THE EFFECTS OF TILLAGE PRACTICES AND CROP ROTATION SYSTEMS ON SOIL PROPERTIES AND WATER USE EFFICIENCY

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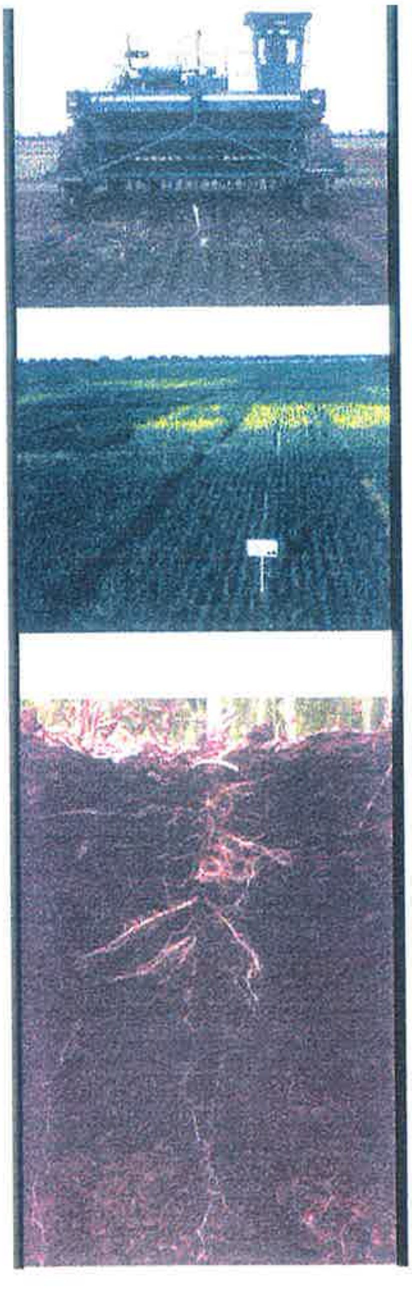

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Mattiga PANOMTARANICHAGUL
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ABSTRACT

The extensive literature on wheat production in dryland farming systems deals largely with empirical relationships between rainfall, available soil water during the growing season and grain yield. The improvement of surface soil structure using direct drilling and conventional cultivation has been widely studied in order to increase the accession of rainfall to the root zone and increase available soil water during the growing season. Direct drilling, conventional cultivation and different crop rotation systems can affect the form and resiliency of both surface and subsurface soil structure. Properties such as bulk density, aeration porosity, aggregate stability, penetration resistance and soil water characteristic may be changed by these practices. These soil properties effect root growth and root distribution which in turn can influence water use, crop growth and yield.

Little research has been carried out on the effect of crop rotation systems on soil profile structural improvement. Some work has been reported on the effects of canola and faba bean on soil properties and on wheat growth that has been preceded by canola or faba bean. The main factor responsible for poor water use efficiency by dryland crops is soil water loss by evaporation from the soil surface. If this can be reduced, water use efficiency can be increased. Rotations with certain crops may, and certainly different systems of tillage can, reduce evaporative losses.

The basic hypothesis of this study was that improved water use efficiency of rainfed crops can be achieved by adoption of tillage and sowing practices and crop rotation systems which improve surface and subsurface soil structure to increase the accession of rainfall and availability of soil water. The aims of the thesis were to (i) evaluate the effects of direct drilling and conventional cultivation on soil structure quality and water use efficiency, (ii) compare the effects of different crop rotations of wheat, canola and faba bean on surface soil structure and water use efficiency, particularly focussing on wheat as the main component in crop rotations and (iii) use modelling to partition soil water evaporation and crop transpiration to evaluate the effects of direct drilling and conventional cultivation on wheat water use efficiency under different weather conditions.

Wheat, canola and faba bean were sown by direct drilling and conventional cultivation treatments. Four replications were used in a randomised split-plot experimental design. Soil water contents were measured through the growing season using a neutron moisture meter and hand sampling, supplemented by time domain reflectometric methods. Other soil properties were measured 1 month before harvest. Soil water evaporation was measured by a microlysimeter technique during selected periods of crop growth from 1993 to 1995. Water use by each crop was calculated as rainfall plus the change of total water stored within a depth of 2 m in the soil profile. Runoff, deep drainage and interception losses were assumed negligible. Crop development at each growing stage was assessed by sampling a 2x2 m row length of above-ground biomass. Root density was measured during crop yield formation. Crop yield was harvested from two quadrants several days after ripening was complete. Water use efficiency of wheat from sowing to maturity, was expressed as dry matter production at different growth stages per unit depth water use.

Measurement of soil water evaporation was not practical other than for brief periods during the project. Therefore in order to partition crop transpiration from soil water evaporation, it was necessary to model one or both processes. Soil water evaporation models available in the literature were rejected because they were judged inadequate to handle fluctuation of evaporative demand and soil water diffusivity arising from repeated small rainfall events common in South Australia. A function combining the three stages of soil water evaporation into a single function was developed in order to overcome this problem and that of arbitrarily deciding when the transition between the three stages of evaporation occurred. The soil water evaporation model was developed using field-measured soil water evaporation data (microlysimeters), evaporative demand (microevaporimeters) and matric suction calculated from soil water content. A soil water evaporation function developed from these measured relationships was used to partition crop transpiration and soil water evaporation in order to assess the transpiration efficiency of the crop.

