is required.
3. In the region of measurement, $K_h$ must be equal to $K_w$.

In most cases, these criteria are believed to have been well enough met with sensors placed immediately above the crop, 0.5-1 m apart, and at least 100 h downwind from the edge of the crop, where $h$ is the height of the plants.

---

*The value of $\rho$ appropriate to ‘field’ conditions will depend on temperature and water content (Monteith, 1973, p. 221). Over the range of conditions in the field site (25°C to 35°C) $\rho$ varies from 1.18 to 1.12 kg m$^{-3}$.
3.2 MATERIALS AND METHODS

3.2.1 Experimental procedure

The observations were made during the 1986 season at an irrigated 3-year old alfalfa crop in Alkharj (for details see Chapter 2). The soil was watered as in normal agricultural practice. When samples were taken for gravimetric determination of water, they were found to be between 17 and 25% of the dry weight. The circular field area was about 45 ha, and was equipped with an irrigation system which sprays water over the crop surface (Plate 3.1). The field was surrounded by a barren area from the north-west and the west, and there were two irrigated fields in the east (Figure 2.1). Observations were made in March, April, May and June 1986. The instruments were placed well inside the field with a ratio of crop height to fetch of between 1:100 and 1:150. The measurements were started after the plants had reached full canopy cover. The plant height varied from 0.10 to 0.50 m. Assessment of the crop height and LAI was made by measuring plants within randomly-placed quadrats (0.25 m²). Leaf area index (LAI) was found by taking a sample of these plants and determining the leaf area using an area meter (LI-COR, Nebraska).

3.2.2 Data collection and analysis

Signals from all the sensors and instruments were captured on a data acquisition system (21X data logger), located in a shielded housing above the crop. Sensors were scanned every ten seconds, converted to the required units and averaged over 15, 30 or 60 minutes before storage on RAM.

At the end of each day the data were written in a notebook. Data files were later compiled on the mainframe computer in Edinburgh, for processing and plotting. The data in this chapter are selected for periods where the ratio of fetch to plant height exceed 1:100, and when the canopy achieved full cover (corresponding to a plant height of 0.10-0.50 m).
3.2.3 Temperature and vapour pressure measurement

Accurate measurements of temperature and vapour pressure differences are necessary for Bowen ratio determination. Hence, both temperatures and vapour pressures were measured with psychrometer units constructed to measure the wet and dry bulb temperatures using copper constantan thermojunctions (42 SWG). Both wet and dry bulb temperatures were referenced to a common reference junction within the data logger (CR21X, Campbell, Utah, USA). The reason for selection of such sensors is mentioned in Chapter 4.2. The wet and dry bulb sensors for a single unit are shown in Figure 3.1 and Plate 3.3. The unit consists of two junctions: one used as a wet bulb and the other as the dry bulb; a double radiation shield; a reservoir and a fan. The units were developed in Edinburgh for a previous project by S. Allen. The wet bulb sensor was fed by a woven cotton sleeve which formed the wick. The sleeve was irrigated from an external distilled water reservoir via flexible plastic tubing (Plate 3.3). The water level within the reservoir
PLATE 3.1: The irrigation system used to spray the water over the crop surface. Note also the large size of the field.

PLATE 3.2: The mast carrying the instruments: (a) two psychrometer units; (b) anemometer; (c) net radiometer; (d) two solarimeters; and (e) CR21X data logger.
PLATE 3.3: Psychrometric unit with sensor mount removed. Air is drawn at 4 m s$^{-1}$ into the orifice on the right, over the sensors (b and c) which are shielded by two layers of white plastic (a). The air is expelled from the orifice on the left, inside which the fan is mounted. The water reservoir (e) provides a small head of water to feed the wick via a flexible tube (d). The unit was designed by S. Allen in 1985, and can be made from locally-obtainable materials, in almost any country.
was above the level of the midpoint of the wick. The height of the reservoir was adjustable within \( \pm 30 \) mm to facilitate regulation. An adjustable clip on the tubing was used for further regulation so the water flowed very slowly to the wick. This was necessary in the very dry conditions, or the wick tended to dry out. The size of the reservoir was 0.25 ml, enough to keep the wick wet for two to three days:

Wet and dry bulbs were ventilated by a small 12V fan (Micronel Radiation Components Limited, 76 Crown Road, Twickenham, Middlesex TW1 3ET, England), powered by a car battery, which continuously drew the air through an inlet and passed it over the sensors at 3.2 m s\(^{-1}\) before expelling it at a point some distance from the inlet. This flow was measured with a hot-wire anemometer. The heights of the sensors above the crop were 0.4-0.9 m.

Calibration of the thermojunctions was carried out at a laboratory in the King Saud University, Riyadh, Saudi Arabia, and similar results to those obtained in Chapter 4.2 were found. The efficiency of the radiation shield was also tested under full sunlight and had previously been tested by S. Allen in an environmental cabinet. At an irradiance of 300 W m\(^2\) the wet bulb depression of the unit was within 0.1°C of that of the Assman psychrometer. Even at higher irradiances, it seemed that the shield would be sufficient to prevent significant radiation errors.

### 3.2.4 Net radiation

Radiation measurements used in this chapter are the same as those of Chapter 2.2. A new Didcot net radiometer was employed, and the maker’s calibration certificate was used.

### 3.2.5 Wind speed

A three-cup anemometer was used to measure wind speed at one level 2 m above the crop surface (Met One 014A, Met One Inc., 481 California Avenue, Grant Pass, OR
This anemometer was mounted on a supporting arm 0.32 m long on the top of a 2 m mast. The output from this anemometer was recorded on the CR21X data logger.

### 3.2.6 Soil sensible heat flux

Heat flux was estimated with two thermocouples placed at 2 cm and 7 cm in the soil. The soil sensible heat flux \( G \) was calculated following Monteith (1973):

\[
G = -\frac{\kappa \Delta T}{\Delta Z}
\]  

(3.7)

where

- \( \Delta T \) is the difference in temperature
- \( \Delta Z \) is the difference in depth
- \( \kappa \) is the thermal conductivity of the soil, taking the value for moist sandy soil as \( 1.7 \times 10^4 \) J m\(^{-1}\)s\(^{-1}\) K\(^{-1}\).

### 3.2.7 Effect of fetch

A preliminary experiment was carried out to assess the requirement for fetch using a hand held humidity sensor which measured temperature and relative humidity (RH) at two levels above the crop along a transect started at the edge of the field and extending to almost the middle. The levels were 0.4 and 0.9 m above the crop surface.

It was expected that the conditions could reach a steady value at some distance from the edge as the boundary layer adjusted to the roughness of the crop. This experiment was carried out by moving one of the masts across the field by carrying both sensors and the mast along a transect whilst taking readings for short time intervals of 5-10 minutes. This proved to be difficult, because of temporal changes and practical difficulties in carrying and adjusting the mast and logger. One transect took 60 minutes to complete, and the experiment was conducted near mid-day when rates of change were minimal. On return to the fetch = 0 position after completion of transect, the temperature was found to have changed by one degree.
3.3 RESULTS

3.3.1 Diurnal patterns of energy fluxes

Examples of diurnal patterns of the fluxes of sensible heat (C), latent heat (LE), net radiation (R_n) and soil sensible heat (G) are shown in Graphs 3.2-3.5. All four days were practically cloudless, as is typical of the area, except when dust storms occur. The graphs also show the gradients of humidity and temperature as sensed above the crop.

Maximum values of sensible heat flux (C) ranged from -200 W m^{-2} to + 300 W m^{-2}, while the latent heat flux values exceeded 800 W m^{-2} (Figure 3.5). Maximal values of latent heat flux occurred around noon. LE exceeded R_n for much of the time. When LE is plotted against R_n combining the data from Figures 3.2 to 3.5, a strong correlation is evident (Figure 3.6).

The ratio LE/R_n often exceeded 1.0, indicating a high downward flux of sensible heat from the air, especially during the hottest part of each day.

Maximum transpiration rate as measured by the latent heat flux (LE), does not increase as plant cover increases, at least not in the range of plant cover over which measurements were made. Daily variations were influenced by cloud cover (Figure 3.3). This graph indicates sharp variations in LE associated with changes in R_n especially in the afternoon period when most of the fluctuations were observed.

The vertical gradient of vapour pressure over the crop shows daily variation, reaching 1.0 kPa m^{-1} (with a negative sign indicating a decrease of VPD with height above the crop), but it is generally around 0.5 kPa m^{-1}. The sign convection used here means that the vapour pressure usually declines with increasing height above this crop. Temperature gradients show similar variability, and are usually positive in sign, indicating cooler temperatures near the surface. During the afternoon, the temperature immediately over the crop could be as much as 3 °C cooler than that 1 m above (Figure 3.3).

Wind speed was variable. On the windiest day, it reached about 4 m s^{-1} (Figure 3.2c), but was generally less than 2 m s^{-1} (Figures 3.3 and 3.5c).
FIGURE 3.2: The daily pattern of hourly measured and derived variables: (a) net radiation measured one metre above the crop; (b) gradient of vapour pressure and temperature measured within the boundary layer above the crop surface; (c) wind speed measured two metres above the ground; (d) soil sensible heat flux (storage) and Bowen ratio; (e) latent and sensible heat fluxes determined using the Bowen ratio and energy balance for the whole crop. These graphs represent data taken on 13/3/86. The crop height was 0.35 m. Each data point is an hourly mean of a series of 10-15 scans.
FIGURE 3.3: As for Figure 3.2. Data taken on 15/4/86 when the crop height was 0.46 (±0.08) m. Each point is a mean of 15 minutes.
FIGURE 3.4: As for Figure 3.2. Data taken on 25/5/86 when the crop height was 0.50 (±0.09) m. Each point is a mean of 30 minutes.
FIGURE 3.5: As for Figure 3.2. Data taken on 23/6/86 when the crop height was 0.44 (±0.05) m. Each point is a mean of 30 minutes.
FIGURE 3.6: The relation between net radiation and evapotranspiration (LE). Points are from days 13/3, 15/4, 25/5 and 23/6/86. Each data point is an hourly (or sometimes a half- or quarter-hourly) mean of a series of 10 second scans. The line indicates a 1:1 relationship.
FIGURE 3.7: This shows comparison of heat flux to the soil on 13/3/86 when there was a full cover, and 24/3/86 after the crop had been cut down (partial canopy cover). The incident radiation fluxes were not very different on these two days. Arrows show the chronological order, from morning to evening.

FIGURE 3.8: Shows the changes in both temperature and saturation deficit at two levels (0.4 and 0.9 m) above the crop surface and across 180 m of the field from the leading edge. The experiment was carried out during midday (10 to 14 hrs) when rate of change was minimal. Each transect took one hour to complete, and the change in temperature at the starting point (distance = 0) was 1°C in this period to return back to the starting point - for more details see Section 3.2.7.
3.3.2 Diurnal pattern of soil sensible heat flux (G)

The flux of sensible heat to the soil increased with time of the day, the maximum values being about 105 W m\(^2\) on 15/4/86 (Figure 3.3). These occurred when the crop height was at minimum. The influence of canopy cover in determining the flux of latent to the soil is shown in Figure 3.7.

3.3.3 Bowen Ratio (β)

Bowen ratios are shown in Figures 3.2-3.5D. β varies with time of day. β values are often negative and very low but in general vary between 0.5 and -0.5. Some positive values occur in the morning (Figure 3.2) but they decrease as the time of the day progresses, reaching very low values in the late evening. This is especially so with full plant cover, but with a shorter crop β values can be higher than zero (Figure 3.2d).

3.3.4 Regional advection from the barren area

To test the influence of regional advection of sensible heat on the microclimate of the field, a preliminary set of observations was made in which VPD and temperature were measured at two heights above the canopy, starting at the centre of the field taking readings at various distances from the field edge. The results are presented in Figure 3.8. Although these data are necessarily ‘noisier’ than those used in the main part of the work, because of the short sampling period, they nevertheless indicate how an air mass moving across the field gives up heat to the field and receives moisture. Most of the change in the air mass occurs over the first 60 m of the crop. After this distance the air in this zone has more or less equilibrated with the vegetation.
TABLE 3.1: The daily and seasonal variability of net radiation ($R_n$), latent heat flux (LE) and Bowen ratio. Columns contain the maximum (Mx), minimum (Mn), and mean of the day-time value ($\bar{x}$). The day is defined as sunrise to sunset. Note that the LE values can be converted to mm of water per hour by multiplying by 0.00141. Positive values of LE imply dew formation.

| Date | $R_n$ (W m$^{-2}$) Mx | LE (W m$^{-2}$) Mx | Bowen ratio Mx | LE (W m$^{-2}$) Mn | Bowen ratio Mn | LE (W m$^{-2}$) $\bar{x}$ | Bowen ratio $\bar{x}$ |
|------|---------------------|-------------------|----------------|-------------------|---------------|----------------|----------------|----------------|
| 13/3 | 519                 | -452.0            | 0.58           | -35               | -277.3        | -280.2         | -0.29          | -0.23          |
| 15/4 | 651                 | -669.7            | 0.00           | -16               | -407.1        | 401.3          | -0.40          | -0.12          |
| 24/5 | 581                 | -650.8            | -0.09          | 2                 | -437.2        | 366.9          | -0.12          | -0.27          |
| 23/6 | 566                 | -795.3            | -0.08          | -41               | -426.0        | 342.2          | -0.006         | -0.26          |

TABLE 3.2: Comparison of various evapotranspiration rates (mm day$^{-1}$) measured or estimated for alfalfa in Saudi Arabia. ET(1) is lysimetric; ET(2) is calculated value from $ET = K_E$; (3) as (1); (4) from Bowen ratio in the present study; (5) as (2) but pan evaporation was taken as a mean for five years. Source of data: (1) and (2) was Hofuf Agricultural Research Center (1973); (3) Saeed and Abdulaziz, 1985; (5) Ministry of Agriculture and Water, 1986.

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<td>7.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>8.7</td>
<td>6.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>6.8</td>
<td>4.4</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>6.1</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.4 DISCUSSION

3.4.1 Daily variation in the fluxes

In well-irrigated herbaceous plants there is often little restriction in water use, so that the daily variation in latent heat flux (LE) can be represented by a curve which resembles that describing the supply of solar energy. However, under high vapour pressure deficit (VPD) and air temperature ($T_a$), two peaks sometimes occur as a result of stomatal closure at mid-day, one in early morning and another late in the afternoon (Larcher, 1975; Kramer, 1983). In the present case, we see no evidence of stomatal control at mid-day (Figures 3.2-3.6).

Leaf area index and plant height have been reported to contribute to the variability in water use. Seasonal variations in the crop water use can often be ascribed to variation in leaf area index (LAI) and age, as the bulk stomatal conductance of the canopy increases with LAI and control of stomatal movements may diminish when leaves senesce.

In the present case, even at its minimum, the canopy displays high rates of water use, a consequence of the high leaf conductance (see Chapters 4 and 5) and a leaf area index exceeding one.

The average daily water use by the crop is similar to that reported by others in the same geographical region (Ministry of Agriculture and Water, 1973; Asseed et al., 1981; Saeed and Abdulaziz, 1985; Saeed, 1987). The latter estimated crop evapotranspiration using a modified Penman equation, calibrating it with a drainage lysimeter which had less-than-sufficient fetch. All of these reports are based on measurements from small patches of land which may not have been representative. Such techniques are likely to yield an LE value which exceeds that of a large field because of the considerable advection, sometimes called the “Oasis” effect. Moreover, the methods used are recommended for use over periods of several days (Doorenbos and Pruitt, 1977), while the method used here is suitable for short-term time intervals (less than 1 hour). The short time interval is potentially useful in elucidating physiological stomatal control.
A comparison between the results reported here and those of the other workers is given in Table 3.2. Water use (mm day\(^{-1}\)) was found to vary between 6-10 mm day\(^{-1}\) which is similar to the rate of evapotranspiration calculated for the same region using a crop coefficient (\(K_c\)) and pan evaporation (monthly value).

3.4.2 Energy partitioning

The energy intercepted and absorbed by the leaves must be dissipated or leaf temperatures would rise above the lethal point. In a climate characterised by a high energy load, plants may be adapted to dissipate the excess energy by morphological and physiological adaptation. These adaptations may involve small leaf size, and high stomatal conductance. Under such conditions, herbaceous plants are expected to transpire at a high rate, as frequently reported in the literature.

The ratio of \(\frac{LE}{R_n}\) in the irrigated semi-arid region is reported to exceed one (Rosenberg, 1969b), though the ratio varies with season as well as with the crop development. It is clear from Figure 3.6 that \(\frac{LE}{R_n}\) exceeds one in many of the data collected over the experimental period (March-June 1986). This implies sensible heat flux from the air to the crop surface.

Brown (1974) and Rosenberg (1969b) reported a value of \(\frac{LE}{R_n}\) of 1.5 for alfalfa growing in a semi-arid region of the USA. A lower ratio from alfalfa was reported by Kerr et al. (1973) and the semi-arid parts of Australia, and Tadmor et al. (1966) for a cooler climate.

3.4.3 Errors in the Bowen ratio determination of LE

3.4.3.1 Voltage resolution

It is desirable to minimise error in the calculated LE values, and as far as possible to estimate the overall magnitude of the error. Error arises from the calibration in the instruments used to measure the wet and dry bulb temperature and possibly by the
FIGURE 3.9: Effect of worst-possible instrument errors. The figures show the (a) upper and (b) lower limit of the latent heat flux produced from adding +0.5 °C to the wet bulb temperature and subtracting 0.5 °C from the wet bulb depression; and subtracting 0.5 °C from the wet bulb temperature and adding 0.5 °C to the wet bulb depression to produce the upper possible error in LE. The error of 0.5 °C was taken as instrument error in temperature measurements in the field. The analysis has been conducted on data of 23/5/86, where the solid line represents the actual values and the broken lines represent new levels introduced by the above procedure.
resolution errors of the recording system. However, these two sources are found to be small, especially that of the recording system. From the manufacturer's specification the micrologger should be able to resolve a little as 0.009 °C, therefore this error is very small and can be neglected.

3.4.3.2 Calibration errors

Thermocouple and psychrometer errors may reach ±0.02 °C. Calibration errors in radiometers are said to be as large as 10%. Moreover, the radiation shield is assumed to have been completely efficient based on test in a controlled environment cabinet. The error in knowledge of the net radiation to the crop depends to some extent on the errors in the measurement of soil flux. This is because the 'available' radiation is obtained by subtracting the soil flux from the total radiation flux. The former is not very accurately determined but usually constitutes a small fraction of $R_n$. In this study it was about one fifth. The psychrometric response is rapid, it reaches a steady state within seconds.

All sensors respond at a rate which is fairly rapid in relation to the rate of change of the variables on a sunny day. The psychrometer units take about ten seconds to reach a steady state, and the radiometers take fifteen seconds. As the net radiation does not change more rapidly than 0.13 W m$^{-2}$ in a second (unless there are rapidly-moving clouds), it is concluded that the errors caused by a synchrony in measurement is small.

3.4.3.3 Exposure error

An additional source of error in radiation sensors is that associated with instrumental exposure. These errors can be eliminated with appropriate instrument exposure (levelling of the net radiometer). Two to 5% may arise with an inappropriate exposure (Rosenberg et al., 1983). Data collected simultaneously using two booms running in the same field demonstrate a substantial discrepancy for some hours of the day (Table 3.3) and a total discrepancy over half a day of about 11%. Some of these discrepancies are greater than
can be accounted for by instrument error and may have been caused by variation within the field.

The accuracy of the thermocouples reached ±0.02 °C which is sufficient for the Bowen ratio (Fuchs and Tanner, 1970; Fritschen et al., 1985). In the field a realistic and practical test was made by exposing two units at the same height. The discrepancy between two wet bulbs was found to be ±0.5 °C. This discrepancy was then introduced into the calculation of LE by applying an 0.5 °C addition and subtraction to the wet bulb reading to produce a 'worst-possible error'. The result of performing the usual calculation on one day’s data to which the error was set to -0.5, 0.0 and +0.5 °C is shown in Figure 3.9.

The error causes a deviation in the calculated value of between 1-15%, similar in magnitude to the errors in calculated LE, reported elsewhere (Fritschen, 1965; Sinclair et al., 1975; San José and Berrade, 1983). Others have suggested larger errors. Lemon (1970) working with maize, Saugier (1975) working with sunflower, found errors as high as 20%.

TABLE 3.3: Evapotranspiration measured with two booms in the same field, 60 m apart. Data for 15/4/86. Units are W m⁻².

<table>
<thead>
<tr>
<th>Time</th>
<th>Boom 1</th>
<th>Boom 2</th>
<th>Boom 1 / Boom 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.00</td>
<td>-630</td>
<td>-681</td>
<td>0.93</td>
</tr>
<tr>
<td>14.00</td>
<td>-426</td>
<td>-423</td>
<td>1.01</td>
</tr>
<tr>
<td>15.00</td>
<td>-382</td>
<td>-318</td>
<td>1.19</td>
</tr>
<tr>
<td>16.00</td>
<td>-375</td>
<td>-289</td>
<td>1.29</td>
</tr>
<tr>
<td>17.00</td>
<td>-227</td>
<td>-198</td>
<td>1.14</td>
</tr>
<tr>
<td>mean</td>
<td>-408</td>
<td>-382</td>
<td>1.11</td>
</tr>
</tbody>
</table>

There is also an uncontrolled error arising from sampling with no replication, caused by spatial variation in the field. From a run on 1/4/86, when both masts were used side-by-side, and when the sensors were swapped by rotating the boom, the error in the wet bulb depression was found to be ±0.5 °C.
FIGURE 3.10: The percentage error in LE caused by errors in the Bowen ratio from -50% to +50%. The Bowen ratio errors are shown by the numbers on the right hand side. Note that the error in LE changes markedly as the Bowen ratio increases from -0.5 to +1.0. The rectangular zone represents the region of Bowen ratio and likely errors in Bowen ratio that may have prevailed in the present study.
FIGURE 3.11: \( K_v/K_w \) plotted as a function of \( \Delta T/\Delta e \) and LE from a lysimeter at three levels above the alfalfa crop in USA (copied from Verma et al., 1978).

FIGURE 3.12: The relationship between the LE calculated from the Bowen ratio (y-axis) and LE which has been 'corrected' using the relationship in Figure 3.11. Data of 23/5/86.
3.4.3.4  **Overall assessment of error in LE**

The precision of the calculated LE is clearly affected by the determination of $\beta$, $R_n$ and $G$, since

$$LE = \frac{-R_n + G}{1 + \beta}$$

We have seen that $R_n$ and $G$ are both subject to error, though $G$ is normally a small fraction of $R_n$ so that in many studies the efficiency in making good determinations of $G$ is not very important. $\beta$ is subject to the instrument errors in measuring the gradient of temperature and humidity. In a hot climate these errors may be rather large in absolute terms, but the gradients themselves are also rather large, so they can be quite well determined. More important is the error in $\beta$ which arises from inequality of $K_h$ and $K_w$.

To explore the way in which errors in $\beta$ affect LE a short computer program was made to calculate LE at various values of $\beta$ (Appendix 2.3). The result shows (Figure 3.10) that very large errors in $\beta$ can be tolerated when $\beta$ is around zero. But below $\beta = -0.5$ the errors become unacceptable. A similar graph was made by Angus and Watts (1984).

In the present study, $\beta$ did not fall below -0.5. The negative values occur at dawn and dusk when $R_n$ is very low, so that LE is low and does not contribute much to the daily total of water use.

The Bowen ratio method depends on the assumption of equality of the transfer coefficient for heat and water vapour. This assumption seems acceptable in a temperate climate (Tanner and Pelton, 1960; Fritsch, 1965; Denmead and McIlroy, 1970), and in tropical regions with high humidity (Fritsch et al., 1985). However, under semi-arid conditions Blad and Rosenberg (1974) observed an inequality of $K_h$ and $K_w$. This ratio is sometimes as high as 2.3 according to Verma et al. (1978). These authors used lysimetric values as their standard and tried to correlate $K_h/K_w$ with $\Delta T/\Delta e$ (Figure 3.11). The correlation, which was good, was then used to correct the Bowen ratio ($\beta$) to obtain a corrected value.
For the present study, the correlation obtained by Verma et al. (1978) was used to correct the calculated LE (Figure 3.12) for 23/5/86. The exercise indicated that there has been about a 15% under-estimation of LE under strongly advective conditions. A larger error in LE under advective conditions was found by Blad and Rosenberg (1974).

3.5 CONCLUSIONS

Although the Bowen Ratio method is widely used and quite convenient, in the arid zone we approach the limits of its applicability. The most serious errors will occur when $\beta$ is below -0.5 or above +0.5. Errors caused by the inequality of $K_n$ and $K_w$ become large when $\Delta T/\Delta e$ is less than about -0.06 °C kPa$^{-1}$, according to Verma et al. (1978). Such values do occur in the desert. As far as irrigated agriculture in Saudi Arabia is concerned the results suggest:

1. Daily water use by the alfalfa crops about 9 mm day$^{-1}$ in the summer (daylight hour only).
2. There is a good relationship between $R_n$ and LE, but $LE/R_n$ usually exceeds one, and often is in the range of 0.9 to 1.4.
3. Fetch requirement is less than 100 times the crop height.
CHAPTER FOUR

LEAF ENERGY BALANCE
CHAPTER FOUR
LEAF ENERGY BALANCE

4.1 INTRODUCTION

In recent years, several techniques have become available to assess water use on a leaf area basis. This type of approach yields information relevant to the physiologist, and in particular provides quantitative estimates of surface resistances. Stomatal resistance may be especially sensitive to water stress and therefore a good index of when to irrigate. A water-stressed plant is likely to shut its stomata, restricting carbon assimilation as well as water loss.

In this part of the thesis, an attempt is made to estimate diurnal and seasonal transpiration rates and surface conductances from continuous measurements of leaf temperature made on sunlit leaves. It was considered important to compare the conditions of plants in two irrigation regimes (‘spray’ and ‘flood’) and to verify earlier findings of very high stomatal conductances in alfalfa (Van Bavel, 1967; Ehrler and Van Bavel, 1968). There are of course difficulties in sampling the crop as a whole (Huband and Monteith, 1986), but the justification for concentrating on sunlit leaves is that:

1. they are likely to be especially sensitive indicators of any water stress;
2. much of the total transpiration is from them; and
3. the technique is relatively robust when applied to sunlit leaves at least when radiation levels are high.

As the method, involving measurement of leaf temperature, has not been used very widely on crops in arid regions, the purpose of this chapter is mainly to evaluate the technique. In Saudi Arabia there has been much interest in water use by such crops but only lysimetry and some empirical models have been used. Surface conductances have not been calculated.
4.2 BACKGROUND THEORY

Leaf temperature measurements have been used to derive water use and stomatal conductances by several other workers for more than two decades (Raschke, 1960; Gates, 1964; Mellor et al., 1964; Impens, 1966; Hunt, Impens 1968; Taylor and Gates, 1970; Landsberg et al., 1975; Thorpe and Butler, 1977; Althawadi and Grace, 1986; Brough et al., 1986). Water loss from the plant surface can be considered as an energy transaction. The energy balance of a leaf exposed to the sun can be expressed in the following equation:

\[ R_n + LE + C + S + P + G = 0 \]  \hspace{1cm} (4.1)

where

- \( R_n \) is the net flux density of all-wave radiation (W m\(^{-2}\));
- \( LE \) is the latent heat flux (used in the evaporation of water) (W m\(^{-2}\));
- \( C \) is the sensible heat flux (heat lost or gained by convection) (W m\(^{-2}\));
- \( S \) is the storage term which determines the rate at which the energy goes to storage below the transpiring surface (W m\(^{-2}\));
- \( P \) is the rate at which the energy is being trapped in chemical bonds by photosynthesis; and
- \( G \) is the rate of the heat conducted down the petiole (W m\(^{-2}\)).

The sign convention is: energy entering the leaf is positive and energy leaving the leaf is negative, so the algebraic sum of the components is zero.

Some of these terms, such as \( S, P, G \), are relatively small in value for short-term measurements (1 hr) compared to \( LE \) and \( C \). Thus, the energy balance equation applied to a leaf is often simplified by omitting these minor terms; the storage, photosynthetic and conduction terms, to give the energy balance only in terms of latent and sensible heat fluxes as follows:

\[ R_n + LE + C = 0 \]  \hspace{1cm} (4.2)
Those two important components, latent and sensible heat fluxes, may be expressed in terms of a gradient and resistance following Ohms law. The expression of LE can be obtained accordingly:

\[
LE = \frac{\text{Potential gradient}}{\text{resistance}}
\]  

(4.3)

Here, the potential gradient can be considered as the difference in water vapour pressure between the interior of the leaf and the surrounding air instead of the concentration gradient, and the resistance is the sum of the resistances encountered by the water vapour in this path, which are mainly stomatal and boundary layer. Therefore, LE can be written in this form:

\[
LE = \frac{\rho c_p (e_a - e)}{\gamma (r_s + r_{aw})}
\]  

(4.4)

where
- \( \rho \) is the density of the air (1150 g m\(^{-3}\) at 20 °C)
- \( c_p \) is the specific heat of the air (1.015 J g\(^{-1}\) °C\(^{-1}\))
- \( \gamma \) is the psychrometric constant (0.066 kPa °C\(^{-1}\))
- \( e \) is the saturated vapour pressure at the leaf temperature (mbar)
- \( e_a \) is the air vapour pressure (mbar)
- \( r_s \) is the stomatal resistance to water vapour (s cm\(^{-1}\))
- \( r_{aw} \) is the boundary resistance to water vapour (s cm\(^{-1}\))

The rate at which energy is lost by convection (C) is proportional to the difference in temperature between the leaf (\( T_l \)) and the air (\( T_a \)), and inversely proportional to the boundary layer resistance. So the sensible heat loss (or gain) can be expressed as follows:

\[
C = \frac{\rho c_p (T_a - T_l)}{r_{ah}}
\]  

(4.5)

where \( T_l \) and \( T_a \) are leaf and air temperatures respectively in degrees Kelvin (K), \( r_{ah} \) is the boundary layer resistance for heat (cm s\(^{-1}\)). \( r_{ah} \) is a function of leaf dimension and wind speed (Grace, 1977; Campbell, 1977; Grace, 1983). Latent heat fluxes can be
estimated from a direct measurement of leaf temperature of a set of actively transpiring leaves \((T_1)\) and another set of leaves which have been stopped from transpiring \((T_{ln})\) (Impens, 1966; Impens \textit{et al.}, 1967; Thorpe and Butler, 1977).

Equation 4.2 can be rewritten by substituting equations (4.4) and (4.5):

\[
(L_d - \sigma T_1^4 + S_d - S_u) + \rho c_p (e - e_l) + \rho c_p (T_a - T_l) = 0
\]

(4.6)

where

\(L_d\) is the long-wave radiation to the leaf surface (W m\(^{-2}\));
\(\sigma T_1^4\) is the long-wave radiation emitted from the leaf surface;
\(S_d\) is the short-wave by the leaf surface;
\(S_u\) is the short-wave reflected from the leaf surface
\(\sigma\) is the Stefan-Boltzmann constant \((5.67 \times 10^8 \text{ W m}^2\text{K}^{-4})\).

We can also write the energy balance for a similar leaf which is prevented from transpiring \((LE=0)\), by coating the leaf surface with petroleum jelly to prevent all water loss. This substance has been found effective in preventing water loss whilst having negligible effect on leaf physical properties (Butler, 1976). The leaf temperature of the coated leaf \((T_{ln})\) will be different from the transpiring leaf as:

\[
(L_d - \sigma T_{ln}^4 + S_d - S_u) + LE + \rho c_p (T_a - T_{ln}) / r_{ah} = 0
\]

(4.7)

By subtracting the equation for the non-transpiring from that of the transpiring leaf we get the following equation:

\[
\sigma (T_{ln}^4 - T_1^4) + LE + \rho c_p (T_a - T_{ln}) / r_{ah} = 0
\]

(4.8)

\[
LE = \sigma (T_{ln}^4 - T_1^4) - \rho c_p (T_a - T_{ln}) / r_{ah}
\]

(4.9)

With the knowledge of \(T_1\), \(T_{ln}\) and \(R_n\), the energy balance of the leaf can simply and completely be determined following these steps:
(a) Calculating $r_{ah}$ by rearranging equation 4.7, we have

$$r_{ah} = \frac{\rho c_p (T_a - T_{ln})}{R_n}$$

(4.10)

where $R_n$ is the net radiation absorbed by the non-transpirating leaf.

(b) Then sensible heat flux to or from the leaf can be determined:

$$C = \frac{\rho c_p (T_a - T_l)}{r_a}$$

(4.11)

or $C$ can be found by substitution in the energy balance equation (4.2):

$$C = -R_n - LE$$

(4.12)

With the knowledge of $LE$, and $r_a$, the stomatal resistance of an amphistomatous leaf like alfalfa can also be estimated from the following equation, given that the aerodynamic resistance for water vapour $r_{aw} = r_{ah} \times 0.93$ (Grace, 1983).

$$r_s = \frac{(\rho c_p (e_a - e_l)) / LE}{\gamma} - r_{aw}$$

(4.13)

By convention the fluxes and resistances are related to plan area rather than surface area of the leaf. For an amphistomatous leaf, radiation, sensible heat and water vapour are transferred on both surfaces. Stomatal resistance derived like this will be different from $r_s$ measured with a porometer on only one surface, but the same as that measured with other porometers in which both abaxial and adaxial surfaces are exposed within the chamber.

In order to make use of these equations to give an estimate of $LE$, $r_s$, and $r_a$, an accurate measurement of $R_n$, $T_a$, $T_l$, $T_{ln}$, and air vapour pressure ($e_a$) must be made. Then with the aid of a computer program, $LE$, $r_s$ and $r_a$ can be determined.

Physiologists prefer to use conductances, $g_s$ and $g_a$, which are the reciprocals of $r_s$ and $r_a$, on the grounds that fluxes are directly proportional to conductances. Accordingly, results in this chapter are given as conductances. The instruments needed to measure the variables will be discussed later.
4.3 MATERIALS AND METHODS

The methods are considered here in four sections. The first section concerns temperature measurements, for air and leaves. The second section deals with humidity and the third is about radiation measurements. The fourth section deals with the data collection and processing.

4.3.1 Temperature measurements

The success of this method relies greatly on an accurate measurement of leaf temperature. Great care is necessary to select the appropriate method for measuring leaf and air temperature in order to make this source of error as small as possible. In the case of temperature measurement, a small sensor such as a fine thermocouple is recommended. They are very easy to make, can be made in any suitable size, are capable of resolving small differences in temperature, and are easily attached to a leaf using glue from Sellotape (Dixon, 1982).

4.3.1.1 Air temperature

Air temperature in the 1985 season was measured by a thermistor bead (R.S. Components Ltd, Corby; Stock no. 151-243). This was housed in a ventilated tube made of white plastic inside a white plastic radiation shield, and aspirated with a small fan which provided an air flow over the sensor of about $3 \text{ m s}^{-1}$. The aspiration system and the radiation shielding have been extensively tested in this laboratory and used by Wilson et al. (1988). The sensor was excited by a 2-volt source from the data logger. Temperature was calculated by the data logger using the manufacturer’s algorithm based on a fitted polynomial curve, matching the character of the thermistor used. The data logger manufacturer quoted a resolution (over the range from 0 °C to 40 °C) of 0.05 °C and absolute accuracy of ±0.09 °C for temperature measured with this thermistor. Independent calibration was made in the laboratory at Edinburgh is shown in Appendix 1, Figure A1.1, and results of the calibration were subjected to a regression analysis.
linear regression accounted for 99.998% of the total variation (Table 4.1). Confidence limits attached to the slope and intercept indicates an accuracy of +0.1 °C.

**TABLE 4.1:** Analysis of variance of the linear regression obtained from the thermistor calibration (see Appendix 1, Figure A1.1 for data). The output from the thermistor and the standard temperature thermometer (see text) was subjected to linear regression analysis.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>regression</td>
<td>1</td>
<td>723.5</td>
<td>723.5</td>
</tr>
<tr>
<td>error</td>
<td>5</td>
<td>0.16</td>
<td>0.03</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>723.7</td>
<td></td>
</tr>
</tbody>
</table>

**4.3.1.2 Leaf temperature**

Leaf temperatures were measured with fine thermocouples constructed by soldering 42 SWG (0.1 mm in diameter) copper and constantan wires. These were obtained as lacquered PVC insulated conductors from Dural Plastics, NSW Australia. Thermocouples were selected for a number of reasons. Firstly, the small size is very important in obtaining true leaf temperature. Idle (1968) suggested that accurate measurements of temperature may be obtained with thermocouples, or thermistors of the smallest practical dimension.