Measurement and modelling showed that direct drilling tends to induce more soil water evaporation compared to conventional cultivation when the soil surface is drying. This is probably due to greater pore continuity between the surface and deeper layers in direct drilled treatments. When the soil surface was wet, evaporation from conventionally cultivated treatments was greater than direct drilled treatments due to the greater surface roughness and higher macroporosity after tilling. However, the overall effects of direct drilling and conventional cultivation on soil water evaporation were dominantly dependent on the changes in the surface soil water retention characteristic and crop growth which affected the surface soil wetness and evaporative demand at the soil surface.

A crop transpiration model was developed using meteorological and the field experimental data measured over the four years from 1992 to 1995. The model was based on daily calculation of crop water use from climatic, crop and soil factors: a pan factor, crop transpiration factor, daily crop factor and daily soil factor. These factors were used to generate the daily potential evapotranspiration and the daily potential crop transpiration which were used to calculate the daily evaporative demand. This was then used to calculate daily soil water evaporation. The daily actual soil water evaporation and actual crop transpiration were calculated from the daily surface soil matric suction and available soil water.

Experimental results showed that direct drilling can improve both surface and subsurface soil structure under normal to wet weather conditions by creating lower values of bulk density and penetration resistance, higher values of aeration porosity and infiltration rate compared with conventional cultivation. These improvements were due to the absence of a tillage pan and the development of larger and more stable surface aggregates by sowing the crop using direct drilling. These improvements in soil structure lead to higher dry matter water use efficiency by wheat during tillering to maturity. However, grain water use efficiency was limited by rainfall during all growing seasons.

High rainfall in 1992 and 1993 caused noticeable deterioration of surface soil structure, (surface crusting and hardsetting) in conventionally cultivated treatments but less so in direct drilled treatments. In 1994, rainfall was low and soil structure destruction did not occur. In 1995 differences between direct drilling and conventional cultivation in terms of surface soil properties were not obvious because the lack of rain in 1994 did not differentiate the surface structural properties of the two treatments as much as in wetter seasons. These results show that intensity and frequency of rainfall during the growing season are important weather factors that govern surface soil structural conditions. Consequently direct drilling sustained better soil structure than conventional cultivation treatment in wet years. In drier years there was no clear effect of tillage.

Dry matter transpiration efficiency from before tillering to late flowering was closely related to the final grain yield. Maximum dry matter during all 4 years of experimentation was also significantly related to grain yield production. The maximum grain yield transpiration efficiency occurred in continuous wheat rotations sown by direct drilling in 1995 while the minimum value was found in 1994. The effects of tillage practices and crop rotations on grain yield and transpiration efficiency were not consistent because of the interaction between rainfall and the applied treatments.

A simple, clear conclusion concerning the effects of tillage practices and crop rotations on water use efficiency was not obtained. Evapotranspiration was influenced by atmospheric evaporative demand, the size of the crop canopy (surface cover) and the water supply or the soil wetness. The total amount of water used by the crop depended on rainfall distribution at each growth stage. Direct drilled treatments had higher soil water evaporation during dry periods, but this was lower than conventional cultivation when the soil surface was wet. Consequently, on balance, cumulative soil water evaporation from conventional cultivation treatments was higher than from direct drilled treatments due to poorer crop cover and degraded structure. Soil water evaporation and crop transpiration were substantially affected by crop growth and surface soil properties. The effects of any treatment on soil water evaporation and crop transpiration were dependent on how those treatments affected surface soil structure and crop growth. In some years the surface soil structure varied as climatic conditions varied. However, the partitioning of soil water evaporation and crop transpiration lead to a better prediction of potential and actual grain yield of wheat grown in a specific soil under different weather conditions.

DECLARATION OF ORIGINALITY

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis, all sources used, have been acknowledged in this thesis.

Mattiga Panomtaranichagul

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"The seed of knowledge is similar to all biological seeds. It needs a professional seeder, an appropriate time of seeding, suitable environmental conditions and a high quality seed to grow and give the best yield. As a Ph.D student, the seed of knowledge that has been grown in my soul has broadened my experience and increased my understanding during the last 5 years. As a lecturer and researcher in the University of Chiangmai, I hope that I can carry the same good seed from Australia to Thailand and in time that my students will harvest as a good yield in their education ".

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LIST OF ABBREVIATIONS AND SYMBOLS