A second reason for using thermocouples was that several junctions can be wired to a sample or a group of leaves, in parallel to provide measurement of the mean temperature difference between the leaves and the reference junction. This is very important in the field since leaves may vary in their temperature according to their exposure in the canopy. Parallel thermocouple junctions allow the mean leaf temperature to be measured as a single signal, thus permitting a reduction in the number of recording channels in the data logger. To obtain the mean temperature like this the sensors must be the same electrical resistance, and are made using a standard length and thickness of the wire.

Each thermocouple junction was formed by stripping about 5 cm off the sleeving, removing about 1 cm of enamel by dipping in lacquer solvent for two minutes, cleaning
the dipped portion with acetone, twisting and soldering the wires. The final stage was clipping the tip of the soldered junction to the smallest size.

Two sets of five thermocouples were calibrated by the following procedure. The five measuring junctions were immersed in a thermostatically controlled water bath (Grant Instruments, Cambridge; model DP50), whose temperature was controlled by a temperature regulator (model DP35, with cooling system model CC20). The standard was an accurate platinum resistance thermometer (Guildline Instruments, Canada; model 9535), with a resolution of 0.001 °C and a long-term accuracy of 0.035 °C. It was used to measure water bath temperature.

Precautions were taken to ensure that the leads connecting the thermocouples to the data logger were properly insulated and not in contact with water. The water bath temperature was varied in steps from 5 °C to 50 °C. The thermocouples were read by a sold-state-data logger (Campbell Scientific, Utah, USA; model CR21). The single 'reference' junction was maintained at 0.0 °C in a thermos flask filled with a slush of crushed ice and distilled water. To check if the response was symmetrical about 0.0 °C, the junction was interchanged between the ice-slush and water bath. A typical calibration is shown in Appendix 1, Figure A1.2.

The standard calibration coefficient for copper-constantan thermocouples, applicable over 'normal' environmental temperatures, is about 38.8 μV °C⁻¹ (Frischen and Gay, 1979). Over the range 0-50 °C the relationship between temperature and voltage was linear. The regression statistics are given in Table 4.2. They show that for the batch of the wire used for all the measurements reported in this work, the coefficient is 28.15 ± 0.32 °C mV⁻¹, implying a figure in the range 34-36 μV °C⁻¹, slightly different from Frischen and Gray's. The value obtained from each individual calibration was used to convert thermocouple output voltage to a temperature reading.

\[ \text{Temperature difference (°C) = 28.17} \times \text{voltage (mV)} - 0.61 \]
After calibration the reference junction was put inside the aspirated, radiation-shielded unit, alongside the thermistor. This reference junction thus was at a known air temperature (sensed by the thermistor). The 'measure' junctions were five parallel junctions attached to this single reference, each of them fixed to the lower surface of a leaf using Sellotape glue. The way of attaching a thermocouple to a leaf surface is described elsewhere (Dixon, 1982; Althawadi, 1985).

**TABLE 4.2:** Regression statistics for the calibration of the thermocouples. The temperature difference between the reference and the measuring junction was raised in steps from 0.0 °C to 50 °C, and the voltage (mV) noted. The result was subjected to a linear regression analysis (r² = 0.997). The slope is the calibration coefficient in °C mV⁻¹.

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>slope (± SD)</th>
<th>intercept (± SD)</th>
<th>F. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>set 1</td>
<td>28.15 (0.32)</td>
<td>-0.60 (0.3)</td>
<td>7561.88</td>
</tr>
<tr>
<td>set 2</td>
<td>28.2 (0.30)</td>
<td>-0.62 (0.29)</td>
<td>7524.50</td>
</tr>
</tbody>
</table>

**4.3.1.3 Solarimeter and its calibration and use**

Short-wave radiation is defined as the waveband 0.3-3.0 μm. A tube solarimeter was made for measuring this radiation in the field. It consists of sensing elements composed of a thermopile made from thin wires of constantan wound on a small piece of plastic sheet, as described in Szeicz et al. (1964). In the present case, this sensing element was shielded by two thick test tubes working as a double glass filter and mounted on a perspex plate 4 cm wide, 26 cm long and 4 mm thick. It has a handle of 26 cm long. A spirit level is included to provide accurate levelling during the field use.

This solarimeter was tested against a Moll-Gorzynski Pyranometer (Kipp solarimeter) twice, first in the growth cabinet with only one glass filter, in which the output was found to vary with temperature. Therefore a double glass shield was then provided. Then the solarimeter was again tested and found to agree well with the Kipp solarimeter. In a Kipp solarimeter the double glass dome is used to reduce convective heat transfer...
from the thermopile to the air. Those heat losses would tend to increase as the temperature
difference between the thermopile and air increases.

The two solarimeters were taken outdoors on a sunny day on October 1984 and their
outputs compared with that of the Kipp solarimeter (Appendix 1, Figure A1.4).
Orientation of the tube was north to south, it was mounted horizontally, and 15 minute
means of a series of 10-15 scans using the CR21 micrologger were used.

4.3.1.4 Net radiation

Net radiation or the balance between the incoming and the outgoing radiation
(available energy) was measured by a home-made net radiometer. The sensing element
was made with constantan wires as described by Szeicz et al. (1964), but winding onto
a 44 x 10 mm perspex former. The domes are polythene as supplied for a net radiometer
by Didcot Instruments (Figure 4.1). The general design of the holder was copied from

Two metal domes were used as a chamber to calibrate this net radiometer. These
domes were painted internally with velvet black paint with an emissivity of 0.98. The
calibration procedure is as follows. One of the domes is immersed in a water bath at a
known temperature and the net radiometer placed in the centre of a circle made by the
lip of the dome and covered by the upper dome. The temperature of both domes is
measured by attaching thermocouples on the inner surface. The output is recorded and

---

**FIGURE 4.1:** Diagram showing the components of the home-made radiometer.
plotted against the calculated net radiation using an approximation given by Monteith (1973) (Appendix 1, Figure A1.4):

\[ R_n = 4 \sigma T_b^3 (T_t - T_b) \]

Where \( \sigma \) is the Stefan Boltzmann constant, \( T_b \) is the bottom dome surface temperature (K), \( T_t \) is the top dome temperature.

### 4.3.1.5 Humidity sensor

A humidity sensing circuit was assembled in the laboratory, using a capacitor sensor obtained from Mullard Limited, Torington Place, London SC1E 7HDT. It consisted of a perforated plastic case containing a stretched membrane of non-conducting foil, coated on both sides with gold. The membrane and the coating form respectively, dielectric and electrodes of a parallel plate capacitor whose capacity (41 pF) depends on the ambient humidity. This sensor is connected to a circuit that generates 10-12 dc voltage which is used to activate a meter.

The humidity sensor was calibrated at several ambient temperatures by a humidity generator type WG6000 (The Analytical Development Co. Ltd). The humidity generator was used to produce a range of saturated vapour pressures at different temperatures. Percentages of any SVP can be produced by use of mixing dials. The output (mV) is plotted against the percentages of SVP, i.e. the relative humidity (Appendix 1, Figure A1.6).

At first, there were variations in sensor output which were found to be caused by a capacitance effect within the circuit. Thereafter the circuit was placed inside a box connected to the ground and calibrated again with the same method.

The sensor output (mV) was proportional to the relative humidity, but when the hysteresis test was carried out by adjusting the humidity first by increasing, then by decreasing the reading, it was found to vary by about 2.5%. Also, the temperature test
was performed by changing the temperature of the circuit and holding sensor temperature stable. The reading changed by 0.5% for a temperature change of 20 °C.

4.3.1.6 Anemometer

Windspeed was measured by a cup anemometer (Porton type, Vector Instruments). This also was calibrated in the wind tunnel (Appendix 1, Figure A1.5).

4.3.1.7 Data collection 1 m above the crop and analysis

All sensors mentioned were connected to a data logger type CR21 (Campbell, Utah), programmed so all the signals were converted to the exact units using the multiplier for each instrument calibration factor. The logger was set to store integrations over a period of 30 minutes, so that in all about 24 readings accumulated each day.

The equipment worked satisfactorily most of the time, despite difficulties during high temperature and wind speed. In this case, detachment of thermocouples occurred, especially with non-transpiring leaflets. During hot days lethal temperatures happened with vaselined leaflets. Such data were discarded.

4.3.1.8 Data analysis

Two programs are available in Edinburgh to analyse and plot both the raw and derived data, provided the raw data consists of \( R_{n}', T_a, T_{ln}, T_{l}' e_a \). The derived quantities are \( C, LE, g_a, g_s \).

4.4 RESULTS

4.4.1 Description of the microclimate

Solar radiation rose rapidly in the morning to about 1000 W m\(^2\) at solar noon (Figures 4.2-4.5 and 4.6-4.9). Sometimes the regular trend was disrupted by clouds (Figures 4.6, 4.8).
FIGURE 4.2: Diurnal values of (a) incoming solar radiation flux ($S_{d}$) and net radiation ($R_{n}$); (b) measured air temperature ($T_{a}$) and derived vapour pressure deficit between the leaf and surrounding air (VPD); (c) wind speed at 1.5 m above the ground ($u$) and air-to-leaf temperature differences ($T_{a} - T_{l}$); (d) calculated stomatal conductance ($g_{s}$) and aerodynamic conductance ($g_{a}$); (e) calculated latent heat flux (LE) and sensible heat flux (C) of alfalfa leaves determined on field-grown plants. These graphs represent a sunny day (19/4/85), on a surface irrigation area.
FIGURE 4.3: These graphs represent data collected on 20/4/85. For detailed information, see Figure 4.2.
FIGURE 4.4: These graphs represent data collected on 21/4/85. For detailed information, see Figure 4.2.
FIGURE 4.5: These graphs represent data collected on 22/4/85. For detailed information, see Figure 4.2.
FIGURE 4.6: These graphs represent data collected on 26/4/85 from a field where sprinkler irrigation was used. For detailed information, see Figure 4.2.
FIGURE 4.7: These graphs represent data collected on 27/4/85. For detailed information, see Figures 4.6 and 4.2.
FIGURE 4.8: These graphs represent data collected on 30/4/85. For detailed information, see Figures 4.2 and 4.6. The positive LE in the late afternoon may have been caused by passage of the irrigation arm over the crop.
FIGURE 4.9: These graphs represent data collected on 2/5/85. For detailed information, see Figures 4.2 and 4.6.
TABLE 4.3  Maximum and minimum values of $S_d$, $R_n$, $T_a$, VPD and $u$ during selected days, for the two irrigation types (a) surface and (b) spray. Each value represents half hourly mean of a series of 5-10 scans.

<table>
<thead>
<tr>
<th>Irrigation used</th>
<th>Day</th>
<th>$S_d$ W m$^{-2}$</th>
<th>$R_n$ W m$^{-2}$</th>
<th>$T_a$ °C</th>
<th>VPD (kPa)</th>
<th>$u$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) 19/4 Max</td>
<td></td>
<td>1010.0</td>
<td>677.0</td>
<td>31.0</td>
<td>3.10</td>
<td>1.7</td>
</tr>
<tr>
<td>Time</td>
<td></td>
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<td>12.00</td>
<td>14.30</td>
<td>13.30</td>
<td>13.00</td>
</tr>
<tr>
<td>Min</td>
<td></td>
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<td>-32.5</td>
<td>10.5</td>
<td>0.40</td>
<td>0.0</td>
</tr>
<tr>
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<td></td>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>8-12</td>
</tr>
<tr>
<td>(a) 20/4 Max</td>
<td></td>
<td>1055.0</td>
<td>736.0</td>
<td>32.0</td>
<td>3.00</td>
<td>3.4</td>
</tr>
<tr>
<td>Time</td>
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<td>12.00</td>
<td>13.30</td>
<td>12.00</td>
<td>11.00</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>21.0</td>
<td>-27.3</td>
<td>11.2</td>
<td>0.17</td>
<td>0.6</td>
</tr>
<tr>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>(a) 21/4 Max</td>
<td></td>
<td>1000.0</td>
<td>728.0</td>
<td>31.5</td>
<td>3.09</td>
<td>3.8</td>
</tr>
<tr>
<td>Time</td>
<td></td>
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<td>12.00</td>
<td>14.00</td>
<td>12.00</td>
<td>11.00</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>53.0</td>
<td>-27.9</td>
<td>15.3</td>
<td>0.60</td>
<td>0.4</td>
</tr>
<tr>
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<td></td>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>9.00</td>
</tr>
<tr>
<td>(a) 22/4 Max</td>
<td></td>
<td>907.0</td>
<td>657.0</td>
<td>33.6</td>
<td>2.90</td>
<td>5.8</td>
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<td>10.30</td>
<td>10.30</td>
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<tr>
<td>Min</td>
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<td>69.50</td>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>(b) 26/4 Max</td>
<td></td>
<td>966.0</td>
<td>666.0</td>
<td>30.30</td>
<td>3.20</td>
<td>4.40</td>
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<tr>
<td>Time</td>
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<td>12.00</td>
<td>14.00</td>
<td>11.30</td>
<td>14.00</td>
</tr>
<tr>
<td>Min</td>
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<td>7.6</td>
<td>9.9</td>
<td>0.21</td>
<td>0.5</td>
</tr>
<tr>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>(b) 28/4 Max</td>
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<td>721.0</td>
<td>682.0</td>
<td>30.6</td>
<td>2.80</td>
<td>5.8</td>
</tr>
<tr>
<td>Time</td>
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<td>14.30</td>
<td>11.30</td>
<td>10.30</td>
</tr>
<tr>
<td>Min</td>
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<td>39.0</td>
<td>-3.2</td>
<td>13.8</td>
<td>2.70</td>
<td>0.3</td>
</tr>
<tr>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>7.00</td>
</tr>
<tr>
<td>(b) 1/5 Max</td>
<td></td>
<td>998.0</td>
<td>693</td>
<td>30.5</td>
<td>3.28</td>
<td>4.6</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td>12.00</td>
<td>12.00</td>
<td>14.00</td>
<td>11.30</td>
<td>8.30</td>
</tr>
<tr>
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<td>53.0</td>
<td>-7.6</td>
<td>13.3</td>
<td>0.45</td>
<td>0.7</td>
</tr>
<tr>
<td>Time</td>
<td></td>
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<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
</tr>
<tr>
<td>(b) 2/5 Max</td>
<td></td>
<td>895.0</td>
<td>620.0</td>
<td>34.4</td>
<td>2.65</td>
<td>2.2</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td>12.30</td>
<td>13.30</td>
<td>13.30</td>
<td>11.30</td>
<td>11.30</td>
</tr>
<tr>
<td>Min</td>
<td></td>
<td>70.0</td>
<td>-1.1</td>
<td>14.9</td>
<td>0.48</td>
<td>0.31</td>
</tr>
<tr>
<td>Time</td>
<td></td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>6.00</td>
<td>7.00</td>
</tr>
</tbody>
</table>
Net radiation over the surface irrigation plot on the same days gave similar daily patterns, the daily variations being almost identical to that of solar radiation (see Chapter 2). The maximum net radiation over the sprinkler-irrigated plot seemed to be lower than that over the surface irrigated plot (Table 4.3), but no great significance can be attached to this small difference as the observations were on different days. Net radiation values at noon reached over 650 W m\(^{-2}\), but this value fluctuated according to the stage of crop and the presence of clouds.

Both air temperature and VPD display daily trends starting with low values in the early morning and increasing gradually (Figures 4.2-4.5 and 4.6-4.9). VPD peaked at about the same time as solar radiation. Air temperature lagged by one or two hours behind radiation (Table 4.3). The maximum values recorded for \(T_a\) were recorded between 12.30-14.30 hrs, while the maximum for VPD was between 11.30-13.30 hrs. Solar noon at this time of the year and at this place is close to 12.00 hrs Saudi Arabian time.

Leaf temperature was lower than the corresponding air temperature most of the time (Figures 4.2-4.9C). There are some occasions where the leaf temperature exceeded air temperatures, especially during the early morning and sometimes during the middle of the day (Figure 4.4 and 4.7). The leaf temperature of the surface irrigation plot seemed to be higher than the plants irrigated with the sprinkler. The differences between leaf and air temperature indicate that the leaf may be four degrees lower than air temperatures (Figure 4.16). This drop in leaf temperature is likely to affect the microclimate of the whole crop, leading to a temperature inversion.

Wind speed was variable during the measurement (Table 4.3). The peak value fluctuated with a maximum of 5.8 m s\(^{-1}\).

### 4.4.2 Leaf energy budget

The latent heat flux \(LE\) dominated the energy balance during much of the day (graph E in Figures 4.2 to 4.9). A good correlation between LE and \(R_n\) was found which
indicates a dependence of LE on the net radiation under these conditions (Figure 4.10A). These correlations are presented for both irrigation types and indicate little variation between the two irrigation treatments.

4.4.3 Latent and sensible heat fluxes

It was found that diurnal trends in LE follow the diurnal changes in $S_d$ and $R_n$, starting with small values in the early morning and peaking at about 10-11.30 hrs when they attain 800 W m$^{-2}$ or even exceed 1000 W m$^{-2}$ (Figure 4.3E). In the surface irrigation site (graphs E in Figures 4.2-4.5), where four consecutive days are presented, LE increased gradually to a maximum value at 11.00 hrs, then showed a reduction to 50-100 W m$^{-2}$ and fluctuated around this value throughout the afternoon until 15.00 hr where a sharp decrease was observed. The sensible heat fluxes are also presented. The sensible heat values indicate positive sensible heat fluxes, i.e. the delivery of sensible heat to the leaves, from the atmosphere (Figures 4.2E and 4.5E). In Figures 4.3-4.5, the same trend is apparent, but in these days there was a greater depression of LE at noon, increasing again later in the afternoon. LE reached a maximal value of around 1200 W m$^{-2}$, which is approximately 1.4 mm hour$^{-1}$. As mentioned earlier, in Section 4.3.1, the microclimatic conditions promote a high rate of water loss, since saturation vapour pressure deficits are high and water is freely available.

Representing the sprinkler irrigation regime, four days are presented (Figures 4.6E-4.9E). Maximum latent heat fluxes were somewhat lower with this system, but there were similar diurnal trends. The general response was similar to the surface irrigation site. On day 2/5/85, there was no depression during the afternoon, indicating a very similar response to that displayed at the surface irrigation treatment on 19/4/85.