β	an experimental parameter of evaporation characteristic during Stage II evaporation in Stroosnijder's model
α	desorptivity or an experimental parameter during Stage II evaporation in Ritchie 's model (m^2 sec^{-1})
θ	general volumetric soil water content (m^3 m^{-3})
λ	latent heat of vaporisation (MJ kg^{-1})
γ	psychrometric constant (kPa $^oC^{-1}$)
Δ	slope of the saturation vapour pressure - temperature curve (kPa $^oC^{-1}$)
$\Delta\rho v$	vapour density differences between the inflow and outflow boundaries (g ml^{-1})
ρa	air density (kg m^{-3})
θo	initial volumetric soil water content (m^3 m^{-3})
θs	soil water content at saturation (m^3 m^{-3})
θi	daily volumetric soil water content (m^3 m^{-3})
ΔSW	the change in total stored soil water (mm)
-BW	wheat sown after faba bean
-CW	wheat sown after canola
-WW	wheat sown after wheat
AP	aeration porosity (m^3 m^{-3})
AWo	initial available soil water (m^3 m^{-3})
AWC	available water capacity (m^3 m^{-3})
AWf	available water fraction
AWi	daily available water (mm)
AWm	maximum available water (mm)
BD	bulk density (Mg m^{-3})
CC	conventional cultivation
CDMi	daily cumulative dry matter (g m^{-2}, kg ha^{-1}, t ha^{-1})
Cp	heat capacity of the air (kJ m^{-3} $^oC^{-1}$)
cp	specific heat at constant pressure (kJ kg^{-1} $^oC^{-1}$)
CR	cumulative rain (mm)
Cw	water capacity (m^3 m^{-3} kPa^{-1})
CWU	cumulative water use (mm)
D	general deep drainage (mm)
D*	weight mean diffusivity (m^2 sec^{-1})
DD	direct drilling
DM or CDM	dry matter or cumulative dry matter (g m^{-2}, kg ha^{-1}, t ha^{-1})
Dri	daily deep drainage (mm d^{-1})
Dv	vapour diffusion coefficient (m^{-2} sec^{-1})
Em	evaporative demand (mm d^{-1})
Epetm	potential (pan) evaporation at maximum evapotranspiration (mm d^{-1})
Epi	daily potential (pan) evaporation (mm d^{-1})

es	saturated air vapour pressure (kPa)
es-ed	daily vapour pressure deficit (kPa) at mean height of crop canopy
Es	general soil water evaporation rate (mm d^{-1})
Espi	daily potential soil water evaporation (mm d^{-1})
ETa	general actual evapotranspiration (mm)
ETc	general crop evapotranspiration (mm)
ETo	reference crop evapotranspiration (mm)
ETp	general potential evapotranspiration (mm)
ETpi	daily potential evapotranspiration (mm d^{-1})
ETpm	maximum potential evapotranspiration (mm d^{-1})
ETptm	potential evapotranspiration at maximum crop transpiration (mm d^{-1})
FC	soil water content at field capacity or 10 kPa matric suction (m^3 m^{-3})
Fwi	daily total fresh weight of biomass (g m^{-2}, kg ha^{-1}, t ha^{-1})
G	heat flux density to the ground (MJ m^{-2} day^{-1}),
Hc	the height of a crop (m)
Hgi	gravitational soil water potential (kPa)
Hmi	matric soil water potential (kPa)
I	water loss through plant canopy interception (mm)
IR	steady state infiltration rate at 0.25 kPa soil matric suction (mm min^{-1})
IWC	initial soil water content (m^3 m^{-3})
$K_{\theta i}$	unsaturated hydraulic conductivity at θ_i soil water content (mm d^{-1})
Kci	daily crop factor
Kp	pan factor
Ksi	daily soil water factor
Kt	crop transpiration factor
L	general soil depth from the ground surface (mm)
LAI	leaf area index
MWD	mean weight diameter (mm)
N	total nitrogen content ((% w/w)
OC	organic carbon content (% w/w)
P	general precipitation (mm)
PD	particle density (Mg m^{-3})
PR	penetration resistance (MPa)
Qv	vapour flux density (g m^{-2} sec^{-1})
R	surface runoff (mm)
Ra	aerodynamic resistance (s m^{-1})
Rc	canopy or surface resistance to vapour transfer (s m^{-1})
RD	root length density (mm m^{-3}, mm m^{-2})
Ri	daily rainfall (mm)
Rn	net radiation (MJ m^{-2} day^{-1}),
Rno	net radiation above the canopy (MJ m^{-2} day^{-1}),
Rns	net radiation at the soil surface below the canopy (MJ m^{-2} day^{-1}),

RWUE	relative water use efficiency
RY	relative yield
S	cropping rotation system
S	general soil matric suction (kPa)
Si	daily soil matric suction (kPa)
SAD	stable aggregate as a fraction or percentage by weight
SAT	stable aggregate as a fraction or percentage by weight of total dry aggregate (g g^{-1} or %)
SD	surface soil depth (mm)
SWi	daily stored soil water (mm)
SWm	maximum stored soil water (at field capacity, mm)
SWw	stored soil water at wilting point (mm)
T	tillage practice
Tc	general crop transpiration (mm)
Tcai	daily actual crop transpiration (mm d^{-1})
Tcpi	daily potential crop transpiration (mm d^{-1})
TSW	total stored soil water (mm)
TxS	interactive effect between tillage practice and crop rotation system
Uz	wind speed (m s^{-1})
WP	soil water content at wilting point or 1500 kPa matric suction (m^3 m^{-3})
WU	general water use (mm)
WUE	water use efficiency (kg ha^{-1} mm^{-1})
Yp	potential or maximum yield (t ha^{-1})
Zi	soil depth of each horizon (mm)
Zw	the height of wind measurement (m)

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CHAPTER 1

GENERAL INTRODUCTION

Dryland wheat production in Southern Australia is limited by soil hydrological imbalances which are controlled by soil physical properties and climatic conditions. In general, wheat growth under rainfed conditions depends mainly on the available water within the root zone which is governed by the amount and distribution of rainfall on the one hand (French and Schultz, 1984) and storage and supply of available water in soil on the other hand (Greacen, 1981b; Hamblin, 1993).

Southern Australia enjoys a Mediterranean climate where rainfall predominates in the early part of the growing season (April to August) and is minimal during the latter part of the season (September to December). Only a small amount of water (<20 %) is used by wheat during the early growing season up to tillering. After tillering to maturity, approximately 80 % of total water use is needed for transpiration, especially during the anthesis stage. However, the amount of rainfall is high during the early growing season (>60 % of the total from April to October), generally exceeding the water requirement of wheat but there is insufficient rainfall during the post-tillering stage. The critical period of wheat production, between anthesis to maturity, falls during this stage. Therefore, wheat growth during the middle to the end of the growing season depends mainly on water stored in the root zone. (Greacen and Hignett, 1976).

The proportion of rainfall stored water within the soil profile and the soil water regime through the season is controlled by the surface and subsurface soil physical properties. The accession of rainfall to the soil profile, water holding capacity of the root zone, drainage below root zone, soil water evaporation and crop transpiration are all dependent on soil structural quality. Optimum total storage of water and maximum availability of water for the crop production demands optimum soil structural qualities. The methods available to improve soil properties under rainfed conditions are generally restricted to improved tillage practices and crop rotation systems.

Adaptation of tillage practices have been used to improve soil structure in dryland farming systems. Both direct drilling and conventional cultivation have both been used to increase water use and water use efficiency on dryland farming systems. However, the soil responses to either direct drilling or conventional cultivation depends on other soil management practices and the cropping systems (Denton and Wagger, 1992). Factors such as soil type, soil wetness, types of tillage machinery and tillage systems play a role in determining the response.

Conventional tillage has been used primarily to provide a fine seedbed to ensure optimum seed germination and also to control weeds, increase infiltration, enhance topsoil aeration, increase water stored in the soil profile, reduce surface runoff and reduce water evaporation loss by capillary rise to the soil surface during drying (Baver, 1968). However, it is now accepted that excessive tillage may induce soil structural deterioration (Cresswell et al., 1991). Conventional tillage may lead to decreased infiltration and hydraulic conductivity due to the decrease in the number of large pores in the subsurface layer (Lindstorm and Onstad, 1984). Generally, tillage tends to temporarily decrease the bulk density and increase the total porosity of the tilled layer. At the same time, soil below the tilled layer suffers increased bulk density from the pressure and remoulding applied by the tillage machinery (Klute, 1982). In time, because of increased oxidation of organic matter, structural stability changes and the physical condition of the tilled layer deteriorates. To minimised these adverse effects, tillage is confined to the sowing operation (direct drilling) by many wheat growers in the cropping areas of South Australia

(Hamblin and Kyneur, 1993). Weed control is achieved by use of herbicides and appropriate crop rotations.

Direct drilling may improve soil structure by retarding the development of a tillage pan and by promoting more stable surface soil aggregates and associated pores. These improved soil structural conditions promote increased infiltration, reduced surface runoff, decreased penetration resistance, increased aeration porosity and improved soil water characteristics (Datiri and Lowery, 1991).

In South Australia there is a need to develop improved farming systems that will optimise water storage and increase crop rooting depth. The factors that provide the means to do this include direct drilling or conventional cultivation and rotations of wheat (*Triticum aestivum L.*), canola (*Canola cache*) and faba bean (*Vicia faba L.*). These elements of a management system have the capacity to improve surface, subsurface and subsoil structure. The improved surface soil aggregate stability, lower bulk density, better aeration, greater available water storage capacity and increased infiltration rate can be expected to increase the accession of rainfall to the root zone and increase the availability of stored soil water. Ultimately these improvements are expected to increase crop water use efficiency. An additional benefit that could account from these advances is that deep drainage to the ground water table would decrease because of improved water storage and increased crop rooting depth.

The single most important step in improving crop productivity in Southern Australia is to improve water use efficiency. Crop water use is defined as the total volume of water (m^3) lost from a unit area (m^2) of crop canopy by evapotranspiration (usually expressed as millimetre of water). Water use efficiency is the mass of dry matter or grain produced per unit area per unit depth water use (kg ha^{-1} mm^{-1}). Water use efficiency in Southern Australia ranges from 16 to 54 kg $ha^{-1}mm^{-1}$ for dry matter and from 4 to 19 kg ha^{-1} mm^{-1} for grain (French and Schultz, 1984). This very large range of values reflect variations of climate (rainfall) and also different soil physical and environmental conditions and management.

Attempts to improve water use efficiency by crops under rainfed conditions assume that any increase in water use efficiency is dependent on increasing crop transpiration and decreasing soil water evaporation. However, few studies have been conducted in which transpiration has been measured separately from evaporation. Crop water use efficiency should therefore be expressed as transpiration efficiency instead of evapotranspiration efficiency. The difficulty in measuring this lies in partitioning total crop water use into soil water evaporation and crop transpiration. One method of doing this is to model soil water evaporation and crop transpiration separately. Crop production (dry matter or grain yield) per unit area per unit depth of water used for crop transpiration is called "transpiration efficiency" which is a better index for crop water use efficiency measurement than the commonly used evapotranspiration efficiency (Tanner and Sinclair, 1983). In South Australia, French and Schultz (1984) obtained maximum transpiration efficiencies of 55 and 20 kg ha^{-1} mm^{-1} for dry matter and grain yield of wheat respectively. Measurement of dry matter transpiration efficiency during sensitive growing stages of the crop may lead to improved understanding of the potential grain yield of wheat for specific soils under different climatic conditions.