The LE values obtained for sprinkler irrigation were a little lower than those for surface irrigation. The depression recorded on 26/4/85 was caused by cloud cover at that time of the day.
FIGURE 4.10: (A) The relation between the latent heat flux (LE) and net radiation (R_n), in both irrigation types (surface irrigation, o, and sprinkler, x).

(B) The relation between calculated stomatal conductance (g_s) and measured solar radiation (S_d).

The two graphs represent data collected on four sunny days where both R_n and S_d were measured 1 m over the ground surface. A and B represent the same days, the dates being (a) 22/4/85 and 2/5/85; (b) 21/4/85 and 30/4/85; (c) 20/4/85 and 26/4/85; (d) 19/4/85 and 1/5/85; where the first day is a surface irrigation and the second is a sprinkler irrigation, respectively. The pairing of days for comparison is arbitrarily made.
Relationships between LE and $g_s$ for the irrigation sites are shown in Figure 4.11A. The values here are mostly for radiation fluxes over 200 W m$^{-2}$ which represent values taken from 8.00 to 15.30 hrs. Low values were rejected because stomata were not fully opened at this time of day and there may have been some dew. The correlation coefficient ranged from 0.98 to 0.87 for both treatments.

4.4.4 Behaviour of stomatal conductance

The behaviour of stomatal conductance is shown in graphs D in Figures 4.2 to 4.9. Stomatal conductance ($g_s$) was found to display diurnal variation. It increased as the light increased, and reached a first peak some time before solar noon, especially in the case of flood irrigation, then increased immediately after solar noon to give another peak later, around 1530 hrs.

In five days out of eight there was clear evidence of partial stomatal closure in the middle of the day. In two of the remaining days (26/4/85 and 30/4/85, Figures 4.6 and 4.8), the conductance displayed rather erratic behaviour, sometimes falling to zero. Both of these days were characterised by some cloud, and the low conductances associated with low irradiances. On the first of these days the decline in irradiance was large enough to lead one to expect a decline of conductance to a very low level. On the second of these days the decline of conductance was much less and the zero conductance is surprising. The decline occurred at a time when the air temperature sensor recorded a change of 6 °C within 30 minutes. This may have been associated with a change in wind direction. The overall measuring system works best when changes are not rapid, as a result of somewhat different time constants for sensors and leaves. Thus, this extreme conductance may not be a reliable observation. The $g_s$ values obtained in this study ranged between 0.01 and 3.5 cm s$^{-1}$.

The differences in the stomatal conductances between the two irrigation types are presented in Figure 4.10B. There is a tendency for $g_s$ to be higher in the flood irrigation (this occurs in three days out of four). In the flood irrigation it reached 3.5 cm s$^{-1}$, while
FIGURE 4.11: (A) The relation between LE and $g_s$.

(B) $(T_a - T_r)$ and $g_s$ for the two irrigation types, surface flooding (o) and sprinkler (x). For more details see text and Figure 4.10.
$g_s$ in the spray irrigation was around 2.0 cm s$^{-1}$, except on 27/4/85 when a higher value was recorded.

Part of the variability in $g_s$ values was caused by the daily variation in $S_d$, VPD, $T_a$, whilst some may have been due to instrumental errors. In general, an increase in $g_s$ with increasing solar radiation was observed (Figure 4.10B), but this increase may depend on VPD and temperature. In the flood irrigation, high $g_s$ coincides with the low VPD values at full sunlight, and since VPD and $T_a$ are correlated the depression during the middle of the day may be caused by high temperatures and VPD.

Stomatal conductance is strongly correlated with LE (Figure 4.11A). All graphs a,b,c and d indicate a good correlation between LE and $g_s$ in both irrigation types. LE in these graph is apparently not limited by $g_s$: as the stomata open fully the transpiration is usually a function of the differences in VPD and the available heat represented by the net radiation $R_n$. The difference between the two irrigation types as mentioned earlier is not large.

The relationship between $(T_l-T_a)$ and $g_s$ was, as expected, a strong negative correlation, reflecting the primary influence of $g_s$ on the energy balance of the leaf. The slope of this relationship may be expected to vary according to the values of the other parameters of the energy balance equation.

An attempt was made to relate $g_s$ to solar radiation and VPD using the model of Jarvis (1976). This involved parameter optimisation by a least squares procedure. The raw data from Figure 4.10B suggested that the conductance increases with $S_d$ and decreases with the leaf-to-air VPD, though there is considerable scatter. It was not possible to fit the model satisfactorily, as the variables $S_d$ and VPD were so highly correlated. In the parameter optimization, the parameter values would not converge.

The boundary layer conductance was obtained from equation (4.11). It was sometimes larger and sometimes smaller than $g_s$. There is a good correlation between $g_a$ and wind speed (Figure 4.12). The relationship between wind speed and boundary layer conductance, based on the leaf dimension (where heat transfer occurs on both adaxial and
FIGURE 4.12: The relation between wind speed and the boundary layer conductance between the leaves and the surrounding air. The line is calculated from work on model leaves in wind tunnels. (Grace, 1983).
abaxial surfaces of the leaf) is shown in Figure 4.12. This theoretical relationship comes from work in wind tunnels using model leaves and near-laminar flows (Grace, 1981). The discrepancy between the 'theoretical' and observed values from the field data was ascribed to highly turbulent air movement over the surfaces. Heat transfer in the field is often higher than that observed in wind-tunnel experiments using laminar flow, sometimes by a factor of two (Grace, 1981).

4.4.5 Error estimates

The probable error in the estimate of LE and $g_s$ was calculated by selecting a standard run and varying the independent variables by a specified amount to simulate the effect of a measurement error which might have been the result of, for example, a faulty calibration. The variables are $R_n$, $T_1$, $T_a$. The percentage measurement error in $R_n$ was assumed to be from +20% to -20%, $T_a$ and $T_1$ from +1 °C to -1 °C. It is assumed that every possible error in the defined band will occur with equal probability, though presumably the extreme errors are less probable than the small errors, and perhaps a Gaussian distribution of probabilities should be assumed. The results of these separate measurement errors were plotted in Figure 4.13.

To explore the limits of the worst possible combination of errors, the calculation was repeated to cover 5400 permutations of errors. It was thought reasonable to define the central two-thirds of the results as the possible combination error. If anything, this approach will over-estimate the seriousness of errors, because of the assumption of equal probabilities, mentioned in the preceding paragraph.

When applied to a particular day, this exercise provided us with an estimate of the errors in our calculated LE and $g_s$ which might occur as a result of all the measurement errors acting together. The conclusion is that between 09.00 and 15.00 hrs the possible combination error is ±20% (Figures 4.14 and 4.15). But in the early morning and late afternoon, the errors become substantial and the calculated values of LE and $g_s$ can no longer be relied upon.
FIGURE 4.13: The calculated errors in LE and $g_s$ that would arise from specified measurement errors in the input variables $R_n$, $T_l$, $T_a$. The standard run was on date 02/5/85 at 12.00 hrs; ($R_n = 604 \text{ W m}^{-2}$; $T_a = 34.24 ^\circ \text{C}$; $T_l = 33.04 ^\circ \text{C}$; $T_{ln} = 37.66 ^\circ \text{C}$; svpd = 27.04 mb)
FIGURE 4.14: Error in the calculation of LE induced by inserting into the calculation many (5400) combinations of probable measurement errors. The errors in the calculated results are shown as a frequency distribution using error intervals of 10%. For example at 9.00 am, nearly all the errors lie within -30% and +30% of the values given in the standard run (the measured values for that time of the day).
FIGURE 4.15: Error in the calculation of $g_s$ induced by inserting into the calculation many (5400) combinations of probable measurement errors. The errors in the calculated results are shown as a frequency distribution using error intervals of 10%. For example at 9.00 am, nearly all the errors lie within -30% and +30% of the values given in the standard run (the measured values for that time of the day).
4.5 DISCUSSION

4.5.1 Evaluation of the technique

The technique has yielded estimates of transpiration rates and surface conductances. Even though these estimates are only for five sunlit leaves at the top of the canopy, they are nevertheless useful as they furnish continuous values over the course of the day, and thus provide greater temporal resolution than many other methods. They enable correlations to be made between conductances and climatological variables, as for example, between \( g_a \) and wind speed. Unfortunately, the climatological variables in this case are highly intercorrelated, especially VPD and radiation, and attempts to fit a model to the stomatal response to the variable VPD and radiation failed. The error analysis suggests that the estimates of LE may be within 20% of real value when \( R_n \) is high (between 09.00 to 15.00 hrs). Probably the biggest measurement error is in \( R_n \). This is because the sensor measures \( R_n \) for the crop as a whole, which is unlikely to be the same as for the individual leaf. It is particularly difficult to estimate \( R_n \) for leaves which display heliotropic movements, as alfalfa does.

4.5.2 Daily variation in the fluxes

Under field conditions, transpiration followed solar radiation, but all the other environmental conditions also tended to be related to the solar radiation. Daily variation in LE was found for alfalfa under these well-watered conditions, and there were only minor differences between the two irrigation types. It is apparent that the leaves transpire freely with little difference in the amount of transpiration, except during periods of high vapour pressure deficit and high temperature (Figures 4.3E-4.5E). A depression in transpiration rates of well-watered plants under high insolation has been reported to be associated either with high temperature or low humidity, both causing a decreased stomatal closure (Grace et al., 1975; Milford and Lawlor, 1975; Squire and Black, 1981; Cock et al., 1983). However, the depression in LE in stressed plants is usually associated with

Alfalfa has been described as a 'water spender', high evapotranspiration (ET) having been reported by Hudson (1965). In his study, ET reached 23 mm day\(^{-1}\) in a semi-arid region (Sudan). Van Bavel (1967) found that this plant did not show any restriction in its water loss until soil water potential reached -0.4 MPa. Kerr and McPherson (1978) recorded 6.6 mm day\(^{-1}\) under field conditions, higher values were reported by Saeed and Abdulaziz (1985), 13 mm day\(^{-1}\). In Saudi Arabia, 16 mm day\(^{-1}\) was recorded during summer time, while in winter the value decreased to two-thirds of this value (Saeed, 1987). This recent work is based on lysimetric determination of ET on a small area of land, and the possibility of advection is very great. The values obtained in the present work are similar to the values reported in the literature, in the range 11 to 21 mm day\(^{-1}\) (Table 4.4).

Such high ET values need a source of energy for evaporation of water. Inspection of Figures 4.2 to 4.9 shows that the ratio of LE/R\(_n\) exceeded unity, indicating that energy as sensible heat is transferred to the leaves during the process of transpiration.

An attempt to relate \(g_s\) to environmental variables did not succeed, and laboratory experimentation is required to elucidate the separate influence of VPD and radiation (Chapter 5).

4.5.3 Latent heat and leaf temperature

Quite recently leaf temperature has been used widely as an indicator of plant water stress (Jackson, 1982; Kirkham et al., 1983; Throssel et al., 1984; Huband and Monteith, 1986). High transpiration rate reduces the leaf temperature and in desert areas the VPDs are often 40 mbars and the leaf temperature is generally cooler than the surrounding air. Leaf-to-air differences (\(T_\text{l} - T_\text{a}\)) reached -15 °C in some desert plants (Gates, 1980), and for crop plant \(T_\text{l} - T_\text{a}\) was reported in cotton to be -7 °C (Wiegand and Namken, 1969; Bartholic et al., 1972). This depression in (\(T_\text{l} - T_\text{a}\)) is associated with the magnitude of
FIGURE 4.16: (A) The relation between LE and \( (T_l - T_a) \).
(B) The relation between \( (T_l - T_a) \) and leaf to air vapour pressure differences. For more details see text and Figure 4.10.
the VPD and is expected to be negatively correlated with it. In fact, the relationship is practically a random scatter (Figure 4.16B) because transpiration is much more tightly linked to the radiation flux.

Irrigation was reported to influence leaf temperature in the alfalfa crop (Donovan and Meek, 1983). They recorded $T_1$ of stressed plants to be +7 °C higher than unstressed plants. Kirkham et al. (1983) reported a similar result with wheat under dry weather but not during wet weather.

### TABLE 4.4: Integration of half hourly values of evapotranspiration expressed in $(Wm^{-2})$ and in mm (30 minutes)$^{-1}$. Date: 2/5/85, given as example.

<table>
<thead>
<tr>
<th>Time</th>
<th>-LE $(Wm^{-2})$</th>
<th>ET (mm(30 minutes)$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.00</td>
<td>26.0</td>
<td>0.04</td>
</tr>
<tr>
<td>7.30</td>
<td>92.0</td>
<td>0.13</td>
</tr>
<tr>
<td>8.00</td>
<td>225.0</td>
<td>0.32</td>
</tr>
<tr>
<td>8.30</td>
<td>342.0</td>
<td>0.48</td>
</tr>
<tr>
<td>9.00</td>
<td>512.0</td>
<td>0.72</td>
</tr>
<tr>
<td>9.30</td>
<td>663.0</td>
<td>0.94</td>
</tr>
<tr>
<td>10.00</td>
<td>853.0</td>
<td>1.20</td>
</tr>
<tr>
<td>10.30</td>
<td>826.0</td>
<td>1.17</td>
</tr>
<tr>
<td>11.00</td>
<td>865.0</td>
<td>1.22</td>
</tr>
<tr>
<td>11.30</td>
<td>865.0</td>
<td>1.22</td>
</tr>
<tr>
<td>12.00</td>
<td>846.0</td>
<td>1.19</td>
</tr>
<tr>
<td>12.30</td>
<td>826.0</td>
<td>1.17</td>
</tr>
<tr>
<td>13.00</td>
<td>652.0</td>
<td>0.92</td>
</tr>
<tr>
<td>13.30</td>
<td>783.0</td>
<td>1.10</td>
</tr>
<tr>
<td>14.00</td>
<td>762.0</td>
<td>1.07</td>
</tr>
<tr>
<td>14.30</td>
<td>650.0</td>
<td>0.92</td>
</tr>
<tr>
<td>15.00</td>
<td>523.0</td>
<td>0.74</td>
</tr>
<tr>
<td>16.00</td>
<td>400.0</td>
<td>0.56</td>
</tr>
<tr>
<td>16.30</td>
<td>-172.0</td>
<td>-0.24</td>
</tr>
<tr>
<td>17.00</td>
<td>-25.0</td>
<td>-0.04</td>
</tr>
<tr>
<td>17.30</td>
<td>00.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

| Total | 14.83 |
| Mean  | 500.8 |

Direct stomatal response to the separate environmental factors, such as temperature, is very difficult to substantiate due to confounding between these factors. Leaf
temperature is correlated to LE, which is not surprising because (a) as leaf temperature increases, VPD increases, and (b) stomatal conductance may be influenced by temperature. Differences between leaf and air temperature were reported to be correlated to $g_s$ for individual leaves (Idso and Reginato, 1982). In that study it was found that, taken once a day at noontime, $g_s$ can be used as an indicator of water stress. It is interesting to find a similar relation for the data taken when radiation is not limiting stomatal opening (Figure 4.11B) in both irrigation treatments (this figure uses data taken when solar irradiance exceeded 200 Wm$^{-2}$).

Crop surface temperature was suggested to be a useful tool in predicting ET by inserting the differences in $(T_s - T_a)$ in an energy balance equation based on calculating ET from surface temperature measurement (Stone and Horton, 1974; Blad and Rosenberg, 1974, 1976; Geiser et al., 1982; Huband and Monteith, 1986).

### 4.5.4 Stomatal conductance

The method used here to obtain stomatal conductance depends on calculation of LE, the vapour pressure difference $(e_a - e_i)$ and the estimation of boundary layer conductance. Other work suggests that the method is apparently capable of making quite good estimates of stomatal conductance, probably just as good as the use of a porometer (Althawadi, 1985).

There are substantial diurnal variations in $g_s$. The maximum value obtained in the field here is very high compared to other values reported for field crops (Denmead and Millar, 1976; Wallace et al., 1981; Grace, 1980; Jones, 1983). Kerr and McPherson (1978) reported a maximum value of $g_s$ for alfalfa of 0.38 cm s$^{-1}$. While a higher value was obtained by Van Bavel (1967), 2.1 cm s$^{-1}$, Hodgkinson (1974) and Carter and Sheaffer (1983) reported a lower value of 1.8 cm s$^{-1}$. The values found here range from 0.01 to 3.5 cm s$^{-1}$. Figure 4.10B shows that $g_s$ increases with irradiance but this response is scattered. The light response is consequently not clear and it will be re-examined in Chapter 5.
CHAPTER FIVE

MODELLING LEAF GAS EXCHANGE
5.1. INTRODUCTION

Stomata normally exert a controlling influence on transpiration and to a lesser extent on photosynthesis. The interplay between the two types of gas exchange (H₂O and CO₂) may be studied in the laboratory by enclosing single leaves in a cuvette and measuring CO₂ and H₂O transfer between the leaf and the air. A large body of such data can be conveniently summarised by fitting a model to the data, such that the CO₂ or H₂O flux, or their ratio, may subsequently be estimated for any defined environment.

The aim in fitting a model to the data is primarily to provide a means of describing the response of gas exchange to environmental variables. The possibility of employing simply a statistical model (based on regression) was rejected in favour of a model which contains physiologically meaningful parameters which can be compared with those of other species, or could be used in any future studies of genotype variation within the species. It was considered that such a model could form part of a canopy model, though this would require profiles of environmental variables within the canopy, and this step of ‘scaling up’ is outside the scope of the present work. It is for the future. Here, it should however be borne in mind that the usefulness of a model derived from laboratory experiments is limited by (i) the differences in the growing conditions of field and laboratory plants; (ii) the requirement for adequate statistical sampling of leaves; and (iii) the extent to which the ‘scaling up’ exercise can be thoroughly done. The alternative, to concentrate only on field observations, has other disadvantages.

Similar gas exchange data may arise from measurements in the field, and such data may be subjected to the same process of model-fitting. However, field data are not always amenable to this approach because of (a) their poorer quality, (b) intercorrelation of variables, and (c) the influence of uncontrolled and unmeasured variables (e.g. attack by
pests or storm action) which create 'noise'. On the other hand, laboratory or glasshouse plants may have somewhat different responses from field-grown plants as a result of different acclimation histories.

Stomatal response to environmental variables is extremely complex as emphasised by several reviewers (Turner, 1974; Biscoe et al., 1975; Burrows and Milthorpe, 1976; Jarvis, 1976; Grace, 1977). A comprehensive explanation of the mechanisms of stomatal responses is elusive, and beyond the scope of the present work.

The purpose of the work in this chapter was to study and describe gas exchange in controlled conditions, using the results as a means of estimating water use efficiency.

5.2 BACKGROUND TO MODELLING

It is now known that stomatal conductances of many species are affected by light, humidity and temperature (see reviews by Burrows and Milthorpe, 1976; Hall, Schulze and Lange, 1976), but the ecological implications of this have not been thoroughly explored for the case of arid-zone agriculture. In alfalfa field grown plants (Chapter 4), it was not possible to elucidate stomatal responses to light and VPD because the two variables were correlated.

The stomatal response to both photon flux density and VPD are important in development of modelling $g_s$ response to the environmental factors. There are several models used to predict stomatal conductance, some are based on one environmental factor (photon flux density, see Thorpe et al., 1980; Callander and Woolhead, 1980), while other models are based on more than one environmental parameter. A model with two environmental parameters was reported by Squire and Black (1979). However, a more complex model which used five parameters was described by Jarvis (1976); these parameters were light, temperature, vapour pressure deficit, carbon dioxide concentration, and leaf water potential. In the present study, a model similar to that of Jarvis (1976) was used to fit the stomatal conductance using a non-linear least squares method to estimate its parameters (see fitting model).
5.2.1 Model of stomatal conductance

The relation between stomatal conductance \( g_s \) (\( \mu \text{mol m}^{-2}\text{s}^{-1} \)) and photon flux density \( \phi \) (\( \mu \text{mol m}^{-2}\text{s}^{-1} \)) has been shown to be adequately described by a rectangular hyperbola (Jarvis, 1976; Whitehead et al., 1981; Grace et al., 1982; Kwesiga et al., 1986):

\[
g_s(\phi) = \frac{P_1 \phi P_2 + P_3}{P_1 + P_2 \phi} \tag{5.1}
\]

where \( P_1 \) is the maximum stomatal conductance (\( \text{mmol m}^{-2}\text{s}^{-1} \)), \( P_2 \) is the initial slope of the relationship between photon flux density and \( g_s \) (dimensionless), and \( P_3 \) is the stomatal conductance in the darkness (\( \text{mmol m}^{-2}\text{s}^{-1} \)).

This equation can be combined with another which describes the reduction in \( g_s \) caused by the leaf to air vapour pressure difference (\( V \)) as found by Grace et al. (1975), Neilson and Jarvis (1975) and Watts et al. (1976).

This has been described by Jarvis (1976):

\[
g_s(V) = 1 + P_4 (V - P_5) \tag{5.2}
\]

where

- \( P_4 \) is the rate at which \( g_s \) changes with \( V \) (\( \text{mmol m}^{-2}\text{s}^{-1}/\text{kPa} \))
- \( P_5 \) is the adjustment to \( V \) required to set \( g_s \) to 1 where \( V = 0 \).

The combination of the above two formulae was used to describe the stomatal response to both \( \phi \) and \( V \) as follows:

\[
g_s(\phi, V) = g_s(\phi) \cdot g_s(V) \tag{4.3}
\]

where \( g_s \) is expressed in molar units (\( \text{mmol m}^{-2}\text{s}^{-1} \)).

The same model was used to describe \( g_s \) for \( \text{CO}_2 \) but \( g_s \) for water vapour was multiplied by a factor 1.6 representing the ratio of \( \text{CO}_2 \) to \( \text{H}_2\text{O} \) diffusion coefficients.

Footnote: To avoid using abbreviations in equations, VPD and PFD are given the symbols \( V \) and \( \phi \) respectively.
5.2.2 Model describing photosynthetic gas exchange

To describe the response of photosynthesis to photon flux density, carbon dioxide and other environmental variables a model outlined by Jarvis, Miranda and Muetzelfeldt (1985) was used:

\[ aP_n^2 + bP_n + c = 0 \]

(5.4)

where

\[ a = \theta + (g_m/g_s) \]

\[ b = \{[2\theta + (g_m/g_s) - 1]R_d - \alpha\phi[1 + (g_m/g_s)] - g_m(C_a - \Gamma)\} \]

\[ c = \alpha\phi g_m(C_a - \Gamma) + R_d(R_d 2\theta + R_d) - g_m(C_a - \Gamma) \]

\[ P_n = -b - \sqrt{b^2 - 4ac} \]

\[ 2a \]

Full details of the derivation are given in Appendix 3. The symbols and units of the parameters are as follows.

\( C_a \) is the ambient CO\(_2\) as a mole fraction (\(\mu\text{mol mol}^{-1}\)), \( P_n \) the net rate of photosynthesis (\(\mu\text{mol m}^{-2}\text{s}^{-1}\)), \( g_m \) the mesophyll conductance (\(\text{mmol m}^{-2}\text{s}^{-1}\)), \( g_s \) the stomatal conductance (\(\text{mmol m}^{-2}\text{s}^{-1}\)), \( \phi \), photon flux density (\(\mu\text{mol m}^{-2}\text{s}^{-1}\)); \( R_d \), dark respiration (\(\mu\text{mol m}^{-2}\text{s}^{-1}\)); \( \theta \), the convexity coefficient of the non-rectangular function as described by Thornley (1976) (dimensionless); \( \Gamma \), CO\(_2\) compensation point (\(\mu\text{mol mol}^{-1}\)); and \( \alpha \) is the initial slope of the photosynthetic response curve to photon flux density (dimensionless).

The model was fitted to data using a parameter optimisation which employs a least squares algorithm (the program PAR within the package BMDP).

5.2.3 Water use efficiency (WUE)

This is usually defined as the ratio of CO\(_2\) assimilated to the water used by the plant or the leaf expressed as the ratio of mass of dry matter accumulated to the mass of water used, or otherwise as \(\mu\)moles of CO\(_2\) fixed to \(\mu\)moles of \(\text{H}_2\text{O}\) used. Micromoles of CO\(_2\) is convertible to dry matter (Jones, 1983), though the multiplier is lower than one ascribed
to loss of some of the dry matter during respiration. In the present work, the WUE is defined as moles of CO₂ assimilated divided by moles of water used, the ratio applying to an individual leaf.

5.3 MATERIALS AND METHODS

5.3.1 Introduction

The data in this chapter were collected from water and carbon dioxide flux measured on single, attached leaves of potted plants of alfalfa. The details of the method used in this experiment, which was conducted from June to the end of December 1987, are presented below. More information concerning the system used can be found in Sandford (1987).

The aim of the work was to examine the effect of two factors, photon flux density and vapour pressure, on stomatal conductance. To undertake such a study it was required to control other factors which have an influence on stomatal conductance. Therefore, it was necessary to standardise the other factors.

5.3.2 Plant material and cultivation

Plants of *Medicago sativa* L. Hejazi were grown in a warm greenhouse during the summer of 1987 in Edinburgh, where the conditions are favourable for plant growth. Supplementary light was provided to stimulate growth rate. This light source was provided by Wotan HQI lamps, giving a photon flux density of 800 μmol m⁻² s⁻¹, and was also used to increase the photoperiod to 18 hrs. The temperature in the glasshouse was partially controlled by regulation of ventilators, varying a few degrees around 20 °C.

Plants were grown in small plastic pots ("4-inch") in a peat-sand mixture (ratio 3:1) with supplementary macronutrients and lime. This rooting medium was found to be suitable. The seeds were sown on June 1987, and took 3-5 days to germinate. Five plants were left in each pot and later plants were thinned to one plant per pot, then
transferred to a "7-inch" pot. The plants were irrigated once or twice a week with a mixture of water and liquid fertiliser as 100:1 parts of water. One part of fertiliser containing NPK in the ratio 3:0:3 supplied as Instant Bio NO₃ (Pan Britannica Industrial Ltd, Britannica House, Waltham Cross, Herts). This fertilizer regime has been found to give healthy growth in the glasshouse environment when crop plants have been raised in the peat-sand mixture. The plants were watered to near field capacity (by watering every one or two days until water ran from the pot). Once fully grown, they were cut down to soil level and allowed to regrow, just as they are in the field.

After nearly five months in the glasshouse, plants were transferred to controlled environmental conditions in a Fisons cabinet (Fisons 2340, Loughborough, UK). The conditions were: photoperiod, 18 hrs; photon flux density, around 800 μmol m⁻²s⁻¹ was produced by Wotan HQI-NDL 250 W power stars with 100 W incandescent tungsten bulbs. Day and night temperatures were 25 and 18 ±0.5 °C respectively, and plants were kept at a water vapour pressure of 1.6 and 1.1 ± 0.1 kPa at day and night respectively. These temperatures are close to the published optima as reported by Carter and Sheaffer (1983). Plants were watered each day using the diluted liquid fertiliser as outlined already and kept in this cabinet for 3-5 weeks until leaves which had developed in those conditions were available. Attached, fully-expanded leaves of this kind were used for gas exchange determinations.

The open-gas exchange system is based on an infra-red gas analyser (URAS 3E, Hartmann and Braun AG, Frankfurt, West Germany, and Dewpoint meter series 3000, Michell Instruments Ltd, Cambridge, England). The system has been described in the form of a manual by Sandford (1987), and calibration was carried out as suggested in the manual. Important features of this system are: (1) results are calculated and printed out automatically; (2) leaf temperature may be controlled; and (3) other variables are automatically controlled within quite fine limits.
5.3.3 Experimental procedure

After calibration, one plant from the Fisons cabinet was randomly selected and leaf area of the fourth leaf from the top (which was fully expanded) was determined. Then the plant was moved to the gas exchange system where this leaf was sealed inside the chamber, with an attached thermocouple, and the temperature and vapour pressure were set to give 25 ±0.5 °C with a VPD of 1.2 kPa. Photon flux density was provided by two 400W metal-halide discharge lamps (HPI 400W - 70 Wotan Lamps Ltd, London, England). A Fresnel lens made of acrylic plastic (Ealing Beck Ltd, Watford, England) produced a parallel beam of light. The plant was brought to the gas exchange system during the night and the light was set to come on simultaneously with those of the growth cabinet.

The light level was changed from very low ("dark") to 1800 µmol m⁻²s⁻¹ in four steps, this being done at four VPD levels: 1.2, 1.4, 1.8 and 2.0 kPa at 25°C. Higher VPD values were very difficult to achieve at this temperature, and further extensive calibrations would have been required to work at higher temperatures. CO₂ was held at 345 µmol mol⁻¹, and the vapour pressure was raised automatically by the computer controller. Photon flux density was raised manually using neutral density filters (Figure 5.1).

5.3.4 Calculation of transpiration rate

The calculation of transpiration rate (T) was based on the ideas presented in von Caemmerer and Farquhar (1981), in which flows are given as molar quantities.

In the case of transpiration (T):

\[ T = \frac{F_{e_o} - F_{e_e}}{pA} \]  \hspace{1cm} (5.5)
FIGURE 5.1: An example of the output values of stomatal conductance over 4 hours during which the photon flux density was increased and then finally decreased. Leaf temperature, 25 ±0.2 °C; CO₂, 345 μmol mol⁻¹. Arrows show increases in light.
where

- $F_0$ is molar flow of air coming out of the chamber (mol s$^{-1}$)
- $F_e$ is molar flow of air entering the chamber (mol s$^{-1}$)
- $e_0$ is water vapour partial pressure coming out of the chamber (μmol mol$^{-1}$)
- $e_e$ is water vapour partial pressure entering the chamber (kPa)
- $A$ is plan leaf area
- $p$ is atmospheric pressure (kPa)

Converting the partial pressure into mole fraction gives:

$$T = \frac{F_0}{W_0} - \frac{F_e}{W_e}$$

(5.6)

Where

- $W_0$ is water vapour mole fraction coming out of the chamber
- $W_e$ is water vapour mole fraction entering the chamber.

Thus

$$T = F_0(W_0 - W_e)$$

(5.8)

5.3.5 Calculation of stomatal conductance

The total conductance to diffusion of water vapour in mmol m$^{-2}$s$^{-1}$, was calculated from the relation derived by Jarman (1974).

$$T = g_t(W_i - W_a) + W_b T$$

(5.9)

where

- $g_t$ is the total conductance to water vapour
- $W_i$ internal water vapour mole fraction at leaf
- $W_a$ ambient water vapour mole fraction
- $W_b$ mean of $W_e$ and $W_i$

and as in a fully-stirred chamber $W_o = W_a'$, then total conductance can be calculated where

$$g_t = \frac{T(1-W_b)}{W_i - W_a}$$

(5.10)
This total conductance for water vapour includes the stomatal conductance $g_s$, cuticular conductance ($g_{cut}$) and boundary layer conductance ($g_a$). With the assumption that $g_{cut}$ is very small, the total conductance then can be presented as:

$$\frac{1}{g_t} = \frac{1}{g_s} + \frac{1}{g_a} \quad (5.11)$$

then

$$\frac{1}{g_s} = \frac{g_a - g_t}{g_t g_a} \quad (5.12)$$

and

$$g_s = \frac{g_t g_a}{g_a - g_t} \quad (5.12a)$$

g_a in the stirred chamber is very high and was taken from other work in this laboratory.

5.3.6 Calculation of net photosynthesis

Using the same procedure as used for $T$, net photosynthesis also can be found as follows:

$$P_n = \frac{(C_e - C_o) F_o (1 - W_e)}{A(1 - W_o)} \quad (5.13)$$

where

$C_e$ is CO₂ mole fraction entering the chamber

$C_o$ is CO₂ mole fraction coming out of chamber

$F_o$ molar flow of air entering the chamber.

It is possible to convert the vapour pressure from molar unit to pressure unit using this formula:

$$V(\text{mbar}) = e_i - e_a = p(W_i - W_a) \quad (5.14)$$

where $e_i$ is internal water vapour partial pressure at leaf temperature.
5.3.7 Fitting the model

The data obtained from the gas exchange system were used to fit the stomatal conductance model mentioned in Section 5.3.4, so that physiological parameters could be estimated from the solution of the non-linear model, by an optimisation procedure.

The data from single leaves were first normalized following Morison (1980) and Sandford (1984). This procedure is necessary to overcome the considerable leaf-to-leaf variation. The data for each leaf are essentially scaled in relation to the datum for a reference treatment. The reference treatment is the one in which VPD is lowest and photon flux density is highest (i.e. the one that gave the highest $g_s$). The normalised $g_s$ is defined as 1.00 at this reference. At other conductances, the $g_s$ values are scaled relative to this, so they are transformed to a scale 0 to 1.00. The purpose is to reduce the variance so that the model can be fitted easily. The model then defines the shape of this response. Any response surface produced in this way can be rescaled so that 1.00 is set to the mean actual conductance at the reference treatment. Sandford (1984) called this process standardization.

**TABLE 5.1:** The $g_s$ data after scaling so that the maximal $g_s$ is 1.00 at 1.2 kPa and 1800 $\mu$mol m$^{-2}$ s$^{-1}$ (showing the mean ± SD).

<table>
<thead>
<tr>
<th>VPD (kPa)</th>
<th>light</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.275 ± 0.05</td>
</tr>
<tr>
<td>160</td>
<td>0.533 ± 0.11</td>
</tr>
<tr>
<td>550</td>
<td>0.766 ± 0.10</td>
</tr>
<tr>
<td>1100</td>
<td>0.851 ± 0.05</td>
</tr>
<tr>
<td>1800</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The parameters of both models, the stomatal response to light and vapour pressure, and the photosynthetic response to photon flux density and VPD were found by optimisation using the non-linear least squares regression program PAR within the BMDP
statistical package (Dixon, 1981). In the photosynthetic model the CO₂ compensation point Γ was assumed to be 70 μmol mol⁻¹ (from Hodgkinson, 1974).

The assessment of goodness of fit of the model to the data, and the error estimates for each parameter derived from the analysis is notoriously difficult (Ross, 1981). The mean square error was used as a qualitative guide only.

5.4 RESULTS

5.4.1 Stomatal conductance and transpiration

Stomatal conductance and transpiration rate increased in response to an increasing photon flux density (Figures 5.2 and 5.3). The trends show some variability between leaves, presumably caused by genetic variation between individual plants. Light saturation of photosynthesis did not always occur. The maximum transpiration rate also varied with individual plant but was usually within the range 800 to 1200 mmol m⁻² s⁻¹, corresponding to stomatal conductance of 0.4 to 0.7 mol m⁻² s⁻¹ (Figures 5.2 and 5.3).

Transpiration and conductance exceeded zero in the dark. The dark value suggests incomplete stomatal closure. Vapour pressure deficit (V) had only a minor influence on stomatal conductance (Figure 5.2), being higher at the lower vapour pressure deficit values. The parameter values obtained when a non-rectangular hyperbola was fitted to the conductance data are given in Table 5.2.

**TABLE 5.2:** Estimated parameters of stomatal conductance model using data obtained at 1.2 kPa. The units are: \( g_{sm} \) mol m⁻² s⁻¹, \( g_{sd} \) mol m⁻² s⁻¹.

<table>
<thead>
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<th>( g_{sm} )</th>
<th>( \alpha )</th>
<th>( g_{sd} )</th>
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<td>± SD</td>
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FIGURE 5.2:
Relationship between stomatal conductance ($g_s$) and photon flux density (PFD) of five mature leaves of six month old alfalfa plants, at four different VPDs at constant leaf temperature ($25 \pm 0.2 ^\circ C$) and air carbon dioxide ($345 \pm 10 \mu\text{mol mol}^{-1}$).

x - 1.2 kPa
o - 1.4 kPa
o - 1.8 kPa
$\Delta$ - 2.0 kPa
FIGURE 5.3:
Relationship between transpiration rate (T) and photon flux density (PFD) of five mature leaves from six month old alfalfa plants, at constant leaf temperature (25 ±0.2 °C) and air carbon dioxide concentration of (345 ±10 µmol mol⁻¹), at four different VPDs.

x - 1.2 kPa
o - 1.4 kPa
o - 1.8 kPa
Δ - 2.0 kPa
FIGURE 5.4:
Relationship between net photosynthesis ($P_n$) and photon flux density (PFD) of five mature leaves from six month old alfalfa plants, at constant leaf temperature ($25 \pm 0.2 \, ^{\circ}C$) and air carbon dioxide concentration of ($345 \pm 10 \, \text{umol mol}^{-1}$), at four different VPDs.