Generally, there is little knowledge available to guide development of improved farming systems in Southern Australia which links soil structural quality to relative losses of water by transpiration as opposed to evaporation. The role of different tillage systems and crop rotations is also not clear in this distinction. An understanding of these interactions should provide a clearer basis for devising farming systems uniquely suited to Southern Australia conditions.

Aims of the research

The objective of the research reported in this thesis was to provide information to improve the productivity of dryland farming systems by improving surface and subsurface soil structure using tillage practices and crop rotation systems which can be expected to improve water use efficiency of crops.

Specific aims were to:

(i) compare the effects of direct drilling and conventional cultivation on surface and subsurface soil structural properties which effect crop production (dry matter and water use efficiency),

(ii) compare the effects of direct drilling and conventional cultivation on soil water evaporation, total stored soil water and cumulative water use (crop evapotranspiration),

(iii) compare the effects of different rotations of wheat, canola and faba bean on surface and subsurface soil structural properties which effect water use efficiency of wheat,

(iv) use modelling to study the effects of direct drilling and conventional cultivation on transpiration efficiency of wheat.

Thesis outline

This thesis consists of eight chapters. The literature review (Chapter 2) deals mainly with the effects of agricultural practices (tillage practices and crop rotations) and rainfall on soil properties, root distribution, crop growth, water use (soil water evaporation and crop transpiration) and water use efficiency including water use models. The experiments and results from this study are presented in three parts. The first part (Chapter 3) describes methodology, experimental and statistical design and computational procedures during 4 years of the experimentation from 1992 to 1995. The experimental results are presented in two sections: empirical results and modelling. Chapters 4 and 5 deal with field and laboratory experimental results. Chapter 4 covers the effects of tillage practices and crop rotation systems on surface and subsurface soil properties and field soil water evaporation. Chapter 5 covers stored soil water, cumulative water use, water use efficiency and crop production (dry matter and grain yield) including root length density distribution. Chapters 6 and 7 deal with modelling of water use to analyse the water use efficiency of wheat by generating and developing a soil water evaporation model (Chapter 6) and partitioning of evapotranspiration into soil water evaporation and crop transpiration (Chapter 7). Chapter 8 provides a general summary of the results and conclusions from the work.

CHAPTER 2

LITERATURE REVIEW:
SOIL PROPERTIES AND WATER USE EFFICIENCY IMPROVEMENT IN DRYLAND FARMING SYSTEMS

2.1 Introduction

In general, crop growth and yield are limited by the amount and distribution of growing season rainfall (French and Schultz, 1984). Within these limitations growth and yield are controlled by soil water availability (largely soil physical conditions) (Greacen, 1981b), and nutrition, especially, nitrogen content (chemical conditions) (French, 1978; Oades, 1981; Hamblin and Kyneur, 1993). Of these two sets of conditions, modern farming systems minimise nutritional limitations more effectively than adverse soil physical conditions. Consequently, the yardstick by which soil quality for grain production and system sustainability are judged tends to be the efficiency with which water is extracted from soil rather than chemical conditions. This indicator is most commonly expressed as water use efficiency (biomass or grain production per unit area per unit equivalent depth of water used by the crop).

Increased crop water use efficiency is not easy to achieve, but one way of accomplishing this is by optimisation of the agricultural water balance system through improved soil and crop management. Success in achieving improvements to water use efficiency by rainfed crops can be assessed by using water balance models which account for soil, crop and climatic conditions.

In reviewing the literature on this topic my aims are to describe (i) the general dryland agricultural water balance system, (ii) systems of soil and crop management used to improve soil properties and water use efficiency, (iii) processes of dryland crop water use with emphasis on evaporation loss of water from the soil surface and (iv) modelling of evapotranspiration, soil water evaporation and crop yields as a tool to improve crop yields and assure sustainable farming systems.

2.2 Dryland agricultural water balance system

The water balance equation for dryland crop production may be expressed as (Campbell and Diaz, 1988)

$$\mathbf{P = I + R + \Delta SW + D + Es + Tc} \qquad \mathbf{(2.1)}$$

where P is the amount of rainfall, I is interception by plant canopy, R is surface runoff or runin, ΔSW is the change in soil water storage, D is deep drainage beyond the root zone, Es is soil water evaporation and Tc is transpiration by the crop. The magnitude of each term of Equation 2.1 depends on climatic conditions, soil type and crop variety.

Rain water reaching the soil surface may be lost in several ways. Some of the water may be intercepted by the crop canopy and may be evaporated without passing through the plant (I). This term is often ignored because it is relatively small. If the rainfall intensity is higher than the infiltration rate of the soil surface, the excess water may be lost as surface runoff or runin (R) depending on slope position. However, R may be negligible for flat land with low rainfall intensity. The amount of water that does enter the soil profile may either be held as soil water (SW) and causes changes in total soil water storage (ΔSW) or may drain beyond the root zone and be lost by deep drainage (D). Stored soil water may be lost directly by evaporation from the soil surface (Es) or consumed by plant roots and transpired by the crop (Tc). Crop transpiration is the process which results in dry matter and grain production.