$\Delta$ - 2.0 kPa
$\sigma$ - 1.8 kPa
$x$ - 1.2 kPa
FIGURE 5.5: Relationship between photosynthetic rate and stomatal conductance \( (g_s) \) for mature leaves of six month old alfalfa plants, at constant leaf temperature \((2.5 \pm 0.2 \degree C)\) and air carbon dioxide concentration of \((345 \pm 10 \mu\text{mol mol}^{-1})\), at four different VPDs.

\( x \) - 1.2 kPa
\( o \) - 1.4 kPa
\( o \) - 1.8 kPa
\( \Delta \) - 2.0 kPa
5.4.2 Photosynthetic light response curves

The rate of net photosynthesis ($P_n$) of five leaves is shown in Figure 5.4. The result indicates a curvilinear relationship in which $P_n$ continues to increase even at 1900 μmol m$^{-2}$s$^{-1}$, corresponding to bright sunlight. Photosynthetic rate was insensitive to vapour pressure deficit. The maximum net photosynthetic rate ranged from 22-32 μmol m$^{-2}$s$^{-1}$. The parameters of the model are given in Table 5.3.

<table>
<thead>
<tr>
<th>Parameters:</th>
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<th>(R_d)</th>
<th>(α)</th>
<th>(g_m)</th>
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<td>3.80</td>
<td>0.10</td>
<td>0.015</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.26</td>
<td>0.67</td>
<td>0.013</td>
</tr>
<tr>
<td>3</td>
<td>0.94</td>
<td>0.12</td>
<td>4.32</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>0.83</td>
<td>0.17</td>
<td>4.72</td>
<td>0.28</td>
</tr>
<tr>
<td>5</td>
<td>0.84</td>
<td>0.14</td>
<td>4.11</td>
<td>0.58</td>
</tr>
</tbody>
</table>

There is a well-defined relationship between stomatal conductance and the rate of the net photosynthesis (Figure 5.5). This does not necessarily imply stomata control of gas exchange, as $g_s$ is so strongly dependent on photon flux density, which is the real independent variate.

5.4.3 Model performance

The model predicting $g_s$ (p. 92) was used to estimate $g_s$ over a range of photon flux densities from zero to 1900 μmol m$^{-2}$s$^{-1}$ and V from 0.5 to 4.0 kPa (Figure 5.6). The predicted stomatal conductance increases with photon flux density in a curvilinear manner, indicating saturation for stomatal conductance at high photon flux density in the model, as in the data. VPD has only a very small effect. The stomatal conductance reached a maximum value of about 0.6 mol m$^{-2}$s$^{-1}$ at a PFD of 1900 μmol m$^{-2}$s$^{-1}$. The goodness of fit between calculated and observed is presented in Figure 5.7.

The response surface has been extrapolated beyond the region over which the data
Physiological behaviour outside that range is unknown.

In the experiments the VPDM range was only 12-20 mmbar and so the actual determining in the gas exchange experiments. In the experiments the VPDM range was only 12-20 mmbar and so the actual

FIGURE 5.6: Stomatal conductance (g) as a function of (PFD) and (VPDM), generated from equation (3), with parameter values set from those
Observed stomatal conductance (mol m$^{-2}$ s$^{-1}$)

Calculated stomatal conductance (mol m$^{-2}$ s$^{-1}$)

FIGURE 5.7: The relation between calculated conductance produced by the model and the observed conductance for the five plants used. The linear relationship and the random scatter about the line suggests that the model adequately summarises the response of the five leaves to PFD and VPD.
were collected embracing all "field" values. This procedure is not normally advised, as the function may change considerably outside the range defined by the experiment. In this case, it was felt that it was justified as V-gs curves determined for many species show only a slight change in slope at higher values of V.

Calculated photosynthetic rate increases in a similar way to stomatal conductance (Figure 5.8). The sudden change in slope around 700 μmol m⁻²s⁻¹ reflects the relatively high value of convexity coefficient (Table 5.3).

The ratio of ‘calculated P_n' to 'calculated T' (i.e. the water use efficiency) was plotted as a function of both photon flux densities from low photon flux density to the highest expected photon flux density of 1900 μmol m⁻²s⁻¹, and of V from a low to a high value such as we expect in the field (4.0 kPa). The dependence of WUE on V and light is shown in Figure 5.9. The diagram is divided into zones of WUE using 2 mbar steps. The WUE ranges from 0 (in the dark) to 12 μmol CO₂ per mol H₂O, being maximal at high light and low V.

5.5 DISCUSSION

Stomatal conductances obtained in this amphistomatous species are very high, 800 mmol m⁻²s⁻¹. Stomatal conductances previously reported in alfalfa are comparable with higher ranges of the herbaceous plant (see a review by Körner et al., 1979). These reported values for herbaceous plants approach a conductance of 3 cm s⁻¹ which is about 1200 mmol m⁻²s⁻¹. The alfalfa gs values reported from field site (p. 89) display stomatal conductance of up to 1365 mmol m⁻²s⁻¹. Very high conductance may be an adaptive feature in wild arid zone plants as a way to keep the leaf cool under the very hot climate, and this may help the plant to survive. However, the soil water must be readily available to the plant, and 'water spenders' often have deep roots (Althawadi and Grace, 1986), as alfalfa indeed does. In fact the species is native to dry parts of Britain, most of Europe, temperate Asia and North Africa. It is not a true desert plant, but has been extensively
FIGURE 5.8: Photosynthesis ($P_a$) as a function of both (PFD) and (VPD), generated from equation (4), using the parameter values derived from the experiment.
FIGURE 5.9: Water use efficiency (WUE) plotted as a function of (PFD) and VPD, isopleths of WUE are presented from 0 to 12 mmol CO$_2$.mol H$_2$O$^{-1}$. The transparent overlay shows the diurnal trend in VPD and photon flux density on two typical days in the field. ☐, a day in March; ◀, a day in May 1986.
FIGURE 5.9: Water use efficiency (WUE) plotted as a function of (PFD) and VPD, isopleths of WUE are presented from 0 to 12 mmol CO$_2$mol H$_2$O$^{-1}$. The transparent overlay shows the diurnal trend in VPD and photon flux density on two typical days in the field. □, a day in March; ♦, a day in May 1986.
used in arid zone agriculture. The variety used in the present work is local to the Arabia Peninsula and may have been recently derived from wild populations. Consequently, its response may differ from European and American cultivars.

The rate at which $g_s$ changes with VPD is rather small. So far, no other study has reported the VPD response for alfalfa. In other species, the response is often steeper (Figure 5.10) but sometimes no response at all to VPD has been shown (Barrs, 1973, working with maize, sunflower, cotton, pepper and tomato, the plants being well-watered or grown in nutrient solution). However, there are more than 70 species found to have a stomatal response to VPD (see review by Hall, Schulze and Lange, 1976; Schulze, 1986).

5.5.1 Light response

The controlled environment of a leaf chamber enables unequivocal light response curves to be obtained, both for photosynthetic rate and stomatal conductance. These have suggested plant-to-plant variation in most parameters. Such variations could be exploited in the future; for example, in the selection of genotypes for breeding programmes. Large numbers of genotypes could be scanned for gas exchange parameters. One could select for maximal photosynthetic capacity, or high water use efficiency. Other characteristics, such as rooting depth and disease resistance, as well as palatability to cattle also have to be taken into account.

The stomatal response to light is not exceptional. In other species both linear (Ludlow and Wilson, 1971a; Turner, 1974; Burrows and Milthorpe, 1976) and curvilinear relationships have been found (Warrit et al., 1980). The photosynthetic response to light is unusual for a C₃ plant in that a very high light saturation point occurs, some leaves behaving like a C₄ plant. A more thorough physiological investigation of this phenomenon would be very interesting. Presumably, what is happening is that the internal CO₂ concentration ($C_i$) remains high, so that the supply of CO₂ does not become
FIGURE 5.10: Stomatal conductance of various species related to the relative leaf/air vapour pressure difference, VPD, with constant leaf temperature and radiation, alfalfa stomatal conductance also shown which indicated a decline in $g_s$ with the increase in VPD. The presented alfalfa data taken from the highest light intensity, from the gas exchange data. Other species are adapted from Hall and Schulze (1982).
as strictly limiting as it does in a ‘normal’ C₃ plant. This view is strengthened by Figure 5.11. Here, the present *Medicago sativa* data are added to a figure obtained from Schulze and Hall (1982) in which *gₛ* and maximal rates of CO₂ assimilation are shown for 5 species, including two tropical grasses (C₄). It would seem from this that if *gₛ* of bean (*Phaseolus vulgaris*) and golden-rod (*Solidago virgaurea*) could be increased to that of *Medicago sativa*, then their rates of photosynthesis would be like those of *Medicago sativa*. Others have also obtained high rates of photosynthesis in alfalfa (Thomas and Hill, 1949; Pearce *et al.*, 1969; Wolf and Blaser, 1972; Hodgkinson, 1974; Baldocchi *et al.*, 1981; Travis and Reed, 1983).

### 5.5.2 Water use efficiency

The impact of environmental variables on water use efficiency (WUE) of alfalfa leaves, especially PFD and VPD may be especially important in an extreme arid country such as Saudi Arabia where a wide range of daily and seasonal variations are experienced (Abdel Rahman, 1986). The predicted *Pₙ* / *T* for alfalfa on a leaf area basis indicates only a weak response to light in the range 1000-2000 μmol m⁻²s⁻¹. The overlay of the diurnal trends in VPD and PFD enable comparison to be made between seasons. In the spring (March), leaves at the top of the canopy would have a WUE mostly in the range 0-6 mmol mol⁻¹, but in the summer WUE is relatively constant throughout the day, and generally lower, scattered around the value of 2. A previously-reported value for alfalfa, average over the season, was 0.2 mmol mol⁻¹, a figure which seems very low compared with the present work and other work in the literature (Schulze and Hall, 1982).

### 5.5.3 Comments on field versus laboratory responses

The field and laboratory stomatal conductances are similar in magnitude. In the field, conductances were obtained in units of cm s⁻¹ as the atmospheric pressure was not available to calculate conductances as molar units. The highest recorded field values were
FIGURE 5.11: Shows the relationship between leaf conductance ($g_a$) in (mmol m$^{-2}$s$^{-1}$) and maximum CO$_2$ assimilation for different species used by many authors for details (see Hall and Schulze, 1982). Alfalfa response was included $g_a$ (in this study).
3.6 cm s\(^{-1}\) which is about 1450 mmol m\(^{-2}\)s\(^{-1}\), but a more typical field value was 1.5 cm s\(^{-1}\), approximately 600 mmol m\(^{-2}\)s\(^{-1}\) (the conversion factor is proportional to pressure and inversely proportional to temperature and so this conversion cannot be given exactly). In the field the aerodynamic conductance \(g_a\) would have been much lower than in the stirred chamber, so the measured VPDs in the field cannot be equated to the physiological VPDs. The latter is the difference between the water vapour pressure in the substomatal cavity and that at the leaf surface (i.e. under the boundary layer of the leaf).

It was unfortunate that the laboratory system did not facilitate experimentation over the full range of conditions experienced in the field. This would have entailed lengthy recalibration of several parts of the system at a range of temperatures.

It is also recognised that field grown material often behaves differently from the same genotype raised in the glasshouse or controlled environment room. This may be caused by differences in diurnal cycles of water stress, by the lack of mechanical action (wind) in the environment room, or by subtle differences in the spectral properties of the radiations or photoperiod.

The water use by the crop as a whole cannot be forecast from the water use of individual leaves without the use of a model to enable ‘scaling up’. Such a model would have to calculate light and VPD distribution within the canopy, and use the WUE result in Figure 5.9 to achieve a numerical integration.
CHAPTER SIX

GENERAL DISCUSSION

AND CONCLUSION
CHAPTER SIX
GENERAL DISCUSSION AND CONCLUSION

6.1 Microclimate

It is important to assess the relationship between the crop and its microclimate, in order to understand the response of the plant to a newly-developed irrigation scheme and to any micrometeorological modification brought about by the characteristics of the crop itself. Research previously conducted to study such changes under an extremely arid environment is limited in extent. Previous studies in the area overlooked some important features of the radiation balance, using a constant albedo, either high, 0.25 (Siam, 1985) or low, 0.05% (Saeed and Abdulaziz, 1985). The result in the present study indicates that albedo shows diurnal and seasonal variations. Albedo enters the calculation of net radiation above the crop. The assumption of constant albedo was possibly responsible for the lower LE values in winter (Siam, 1985) and the higher winter value (Saeed and Abdulaziz, 1985).

The size of the irrigation scheme has an important implication on crop microclimate. As the scale of farming increases, there comes a point where ‘edge effect’ is completely negligible as a fraction of the total; and the farm as a whole experiences an ameliorated microclimate. Grouping farms together would presumably be advantageous, creating a regional climate.

6.2 Relation between different parts of the work

Accurate information is essential in modelling water use by field crops. As mentioned in Chapter One of this thesis, one of the aims was to implement three different approaches:

(i) to measure water use by the crop as a whole using a standard technique known as the Bowen Ratio method;
(ii) to explore a less widely used method based on the energy balance of leaves at the top of the canopy; and

(iii) to carry out model calculations based on data from the laboratory gas exchange system.

In the first approach it was found that the Bowen Ratio method worked well in the day time when net radiation was high, but that it failed during the night, early morning and late afternoon. There are also difficulties arising from an inequality of $K_h/K_w$ which has been found before by Verma et al. (1978), and can be corrected for. The application of the Bowen ratio requires large fetch, in the region of 50-150 times the plant's height, so that sensors at both heights are within a boundary layer which is characteristic of the vegetation surface. For this reason, the Bowen Ratio method cannot safely be applied to small areas in the desert. This technique also needs precise instruments to resolve small differences in temperature and vapour pressure. Where their gradient above the canopy is very small, the measuring system requires more resolution (Fritschen et al., 1985). In the present case, however, the gradient of both temperature and water vapour pressure was rather large. It may be concluded that the Bowen ratio method is best used in very large fields, tens of hectares rather than hectares or fractions of a hectare. Commercial systems do exist, for example the one marketed by Campbell Scientific, Loughborough. This system uses a mirror hygrometer to measure humidity and this would probably require less maintenance than a wet bulb psychrometer.

The leaf energy balance technique was used to evaluate differences in the water use between two irrigation types. This method also depends on the accurate measurement of the temperature and vapour pressure deficit, but in this case the gradient is between the surface and the air above the crop. This method needs very accurate measurement of leaf temperature, though this can be achieved by means of calibrated thermocouples used in conjunction with a suitably sensitive microvoltmeter. The CR21X micrologger is capable of resolving 0.33 μV, corresponding to 0.01 °C, and so is quite suitable.
resolution was not rigorously checked but in the laboratory the micrologger can readily resolve 1 μV supplied using a microvoltage calibrator (Microvoltage Calibrator, Time Electronic Company Ltd, Kent, England).

The method does however depend on an adequate sample of leaves, and perhaps this is its main limitation. The actual number of leaves depends on the variability of their exposure, and a minimum of five is recommended. In the present work, the resultant water losses seem to be higher than those from the Bowen Ratio, but this is to be expected as only sunlit leaves are being sampled. For sunlit leaves, the method has been checked against a gravimetric technique by Althawadi (1985) who also used it to estimate the water use of a desert cucurbit in Saudi Arabia. The accuracy of hourly fluxes calculated by this method was evaluated by sensitivity analysis, and it was found to give a good estimate during the day time hours but poor estimates in the early and late hours of the day (Figures 4.13 to 4.15).

The precision of the net radiation measurement is questionable in the case of the leaf energy balance. Here, net radiation is used to derive $g_a$. It is very difficult to estimate $R_n$ on a leaf basis because of the posture which changes with the sun angle (Travis and Reed, 1983). The second problem in estimating $R_n$ was that the net radiometer measured the net downward flux of radiant energy to the crop as a whole, and this may bear only a poor relationship to net energy balance of the leaf. Error may be large with low sun angle, in both early morning and late afternoon; but since transpiration is not great during these times even a large error of 40% of $R_n$ is not so important at this time of day. An additional problem is that any transpiration by the lower leaves of the canopy is not measured at all, even though this may constitute a significant part of the total.

As a result of these problems (sampling, poor estimation of radiation absorbed and neglect of the lower part of the canopy), it must be concluded that leaf energy balance does not provide a measure of water use by the crop. It does, however, provide some kind of information which the Bowen ratio does not. In particular, it provides estimates of
$g_a$ and $g_s$ on a plan leaf area basis for leaves at the top of the canopy, subject to a potentially very serious error which derives from the uncertainty in $R_n$. Despite this error, it is possible to see diurnal trends in stomatal conductance and such trends may be interpreted in terms of plant water stress. The alternative and more traditional method of obtaining $g_s$ using a porometer does not lend itself to continuous recording and suffers from even larger sampling problems as well as the criticism that the microclimate within the chamber is different from the natural one. Any method which focuses on single leaves also has the potential of being applicable to very small areas, and in the case of a circular field in a desert, could be applied for example to study the 'edge effect'.

There are other problems related to the use of the leaf energy balance approach where continuous sampling is required. It leads to a high number of data, which requires modern data acquisition and storage systems. In remote areas and in the Third World countries, there are difficulties of servicing such systems, and it is generally harder to keep everything working all the time. This was why only a limited number of days were complete. Another problem which is specific to a particular data logger, is the limited channels available for continuous recording, especially if a large sample of leaves is to be used. When thermocouple probes are used in parallel to economise on the number of channels, no estimation of variance is available, and the mean may be weighted in favour of some individual leaves if the sensors have a different electrical resistance. Some data loggers combine high sensitivity with very large numbers of channels, but the CR21X is severely limited in the number of channels it has.

The third approach, using gas exchange data from the laboratory, has both advantages and disadvantages. It provides very precise measurements of both CO$_2$ and H$_2$O flux from a rather limited sample of leaves, and it enables the environment to be manipulated experimentally, exploring one variable at a time. Thus, uncertainties in leaf response to VPD and PFD, which arise from the field, can be resolved; hence providing a 'response surface' or enabling one to fit a physiological model. Underlying concerns
are: (a) that plants grown in the glasshouse may not display the same behaviour as field
grown plants; and (b) that the sample of leaves is inevitably very small, so that the
estimate of the mean conductance is not exact, even though the information for each leaf
is precise.

If such information is to be used in practice, then it is necessary to ‘scale up’ from
the leaf to the crop level. This process is one which concerns many physiologists at
present, as they try to use the very considerable information about leaf responses to make
statements about how crops respond, for example, to CO$_2$ elevation and climatic change.