Understanding the magnitude and dynamics of different components of the crop water balance is the basis for developing management options to improve water use efficiency. Improved water use efficiency implies that either grain yield is increased or I, R, D and Es are reduced, or both.

2.2.1 Rainfall and dryland crop production

Growing season rainfall has been used as a predictor of the water available for dryland crop production because of a high correlation observed between rainfall, water use, and crop yields. (Angus et al., 1980; French and Schultz, 1984; Greacen and Hignett, 1976). However, the total amount of rainfall may not necessarily be related to grain yield because other water balance components, such as soil water evaporation (Es), canopy interception (I), surface runoff (R), and deep drainage (D) may significantly influence the relationship between yield and rainfall. This is apparent from data presented by French and Schultz (1984).

2.2.1.1 Effective rainfall

Effective rainfall is the fraction of total rainfall which is used by crops (Jensen et al., 1990). Effective rainfall is closely related to crop evapotranspiration (ETc), the sum of soil water evaporation (Es) and crop transpiration (Tc). Jensen et al. (1990) showed that the amount of effective rainfall stored in the soil profile is dependent upon the frequency, amount, duration and intensity of rainfall as well as soil surface condition and soil water storage capacity. The availability of the stored soil water varies with soil depth and soil water characteristics within the root zone. In general, the effectiveness of rainfall increases with increasing the amount of total stored soil water within the root zone.

2.2.1.2 Relationships between wheat yield and rainfall

Effective rainfall is the most important limiting factor in dryland crop production. Cornish (1950, quoted by French and Schultz, 1984) reported that 65 % of wheat yield variation in South Australia is associated with the amount and distribution of rainfall during April to October. The amount of rainfall during June to August was particularly critical for grain yield. This was because the maximum water requirement for wheat occurs during the critical growing period from anthesis to maturity. Sief and Pederson (1978) found that spring rainfall in New South Wales between three weeks before anthesis to two weeks after, accounted for 86% of the variation in yield.

French and Schultz (1984) determined the relationships between the amount of rainfall, wheat growth and grain yield and water use for 61 locations in South Australia. They found a close relationship between total dry matter production or total grain yield per millimetre of water used (water use efficiency) and the yield per millimetre of rainfall during the growing season (April to October). The highest water use efficiency (WUE) for dry matter production was 37 kg ha^{-1} mm^{-1} and the highest WUE for grain yield reached 12.7 kg ha^{-1} mm^{-1}.

French and Schultz (1984) found that the rainfall which occurred between April and October rainfall, (X, mm) was a good approximation of crop water use and soil water availability (WU, mm) (Equation 2.2) except if rainfall exceeded 475 mm. This model predicted that potential yield (Yp) could be estimated from these parameters as shown in Equation 2.3

$$WU = 1.04 X - 18.4 \tag{2.2}$$

$$Yp = 0.018 WU - 1.98. \tag{2.3}$$

Equations 2.2 and 2.3 can only be applied to well managed crops of high yielding varieties of wheat under constraints of no deep drainage, no surface runoff or surface ponding, no waterlogging and minimum soil surface evaporation loss. As these equations are stochastically based, without accounting for rainfall distribution they are likely to fail in years of unusual rainfall conditions.

Greacen and Hignett (1976) avoided the problem of seasonal limitations by using a water use estimation based on daily water balance and soil properties. They also noted that there was surplus rainfall and possibly deep drainage during the early growing season and often insufficient rainfall during the post-tillering stage. Therefore, wheat growth during the middle to the end of growing season depends mainly on water stored in the root zone.

2.2.2 Availability of stored soil water

2.2.2.1 Available soil water capacity

Plant available water capacity (AWC) is the water held between the states of "field capacity" and "permanent wilting point". There are, however, difficulties in defining these boundaries which causes available water capacity to be a rather imprecise quantity to estimate in the field.

Field capacity is defined as the water content of soil following rainfall and after a period of free drainage has taken place until the downward movement of the water becomes negligible which approximately occurred within 2 to 3 days (Cassel and Nielsen, 1986; Kutilek and Nielsen, 1994). Marshall and Holmes (1988) pointed out, however, that field capacity is not well defined because the definition of "negligible downward movement of water" is imprecise, particularly under field conditions. As a compromise, field capacity is often taken to be the water content at either 10 or 33 kPa of matric suction (Doorenbos and Pruitt, 1977; Kutilek and Nielsen, 1994). In this thesis a value of 10 kPa will be used.

Wilting point is equally poorly defined. The lower limit of water availability, when permanent wilting by plants sets in, is the final stage in water stress and signals the onset of plant death as a result of water limitations. The water content at the onset of permanent wilting is usually taken to be "wilting point". However, this point is not a practical field parameter for obvious reasons, so that as a practical measure the water content at a matric suction of 1500 kPa is usually regarded as the lower limit of available water.