To ‘scale up’ in the present case would require more work to be done. What would
be required is a knowledge and understanding of vertical profiles of radiation, temperature,
vapour pressure and wind speed within the canopy. Also, the vertical profile of leaf area
should be known. Then it ought to be possible to calculate, layer by layer and hour by
hour, the rate of water use and carbon assimilation. Even if such information were
available, the scaling up process would still have uncertainties and the result should be
confirmed by an independent method, especially so in view of the small and probably
unrepresentative nature of the initial sample of leaves, and the likelihood that leaf
parameters will change significantly with the age of the leaf. A suitable independent
method in this context would be that the eddy correlation (Shuttleworth, 1979; Rosenberg
et al., 1983). This technique is currently being developed for CO$_2$ as well as for H$_2$O.
Its major limitation is that the sensors are not very robust and are very expensive. The
instruments were not readily available when the present project was conceived.

6.3 Practical recommendations

6.3.1 Irrigation control

Knowledge of water use by the crop is very important in irrigation management.
Water delivery should be controlled on the basis of the known water consumption, rather
than on an arbitrary basis according to visual inspection of the soil surface or crop
appearance.
(i) An estimate of water consumption could be made from continuous recording of radiation over the vegetation. This estimate would be subject to error, as LE frequently exceeds $R_n$.

(ii) A more exact estimate for the case of large fields could be provided by Bowen Ratio equipment, although the sensing head would have to be made especially robust for continuous operation, with special software to calculate LE and activate the irrigation system when required.

(iii) The sensing of leaf and air temperature could in principle be used to estimate water use and to detect when stomata close. The method using thermocouples does not lend itself to continuous use in farming practice because of the fragility of the sensors. However, crop temperature could be sensed using an infra-red thermometer (Jackson, 1982; Huband and Monteith, 1986). This overcomes the sampling problems encountered with thermocouples as the field of view of the infra-red thermometer can be large.

(iv) Sensing soil water is another approach, not used in the present study. This can be achieved by introduction of the neutron probe technique or soil psychometers which can detect changes in soil moisture continuously, but both these techniques need large numbers of samples to characterise the changes in soil moisture content. Moreover, the neutron probe is expensive and needs calibration for each soil type.

Precise estimation of water consumption is only useful if matched by a precise system for delivering water. Spatial variation can be expected from any system. Irrigation by spraying may be more efficient in water conveyancy and uniformity, but loss by direct evaporation may be significant. Irrigation by flooding or surface irrigation also has disadvantages, because it needs manpower to do it, which is important in a country which relies on imported workers to do such work.
6.3.2 Agronomic aspects

As an important priority, varieties of alfalfa should be screened for their water use efficiency. Consideration should be given to collecting wild forms from different parts of Saudi Arabia, with the intention of starting a breeding programme designed to produce suitable varieties for the extreme climate. These varieties should have a high yield as well as a high WUE, and they must still be easily digestible for cattle. The possibility of using gas exchange data to select for high WUE has already been suggested in Sections 5.5.1 and 5.5.2. Anatomical and morphological features can also be selected for. For example, a high leaf reflectance would probably reduce transpiration more than it would reduce photosynthesis, in a leaf which is light saturated or nearly so.

6.4 Conclusions

1. The climate of the nearby desert is characterised by high albedo (0.40), low water vapour pressure (<10% RH) and high temperature (22-45 °C). After the air had flowed 50-100 m over the irrigated crop, the temperature decreased by ~6 °C, and the vapour pressure increased by 2.0 kPa. Crop albedo varied diurnally and seasonally and was much lower than the desert. Net radiation over the crop was a near-linear function of short-wave irradiance.

2. Analysis of the diurnal microclimate of the two irrigation types indicates slight differences. The sources of the differences may be related to the scale of the field size and the irrigation frequency.

3. The Bowen Ratio method was used to estimate water use by the crop. The equipment was placed well in from the leading edge of the field (150 h). The Bowen Ratio was in the range -0.5 to 0.5. An examination of probable errors suggested that the technique is close to the limit of its applicability in this case, but it nevertheless provides an estimate of day time evaporation to within 20%.
The daily total of evapotranspiration in the summer months was in the range of 9-15 mm day\(^{-1}\).

4. Water use by a sample of leaves at the top of the canopy was assessed. It was clear that the leaf energy balance method can be used to track stomatal conductance and thus indicate times of atmospheric stress indicated by stomatal closure. The maximal stomatal conductance was 3.5 cm s\(^{-1}\) and the corresponding maximal leaf surface transpiration rate was 800 W m\(^{-2}\). A type of error analysis was devised to explore the effect of making errors in the measurement of the important variables. It was concluded that the technique was most useful between 09.00 and 15.00 h, when the probable error was about ±20%.

5. Gas exchange in the laboratory provided light response curves of photosynthetic rate and stomatal conductance. Maximal photosynthesis was 22-32 \(\mu\)mol m\(^{-2}\)s\(^{-1}\), but light-saturation did not always occur even a photon flux density of 1800 \(\mu\)mol m\(^{-2}\)s\(^{-1}\). The stomatal conductance was only weakly dependent on leaf-air vapour pressure deficit and the maximal value was 800 mmol m\(^{-2}\)s\(^{-1}\). In the dark, there was a considerable conductance, suggesting a possible importance of nocturnal transpiration. However, under field conditions the leaves become colder than the air at night and dew is detected as early as 17.00 hrs.

6. The gas exchange data were used to calculate water use efficiency (WUF); these varied with light and humidity over the range of 2 to 10 mmol mol\(^{-1}\).

7. Suggestions are made to improve the water use efficiency of the alfalfa crop in Saudi Arabia, by supplying only sufficient water to replace water which is lost and by exploring alternative genotypes.
REFERENCES


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"He who is not thankful to the people through whom Allah [God] has granted his tidings is actually not thankful to Allah."

Prophet Mohammad

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Finally, I would like to express my profound appreciation and gratitude to my parents and brothers for their understanding and encouragement. To my wife and sons (Khalid and Majed) and daughters (Ahlam and Maha) who have patiently and pleasantly tolerated my absence in mind and body during the field and laboratory work and writing of this thesis, goes my deep appreciation.
APPENDICES
APPENDIX 1: Calibration curve obtained for the equipment used in Chapter Four.

FIGURE A1.1: Relationships between measured temperature and calculated temperature (°C), using the program of the CR21 logger, \( r^2 = 0.997 \).

FIGURE A1.2: Relationships between measured temperature and thermocouple output (mV). The reference junction was at 0 °C \( (r^2 = 0.997) \).
FIGURE A1.3: Relationship between $R_n$ (W m$^{-2}$) and home made net radiometer (mV), $r^2 = 0.974$. Calibration method is given in Section 4.3.1.4.

FIGURE A1.4: Relationship between Kipp solarimeter and tube solarimeter taken on a sunny day out doors at FNR Department.
FIGURE A1.5:
Calibration of the anemometer using Pitot-static tube in the windtunnel of FNR Department (a straight line relationship can be drawn through the points by which wind speed \( u \, (\text{ms}^{-1}) = 0.353 \, (\pm 0.047) + 0.141 \, (\text{counts s}^{-1}) \, (\pm 0.002), (r^2=1.00) \).

FIGURE A1.6:
Relationships between RH % and mV output of the humidity sensor. The relationship can be approximated as a straight line where RH = -32.3 (± 0.96) + 106 (sensor output) (± 1.31). Then RH was expressed as % \((r^2=0.988)\).
APPENDIX 2: A list of the programs used to calculate transpiration and conductance, and error involved

A2.1 Program used to simulate the error in the calculation of latent heat of evaporation and stomatal conductance as a result of error in either leaf temperature or relative humidity.

DIMENSION IFREQ1(600),IFREQ2(600),IFREQ3(600)

89  DO 88 I=1,600
    IFREQ1(I)=0
    IFREQ2(I)=0
    IFREQ3(I)=0
88  CONTINUE

READ(5,*)TIME,RNTZ,TAZ,TLNTZ,TLTZ,rhz
rtz=rntz
CALL PENMONT(RNTZ,RTZ,TAZ,TLNTZ,TLTZ,RHZ,CCZ,ZZZ,EZ,RAZ,rsz)
GA=1.0/RAZ
GS=1.0/RSZ
WRITE(6,100)TIME,CCZ,ZZZ,EZ,GA,GS
E1=EZ
GA1=GA
GS1=GS
WMLOW=RNTZ*0.90
WMSTEP=RNTZ*0.02
ATLOW=TAZ-0.3
ATSTEP=0.1
TLNOW=TLNTZ-0.3
T1STEP=0.1
T2LOW=TLTZ-0.3
T2STEP=0.1
RHLOW=RHZ*0.90
RHSTEP=RHZ*0.02
DO161=1,11
WMNOW=WMLOW+(FLOAT(I)*WMSTEP)
DO 16 J=1,6
ATNOW=ATLOW+(J*ATSTEP)
DO 16 K=1,6
T1NOW=TLNOW+(K*T1STEP)
DO 16 L=1,6
T2NOW=T2LOW+(L*T2STEP)
DO 16 M=1,11
RHNOW=RHLOW+(FLOAT(M)*RHSTEP)
CALL PENMONT(WMNOW,RTZ,ATNOW,T1NOW,T2NOW,RHNOW,CCZ,ZZZ,EZ,RAZ,rsz)
GANOW=1.0/RAZ
GSNOW=1.0/RSZ
C WORK OUT PROPORTIONTE ERRORS
AERR=GANOW/GA1
SERR=GSNOW/GS1
EZERR=EZ/E1
C MULTIPLY ERROR BY twenty AND ROUND OFF
C TO CLASSIFY INTO 5-PERCENTILES
IQ1=IFIX(AERR*20)
IQ2=IFIX(SERR*20)
IQ3=IFIX(EZERR*20)
IF(IQ1.LT.1)IQ1=1
IF(IQ2.LT.1)IQ2=1
IF(IQ3.LT.1)IQ3=1
IF(IQ1.GT.599)IQ1=600
IF(IQ2.GT.599)IQ2=600
IF(IQ3.GT.599)IQ3=600
IFREQ1(IQ1)=IFREQ1(IQ1)+1
IFREQ2(IQ2)=IFREQ2(IQ2)+1
IFREQ3(IQ3)=IFREQ3(IQ3)+1
CONTINUE
DO 50 I=1,100
WRITE(6,101)IFREQ1(I),IFREQ2(I),IFREQ3(I)
50 FORMAT(1H,6F13.6)
100 FORMAT(1H,3I10)
GOTO 89
END

SUBROUTINE PENMONT(RNT,RT,TA,TLNT,TLT,RH,CC,LE,E,RA,RS)
REAL *4 A,ES,SVP,CP,EL,CC,E,EA,GAMMA,LAMBDA,LE,P,RA,RHO,RNT,RS,RT,SIGMA
1,ta,TLNT,TLT,RH
DATA N6.666E-04/,CP/1.01/,GAMMA/0.66/,LAMBDA/2454./,P/1000./,RHO/
11150.,SIGMA/5.67E-8/
RA=(RHO*CP*(TLNT-TA))/RNT
LE=SIGMA*(B273.16)**4*(B273.16)**4*RHO*CP*(TLNT-TA)/RA
CC=RNT-LE
E=LE/LAMBDA
EA=RH/100*ES
EL=SVP(TA)
RS=((RHO*CP*(EL-EA))/(GAMMA*LAMBDA*E))/RA
RETURN
END
C CALCULATE SATURATED VAP. PRESSURES(MB.) FROM THE NEW

GOFF-GRATCH EQN.
REAL FUNCTION SVP(TEMP)
B=TEMP+273.15
IF(B.LT.273.15)GOTO 1
SVP=-10**(-1.79574*(1-(273.15/B)))+5.02800*ALOG10(273.15)
+1.50475E-4*(1-(10**(-8.2969*((B/273.15)-1))))
+0.42873E-3*(10**((-4.76955*(1-(273.15/B))))-1)
+0.78614)
GOTO 2
1 SVP=-10**(-9.09690*(273.16/B-1))
+3.56654*ALOG10(273.16)
+0.87682*(1-B/273.16)
+0.78614)
2 CONTINUE
RETURN
END
A2.2 Leaf energy balance calculation

REAL RNTZ, RTZ, TA1Z, TA2Z, TW1Z, TW2Z, TS1Z, TS2Z, CZ, EZ, LEZ,
1 BWZ, RAZ, GZ, AZ, EA1, EA2, DEA, RTZ, RCZ, GCZ, SZ, SHIZ, SHRZ, UZ,
1 ALBZ, C, EW, RW, RA, G, EA1, EA2, DEA, RC, RTZ, TS1Z, TS2Z,
1 = 0
1
CWRITE(6,2)
1
C FORMAT(' TIME RNT G C LE
1 X B W RA EA EA2 D T A')
1 READ(3,*) TIME, SHIZ, SHRZ, UZ
1 READ(5,*) TIME, RNTZ, TA1Z, TA2Z, TW1Z, TW2Z, TS1Z, TS2Z
1 = 1 + 1
1
1 ALBZ = SHRZ / SHIZ
1 RTZ = RNTZ
1 CALL BOWEN(RNTZ, RTZ, TA1Z, TA2Z, TW1Z, TW2Z, TS1Z, TS2Z,
1 CZ, EZ, LEZ, BWZ, RAZ, RCZ, EA1, EA2, DEA, SZ, DTAZ, GZ)
1 GAZ = -1 * RAZ * 100
1 CZ = 1 * CZ
1 LEZ = - LEZ
1 GCZ = 1 / RCZ * 100
1
1 IF (GAZ .LT. 0.0) GAZ = 0.0
1 IF (GAZ .LT. 0.0) WRITE (7,101) TIME
1 IF (GCZ .LT. 0.0) GCZ = 0.0
1 IF (GCZ .LT. 0.0) WRITE (7,102) TIME
1
101 FORMAT('GAZ SUB ZERO AT - ,F13.5)
102 FORMAT('GCZ SUB ZERO AT - ,F13.5)
1
1 WRITE(2,120) TIME, RNTZ, CZ, GZ, LEZ, BWZ, DEA, DTAZ, GCZ
1
1 WRITE(7,115) TIME, SHIZ, SHRZ, RNTZ, ALBZ, EA1, EZ, LEZ, BWZ,
1 WRITE(6,100) TIME, RNTZ, GZ, CZ, LEZ, BWZ, EA1, EA2, DTAZ, UZ
1
115 FORMAT(1H ,F5.2,1H ,5F8.2,10F12.5)
120 FORMAT(1H ,F5.2,1H ,5F8.2,1H ,4F10.2,1H ,5F8.2)
120 FORMAT(1H ,F5.2,1H ,5F8.2,1H ,5F10.4)
1 IF (I .EQ. 60) GOTO 110
1 GOTO 1
1
110 END

SUBROUTINE BOWEN(RNT, RT, TA1, TA2, TW1, TW2, TS1, TS2, C, E, LE, BW, RA, RC,
1 EA1, EA2, DEA, DTA, G)
1 REAL A, CS, C, E, EA, EL, GAMMA, LAMBDA, LE, P, RA, BW, RC, RT, SIGMA,
1 TA1, TA2, TW1, TW2, EA1, EA2, G, K, S, ES, DTA, DEA, B
1 DATA K/1.800/
1 DATA A',6.666E-04/, CP/1.01/, GAMMA/0.66/, LAMBDA/2454/, P/1000/, RHO/
11150/, SIGMA/5.67E-8/
1 G = K * (TS1 - TS2) / 0.05
1 DTA = TA1 - TA2
1 RA = (RHO * CP * (TA1 - TA2)) / (RNT - G)
1 WB1 = (TA1 - TW1)
1 WB2 = (TA2 - TW2)
1
1 V...PRSS.GRADIENT
1 EA1 = SVP(TW1) - WB1 * A * P
EA2 = SVP(TW2) * WBD2 * A * P
DEA = EA1 - EA2
CC  TEMPERATURE GRADIENT
S = DTA / DEA
CC  BOWEN RATIO
BW = GAMMA * S
LE = (RNT - G) / (1 + BW)
E = (LE / LAMBDA)
C = BW * (RNT - G) / (1 + BW)
RC = ((RHO * CP * DEA * (GAMMA * LAMBDA * E)) - RA)
RETURN
END

C CALCULATE SATURATED VAP. PRESSURES (MB.) FROM THE NEW GOFF-GRATCH EQN.
FUNCTION SVP ( TEMP )
B = TEMP + 273.15
IF (B .LT. 273.15) GOTO 1
SVP = 10**(10.79574*(1-(273.16/B)))
!-5.02800*ALOG10(B/273.16)
!+1.50475E-4*(1-(10**(-8.2969*((B/273.16)-1))))
!+0.42873E-3*((10**((4.76955*(1-(273.16/B)))))-1)
!+0.78614)
GOTO 2
SVP = 10**(9.09685*(273.16/B)-1)
!-3.56654*ALOG10(273.16/B)
!+0.87682*(1-B/273.16)
!+0.78614)
2 CONTINUE
RETURN
END

A2.3  Calculation of LE C, and b

1  READ(5,*)TIME, RNTZ, TAZ, TLNTZ, TLTZ, WBDZ
RTZ = RNTZ .
CALL PENMONT(RNTZ, RTZ, TAZ, TLNTZ, TLTZ, WBDZ, CZ, ZZZ, EZ, RAZ, RSZ, VPDZ)
GAZ = 1/RAZ
GSZ = 1/RSZ
WRITE(6,100)TIME, CZ, ZZZ, EZ, GAZ, GSZ, VPDZ
GOTO01
100  FORMAT(1H, 7F13.4)
END
SUBROUTINE PENMONT(RNT,RT,TA,TLNT,TLT,WBD,C,LE,E,RA,RS,VPD)
REAL*4 A,CS,C,E,EA,VPD,EL,GAMMA,LAMBDA,LE,P,RA,RHO,RNT,RS,RT,SIGMA,TA,
1 TLNT,TLT,WBD,WBT
DATA A/6.666E-04/,CP/1.01/,GAMMA/0.66/,LAMBDA/2454./,P/1000./,RHO/
11150./,SIGMA/5.67E-8/
RA=(RHO*CP*(TLNT+TA))/RNT
LE=SIGMA*(((TLNT+273.16)**4-(TLT+273.16)**4)-RHO*CP*(TLT-TLNT)/RA
E=LE/LAMBDA
C=RT-LAMBDA*E
WBT=TA-WBD
EA=SVP(WBT)-A*P*WBD
ES=SVP(TA)
VPD=ES-EA
EL=SVP(TLT)
RS=((RHO*CP*(EL-EA))/(GAMMA*LAMBDA*E))-RA
RETURN
END

C CALCULATE SATURATED VAP. PRESSURES(MB.) FROM THE NEW GOFF-GRATCH EQN.
REAL FUNCTION SVP*4(*TEMP*)
B=TEMP+273.15
IF(B.LT.273.15)GOTO 1
SVP=10**(10.79574*(1-(-273.16/B)))
1-5.02800*DLOG10(B/273.16)
1+1.50475E-4*(1-(10**(-8.2969*((B/273.16)-1))))
1+0.42873E-3*((10**(-4.76955*(1-(273.16/B))))-1)
1+0.78614)
GOTO 2
1 SVP=10**(-9.09685*(273.16/B-1)
1-3.56654*DLOG10(273.16/B)
1+0.87682*(1-B/273.16)
1+0.78614)
2 CONTINUE
RETURN
END
APPENDIX 3: Derivation of the model used to describe photosynthetic light response.

Physiological parameters can be estimated by fitting appropriate models describing photosynthesis to laboratory data obtained by conducting experiments in gas exchange systems. The response of photosynthesis to PFD and internal CO₂ concentration can subsequently be obtained by applying models which contain such parameters (Von Caemmerer and Farquhar, 1981). The general approach is outlined by Jarvis et al. (1985), but the derivation has not been given. The basic relationship is a quadratic equation:

\[ 0 = P_G^2 \theta - P_G (\alpha \phi + P_{Gm}) + \alpha \phi P_{Gm} \]  

where \( P_G \) is the gross CO₂ exchange rate (\( \mu \text{mol m}^{-2} \text{s}^{-1} \))
\( \phi \) is the photon flux density PFD (\( \mu \text{mol m}^{-2} \text{s}^{-1} \))
\( P_{Gm} \) is the asymptotic rate of assimilation at saturating \( \phi \) (\( \mu \text{mol m}^{-2} \text{s}^{-1} \))
\( \alpha \) is quantum efficiency (initial slope, dimensionless)
\( \theta \) is convexity parameter (dimensionless)

The convexity has a value from 0 to 1, where 0 results in rectangular hyperbola and 1 results in "Blackman response function". For more information see Thornley (1976).

The gross photosynthesis is related to both net assimilation rate and dark respiration as follows:

\[ P_G = P_n + R_d \]  

and \( P_{Gm} \) also has the same form

\[ P_{Gm} = P_{nm} + R_d \]

where \( P_n \) is net assimilation rate (\( \mu \text{mol m}^{-2} \text{s}^{-1} \))
\( P_{nm} \) is maximum assimilation rate
\( R_d \) is dark respiration (\( \mu \text{mol m}^{-2} \text{s}^{-1} \))
It is possible to express $P_{nm}$ in relation to intercellular CO$_2$ concentration and stomatal conductance according to experimental evidence reported by Watson, Landsberg and Thornley (1978).

Where $P_{nm} = C_i g_m - R_d$ \hspace{1cm} (A1.4)

$R_d$ has also reported to be related to CO$_2$ compensation point ($\Gamma$) and the mesophyll resistance by Reed et al. (1976).

$$R_d = \Gamma g_m \hspace{1cm} (A1.5)$$

from the previous equation it is possible to express maximum photosynthesis as follows:

$$P_{nm} = C_i g_m - \Gamma g_m \hspace{1cm} (A1.6)$$

Photosynthesis has been expressed in relation to the potential differences between $C_a$ and $C_i$ and the conductance of the diffusion of CO$_2$ between the ambient air and the intercellular spaces inside the leaf where:

$$P_n = (C_a - C_i) g_s \hspace{1cm} (A1.7)$$

$$C_i = \frac{C_a - P_n}{g_s} \hspace{1cm} (A1.8)$$

and

$$P_{nm} = \frac{(C_a - P_n) g_{m} - \Gamma g_m}{g_s} \hspace{1cm} (A1.9)$$

Then

$$P_{nm} = g_{m} \frac{C_{a} - P_{nm} g_{m} - g_{m} \Gamma}{g_s} \hspace{1cm} (A1.10)$$

where $g_m$ is in (µmol m$^{-2}$ s$^{-1}$)

$C_a$ is in (µmol mol$^{-1}$)

$\Gamma$ is CO$_2$ compensation point (µmol mol$^{-1}$)

The derivation of $P_n$ in equation (A1.5) can be obtained by substituting A1.2, A1.3, A1.4 in equation (A1.1), which can take the form of

$$\theta(P_n + R_d)^2 - (P_n + R_d) (\alpha \phi + (P_{nm} + R_d) + \alpha \phi (P_{nm} + R_d) = 0 \hspace{1cm} (A1.11)$$
Expanding the first and the second parts of equation (A1.1)

\[ \theta P_n^2 + 2\theta P_n R_d + \theta R_d^2 \]

\[-P_n \alpha \phi - P_n P_{nm} - P_n R_d - R_d \alpha \phi - P_{nm} R_d - R_d^2 \]

\[ + \alpha \phi P_{nm} + \alpha \phi R_d = 0 \]  \hspace{1cm} (A1.12)

rearrangement of (A1.12) gives

\[ \theta P_n^2 + 2\theta P_n R_d + \theta R_d^2 \]

\[-P_n \alpha \phi - P_n R_d - R_d^2 + P_{nm}(\alpha \phi - R_d - P_n) = 0 \]  \hspace{1cm} (A1.13)

rearrangement and substitution for (P_{nm})

\[ \theta P_n^2 + 2\theta P_n R_d + \theta R_d^2 \]

\[-P_n \alpha \phi - P_n R_d - R_d^2 + (g_m C_a - \frac{P_n g_m}{g_s} - g_m \Gamma) \]  \hspace{1cm} (A1.14)

\[ (\alpha \phi - R_d - P_n) = 0 \]

expanding of the third term of equation (A1.14) gives

\[ \theta P_n^2 + 2\theta P_n R_d + \theta R_d^2 \]

\[-P_n \alpha \phi - P_n R_d - R_d^2 + \alpha \phi g_m C_a - \frac{P_n g_m \alpha \phi}{g_s} - g_m \Gamma \alpha \phi \]

\[-g_m C_a R_d - P_n g_m / g_s R_d - g_m \Gamma R_d - g_m C_a P_n - P_n^2 g_m - g_m \Gamma P_n = 0 \]  \hspace{1cm} (A1.15)

rearrangement

\[ \left[ \theta P_n^2 + P_n^2 \frac{g_m}{g_s} \right] + \left[ (2\theta R_d P_n - P_n R_d - P_n \frac{g_m}{g_s} R_d) \right] \]

\[-P_n \alpha \phi - P_n g_m \alpha \phi - (g_m C_a P_n - g_m \Gamma P_n) + (\alpha \phi g_m C_a - g_m \Gamma \alpha \phi)] \]

\[ + \left[ (\theta R_d^2 - R_d^2) - (g_m C_a R_d - g_m \Gamma R_d) \right] = 0 \]  \hspace{1cm} (A1.16)
This equation has the quadratic form of

\[ ax^2 + bx + c = 0 \]

It can be solved for \( P_n \) using the negative root of

\[ P_n = \frac{-b \pm (b^2 - 4ac)^{0.5}}{2a} \]

where

\[
\begin{align*}
    a &= \left( \theta + \frac{g_m}{g_s} \right) \\
    b &= \frac{[R_d(2\theta + g_m - 1) - (\alpha\phi g_m + 1) - g_m(C_a - \Gamma)]}{g_s} \\
    c &= \alpha\phi g_m(C_a - \Gamma) + R_d(2\theta R_d - R_d) - g_m(C_a - \Gamma)
\end{align*}
\]
APPENDIX 4: Computer software acknowledgements, details of computer package used for data analysis and presentation in this thesis.

1. Easygraph
   Author: N. Stroud (originator, N.A. Watson)
   Reference: User note 12, Edinburgh Regional Computing Centre, JCMB, Kings Buildings, Mayfield Road, Edinburgh

2. BMDP
   Author: M. Ralston

3. Minitap
   Author: F. Ryan, B.L. Joiner and T.A. Ryan Jr. (1986)
APPENDIX 5: A list of the symbols, units and abbreviations.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Leaf area</td>
<td>cm², m²</td>
</tr>
<tr>
<td>C</td>
<td>Flux density of sensible heat</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Cₐ</td>
<td>Ambient CO₂ mole fraction</td>
<td>μmol m⁻²s⁻¹</td>
</tr>
<tr>
<td>Cₐᵦ</td>
<td>Mean of Cₑ and Cᵢ</td>
<td>μmol m⁻²s⁻¹</td>
</tr>
<tr>
<td>Cₑ</td>
<td>CO₂ mole fraction entering the chamber</td>
<td>μmol m⁻²s⁻¹</td>
</tr>
<tr>
<td>Cᵢ</td>
<td>Internal or intercellular space CO₂ fraction</td>
<td>μmol m⁻²s⁻¹</td>
</tr>
<tr>
<td>Cₒ</td>
<td>CO₂ mole fraction coming out from the chamber</td>
<td>μmol m⁻²s⁻¹</td>
</tr>
<tr>
<td>Cₑᵦ</td>
<td>Specific heat of air at constant pressure</td>
<td>J kg⁻¹ K⁻¹</td>
</tr>
<tr>
<td>D</td>
<td>Sensible heat advection term</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>eₐ</td>
<td>Water vapour pressure at air temperature</td>
<td>kPa</td>
</tr>
<tr>
<td>eₑ</td>
<td>Water vapour pressure entering the chamber</td>
<td>kPa</td>
</tr>
<tr>
<td>eᵢ</td>
<td>Internal partial water vapour pressure of the leaf</td>
<td>kPa</td>
</tr>
<tr>
<td>eᵢᵦ</td>
<td>Water vapour pressure at leaf temperature</td>
<td>kPa</td>
</tr>
<tr>
<td>eₒ</td>
<td>Water vapour pressure coming out of the chamber</td>
<td>kPa</td>
</tr>
<tr>
<td>E</td>
<td>Evaporation rate</td>
<td>mm</td>
</tr>
<tr>
<td>Eₒ</td>
<td>Pan evaporation rate</td>
<td>mm</td>
</tr>
<tr>
<td>ETₒ</td>
<td>Reference crop evapotranspiration</td>
<td>mm</td>
</tr>
<tr>
<td>ETᵢᵦ</td>
<td>Potential evapotranspiration</td>
<td>mm</td>
</tr>
<tr>
<td>Fₑ</td>
<td>Molar flow of air entering the chamber</td>
<td>mol m⁻²s⁻¹</td>
</tr>
<tr>
<td>Fₒ</td>
<td>Molar flow of air coming out of the chamber</td>
<td>mol m⁻²s⁻¹</td>
</tr>
<tr>
<td>G</td>
<td>The energy at which energy conducted down the petiole</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>gₑᵦ</td>
<td>Aerodynamic conductance</td>
<td>cm s⁻¹, mm s⁻¹</td>
</tr>
<tr>
<td>gᵦᵦ</td>
<td>Crop conductance</td>
<td>cm s⁻¹, mm s⁻¹</td>
</tr>
<tr>
<td>gₛᵦᵦ</td>
<td>Cuticular conductance</td>
<td>cm s⁻¹, mm s⁻¹</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>$g_m$</td>
<td>mesophyll conductance</td>
<td>$\mu$mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$g_{mx}$</td>
<td>Maximum mesophyll conductance</td>
<td>$\mu$mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$g_s$</td>
<td>Stomatal conductance</td>
<td>cm s$^{-1}$, mm s$^{-1}$, mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$g_{sd}$</td>
<td>Stomatal conductance at dark</td>
<td>mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$g_t$</td>
<td>Total conductance</td>
<td>mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$h$</td>
<td>Crop height</td>
<td>cm, m</td>
</tr>
<tr>
<td>IR</td>
<td>Irrigation requirement</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal conductance of the soil</td>
<td>J m$^{-2}$s$^{-1}$ c$^{-1}$</td>
</tr>
<tr>
<td>$K_c$</td>
<td>Crop coefficient</td>
<td></td>
</tr>
<tr>
<td>$K_h$</td>
<td>Heat transfer coefficient</td>
<td>cm$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>$K_w$</td>
<td>Water vapour coefficient</td>
<td>cm$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>$K_p$</td>
<td>Pan coefficient</td>
<td></td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf area index</td>
<td></td>
</tr>
<tr>
<td>LE</td>
<td>Latent heat of evaporation</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$L_u$</td>
<td>Upward long-wave radiation</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$L_d$</td>
<td>Downward long-wave radiation</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$M_a$</td>
<td>Molecular weight of air</td>
<td>mole</td>
</tr>
<tr>
<td>$M_w$</td>
<td>Molecular weight of water</td>
<td>mole</td>
</tr>
<tr>
<td>$P$</td>
<td>Set of parameters</td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>Energy trapped in photosynthesis</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>$p$</td>
<td>Atmospheric pressure</td>
<td>kPa</td>
</tr>
<tr>
<td>PFD</td>
<td>Photon flux density</td>
<td>$\mu$mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$P_n$</td>
<td>Rate of photosynthesis</td>
<td>$\mu$mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant</td>
<td></td>
</tr>
<tr>
<td>$r_{aw}$</td>
<td>Aerodynamic resistance for water vapour</td>
<td>s m$^{-1}$</td>
</tr>
<tr>
<td>$r_{ah} = r_h$</td>
<td>Aerodynamic resistance for heat transfer</td>
<td>s m$^{-1}$</td>
</tr>
<tr>
<td>$R_d$</td>
<td>Rate of respiration</td>
<td>$\mu$mol m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td>(r_m)</td>
<td>Mesophyll resistance</td>
<td>s cm⁻¹, s mm⁻¹</td>
</tr>
<tr>
<td>(r_s)</td>
<td>Stomatal resistance</td>
<td>s cm⁻¹, s mm⁻¹</td>
</tr>
<tr>
<td>(r_{st})</td>
<td>Total stomatal resistance</td>
<td>s cm⁻¹, s mm⁻¹</td>
</tr>
<tr>
<td>(R_n)</td>
<td>Net radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(R_s)</td>
<td>Solar radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>S</td>
<td>Chemical storage</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>SD</td>
<td>Standard error</td>
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</tr>
<tr>
<td>(S_d)</td>
<td>Short-wave radiation downward</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(S_n)</td>
<td>Net short-wave radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(S_r)</td>
<td>Albedo</td>
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</tr>
<tr>
<td>(S_s)</td>
<td>Sunshine</td>
<td>hrs</td>
</tr>
<tr>
<td>(S_t)</td>
<td>Total short-wave radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>(S_u)</td>
<td>Short-wave radiation upward</td>
<td>W m⁻²</td>
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<tr>
<td>T</td>
<td>Transpiration rate</td>
<td>mol m⁻² s⁻¹</td>
</tr>
<tr>
<td>(T_a)</td>
<td>Air temperature</td>
<td>°C, K</td>
</tr>
<tr>
<td>(T_b)</td>
<td>Bottom dome temperature</td>
<td>°C, K</td>
</tr>
<tr>
<td>(T_{bb})</td>
<td>Dry bulb temperature of the lower boom</td>
<td>°C, K</td>
</tr>
<tr>
<td>(T_{dw})</td>
<td>Dry bulb temperature of the upper boom</td>
<td>°C, K</td>
</tr>
<tr>
<td>(T_l)</td>
<td>Leaf temperature</td>
<td>°C, K</td>
</tr>
<tr>
<td>(T_{ln})</td>
<td>Non-transpiring temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{mx})</td>
<td>Maximum air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{mn})</td>
<td>Minimum air temperature</td>
<td>°C</td>
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<tr>
<td>(T_m)</td>
<td>Mean air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_s)</td>
<td>Surface temperature</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{s1})</td>
<td>Soil temperature, upper level</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{s2})</td>
<td>Soil temperature, lower level</td>
<td>°C</td>
</tr>
<tr>
<td>(T_{wb})</td>
<td>Wet bulb temperature, lower boom</td>
<td>°C</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Units</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
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</tr>
<tr>
<td>$T_{wu}$</td>
<td>Wet bulb temperature, upper boom</td>
<td>°C</td>
</tr>
<tr>
<td>$U$</td>
<td>Horizontal wind speed</td>
<td>m s$^{-1}$, km hr$^{-1}$</td>
</tr>
<tr>
<td>$V$ or VPD</td>
<td>Vapour pressure deficient</td>
<td>kPa</td>
</tr>
<tr>
<td>$W_a$</td>
<td>Ambient water vapour mole fraction</td>
<td></td>
</tr>
<tr>
<td>$W_b$</td>
<td>Mean of $W_e$ and $W_i$</td>
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<tr>
<td>$W_e$</td>
<td>Water vapour mole fraction entering the chamber</td>
<td></td>
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<tr>
<td>$W_i$</td>
<td>Water vapour mole fraction of leaf temperature</td>
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<tr>
<td>$W_o$</td>
<td>Water vapour mole fraction coming out of the chamber</td>
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</tr>
<tr>
<td>WBD</td>
<td>Wet bulb depression</td>
<td>°C</td>
</tr>
<tr>
<td>WUE</td>
<td>Water use efficiency</td>
<td>μmol mol$^{-1}$</td>
</tr>
</tbody>
</table>

$$\alpha$$ Quantum efficiency ($P_o/\phi$) dimensionless

$$\beta$$ Bowen Ratio dimensionless

$$\gamma$$ Psychrometric constant kPa °C$^{-1}$

$$\Delta$$ Finite differences

$$\Delta$$ Slope of saturated vapour pressure kPa °C$^{-1}$

$$\frac{\Delta e}{\Delta T}$$ Temperature

$$\varepsilon_s$$ Apparent emissivity of the surface dimensionless

$$\theta$$ Convexity coefficient dimensionless

$$\kappa$$ Thermal conductivity of the soil W m$^{-1}$ K$^{-1}$

$$\lambda$$ Latent heat of vaporisation W m$^2$

$$\rho$$ Density of the air kg m$^{-3}$

$$\sigma$$ Stefan-Boltzmann constant W m$^2$ K$^{-4}$

$$\phi$$ Photon flux density μmol m$^{-2}s^{-1}$

$$\Gamma$$ Compensation point μmol m$^{-3}$