The field capacity water content (FC) is often reached in a soil profile while the wilting point (WP), which depends on a substantial active root concentration, is seldom reached in the deep soil layers. Capillary rise from the deeper layers beyond root zone can supply water to the crop even if the soil water content in the root zone is lower than wilting point. The soil water content at a matric suction of -1500 kPa may have some limitations for predicting available water capacity (AWC) in field situations.

Most researchers (eg. Ritchie, 1972; Greacen and Hignett, 1976; Shouse et al., 1982; Campbell and Diaz, 1988) have estimated available water capacity by measuring field capacity and wilting point directly under field conditions in order to calibrate their water balance models. This approach is most accurate as it takes into account typical root density and depth, but is time consuming and expensive.

Others have adopted different approaches. For example, Shanholtz and Younos (1994) presented an equation to estimate the plant available water from only rooting depth and the saturated soil water content. They assumed that a deeper root system increased the available water supply because of the greater storage volume. Their equation was written as

$$AW = 0.5\,[-1 + (1 + 4\,a\,RD^{b})^{1/2}] \tag{2.4}$$

where AW is available soil water (cm), RD is root depth (cm), a and b are constants related to soil water content at saturation.

Unfortunately the approach of Shanholtz and Younos (1994), ie Equation 2.4, only gave good results for uniform soils of about 300 mm depth. In Australia uniform soil depths of this magnitude are seldom found in cultivated dryland cropping areas. Consequently Equation 2.4 may not give a reliable value of estimated available soil water and usually researchers rely on the more conventional techniques described earlier.

2.2.2.2 Actual available soil water

At any instant in time the soil water content (θ) in excess of wilting point (θ - WP) is defined as the actual available water content which represents the water available to a crop (AW) and depends on water stored within the soil profile (Doorenbos and Pruit, 1977; Cassel and Nielsen, 1986; Marshall and Holmes, 1988). When root depth is taken into account and roots are distributed in many soil horizons (Greacen and Hignett, 1976) the amount of stored water within the root zone (SW), and the changes in the amount of stored water (ΔSW) during a period of crop growth from t_1 to t_2 can be written as:

$$SW = \sum_{i=1}^{n} \theta_i Z_i \qquad (2.5)$$

and

$$\Delta SW = \sum_{i=1}^{n} \theta_i t_2 Z_i t_2 - \sum_{i=1}^{n} \theta_i t_1 Z_i t_1 \qquad (2.6)$$

where i is the number of horizons which is occupied by plant roots. θ_i and Z_i are the volumetric water content and thickness of the i th horizon respectively.

ΔSW during a period of crop growth can be accounted for water use by the crop, losses by deep drainage and evaporation from the soil surface, and additions by infiltration of rainfall.

2.2.3 Surface runoff

Surface runoff occurs on sloping sites when the rainfall intensity exceeds the infiltration rate or when the cumulative rainfall exceeds the soil water storage capacity and drainage rate is slow. Runoff can be estimated from several of models which use slope, rainfall intensity, soil type and other parameters which depend on precision required.

Steward et al. (1976, quoted by Campbell and Diaz, 1988) proposed a "runoff parameter", to estimate the amount of surface runoff that would occur in different soil conditions. They grouped soils into 4 types based on high, moderate, low and very low infiltration and drainage rates. Higher infiltration and drainage gave a higher values of infiltration and a lower amount of water loss through surface runoff. The relationships between runoff and rainfall at different values of the runoff parameter.

Runoff is often negligible on flat sites, surplus water simply ponds on the surface and eventually saturates the surface soil, often causing anaerobic conditions in the surface layers. On a sloping surface, runoff varies with the angle of the slope, drainage rate and initial infiltration rate (Saxton et al., 1974; Campbell and Diaz, 1988).

2.2.4 Drainage

The drainage component of the soil water balance equation is difficult to measure accurately under the field conditions because it is transient and varies as a function of the other components of the equation. It can be determined by measuring the soil water regime and soil water retention during a period of time.

Hillel et al. (1972) proposed a field method for measuring drainage which requires frequent and concurrent measurements of the soil wetness and soil water potential profiles. The drainage values were calculated based on the instantaneous values of the hydraulic potential gradients ($\partial H/\partial Z$), hydraulic conductivity (K_θ) and fluxes operating ($\partial\theta/\partial t$) within the profile based on the following equations (Cassel and Neilsen, 1986):

$$\partial\theta / \partial t = [\partial (K_{\theta i}\, \partial H/\partial Z) / \partial Z] \quad (2.7)$$

where θi is the volumetric water content of each horizon, t is time, Zi is soil depth of each horizon, $K_{\theta i}$ is hydraulic conductivity at θi, H is the hydraulic head (matric plus gravitational suction).

In a heterogeneous soil profile with different soil layers of different hydraulic properties, it assumed that the value of matric potential gradient ($\partial Hmi/\partial Zi$) in each soil layer approaches zero and only gravitational potential gradient ($\partial H_{gi}/\partial Z_i$) was taken into account. Hence, integration of Eq. (2.7) from the surface to depth L yields

$$\partial \left({}_{o}\int^{L}\theta_i\, dZ_i\right) / \partial t = [K_{\theta i} (\partial H_{gi}/\partial Z_i) |_{zi = L}] - [K_{\theta i} (\partial H_{gi}/\partial Z_i) |_{zi = 0}] \quad (2.8)$$

$$\text{or} \qquad L\,(\partial\theta / \partial t) = -K_\theta \quad (2.9)$$

where θ is the mean soil water content within soil depth from the surface to L and was calculated as:

$$\theta = (1/L)\, {}_{o}\int^{L} \theta_i\, dZ_i. \quad (2.10)$$

The drainage rate at depth L can be calculated from the rate of change of θ or K_θ at depth L (Equation 2.9) (Hillel et al., 1972). If water content is not changing, $\partial\theta / \partial t = 0$, then Equation 2.9 implies that drainage does not occur when soil water is constant (Hillel et al., 1972). However, Rose and Stern (1965) asserted that drainage can occur under steady state conditions without changing soil water content at any given depth because inflow rate is equal to out flow rate.

Cassel and Nielsen (1986) asserted that a drainage rate of 1 mm d^{-1} compared to an evapotranspiration rate of 5 mm d^{-1} may seem negligible, but in the Northern Great plain of the USA., a drainage rate of only 0.1 mm d^{-1} can cause a significant development of saline seeps over several years.

2.2.5 Soil water evaporation

Evaporative loss of water from the soil surface is a major component of the soil water balance and can substantially affect crop water use efficiency in dryland agricultural systems. French and Schultz (1984) found that evaporation accounts for losses of as much as one-third of the rainfall from April to October in many wheat-growing areas of SA. Marshall and Holmes (1988) stated that soil water evaporation from an incomplete crop canopy can account for half the total losses of water during the growing period of an annual crop. However, Jalota and Prihar (1990) stated that even under a fully developed crop canopy, water loss by evaporation may be as high as 50% of water loss through evapotranspiration and it may vary from 40% to 75% of precipitation in semi-arid and arid regions (Jalota, 1993; Minhas et al., 1986). Furthermore, Pilbeam et al. (1995) showed that surface evaporative losses can account for between 70% and 85% of evapotranspiration which ranged from 150 to 325 mm. Thus this process can reduce crop water use efficiency under dryland farming systems.

Water use efficiency can be increased by reducing soil water evaporation. Angus, et al. (1980) noted that the maximum water use efficiency (15.8 kg ha^{-1} mm^{-1}) for grain production of wheat in a subtropical environment was obtained when a minor proportion (14%) of water used or evapotranspiration was lost by evaporation from the soil surface.

Evaporation from the soil is limited by available energy received at the soil surface and the surface soil water content. When the soil water content is high and soil surface is wet, evaporation is dependent on the available energy (Bond and Willis, 1970; Ritchie, 1972). If the soil water content drops below a critical level and the soil surface is drying, evaporation is chiefly controlled by the soil moisture content and the soil hydraulic conductivity. (Gardner, 1959; Jackson et al., 1973; Idso et al., 1974). The mechanism of the soil water evaporation process and the effects of the agricultural practices on soil water evaporation are discussed more fully in Section 2.4.

2.2.6 Transpiration

Transpiration is the process of water loss from the soil via plant leaf stomata. Kutilek and Nielsen (1994) partitioned water use into that used in metabolic processes in the plant tissue and water transpired into the atmosphere.

2.2.6.1 Transpiration process

According to the Soil-Plant-Atmosphere-Continuum (SPAC) model, the driving force of the water transport is dependent on the gradient of matric suction in the soil adjacent to the root surface and the, resistance at the soil-root and leaf-atmosphere interfaces and those inside the plants conducting system.

A plant may temporarily wilt during high evaporative demand conditions if the influx of water to the roots is lower than the transpiration loss from the leaves. Subsequently, when evaporative demand diminishes, turgor in the leaf tissue may return. When the soil is relatively dry and extreme evaporative demand conditions exist, the loss of cell turgor pressure is accompanied by irreversible changes in the plant which finally cause permanent wilting. Stomata also provide the accession of CO_2 to the plant for photosynthesis and plant growth. Hence, there is high correlation between transpiration and crop yields (Kutilek and Nielsen, 1994).

2.2.6.2 Potential and actual transpiration

Potential crop transpiration (Tcp) or unstressed transpiration is defined as the loss from the plant tissues to the atmosphere at atmospheric evaporative demand with the stomata fully opened, and when water deficit does not limit transpiration.

Actual water transpired (Tca) from a crop is often less than potential transpiration (Tcp). This is usually attributable to low flux of water towards plant roots as the soil dries. The low flux occurs because of the decline in unsaturated hydraulic conductivity of the soil as a result of lower soil water content. The reduced flux of water towards the roots causes an increased soil water suction gradient at the root-soil interface. This suction gradient is propagated to the leaf cells which undergo a decrease of cell turgor and this initiates closure of leaf stomata. The critical value of turgor pressure which cause stomatal closure depends upon the value of potential transpiration and the root density of the crop. The variations of actual transpiration rate (Tca) as a function of soil water content, θi is presented in Figure 2.1.

The daily amount of water transpired by a plant depends on the evaporative demand of the atmosphere, the leaf area, the energy received by the plant, and the water suction gradient between the leaf and the soil. The substomatal water potential is the driving force which moves water from soil into the plant system. When the transpiration rate decreases at night or on humid days and soil water is available at greater water potential, absorption of water by plant root takes place until the water potential of the soil and the leaves are at equilibrium.

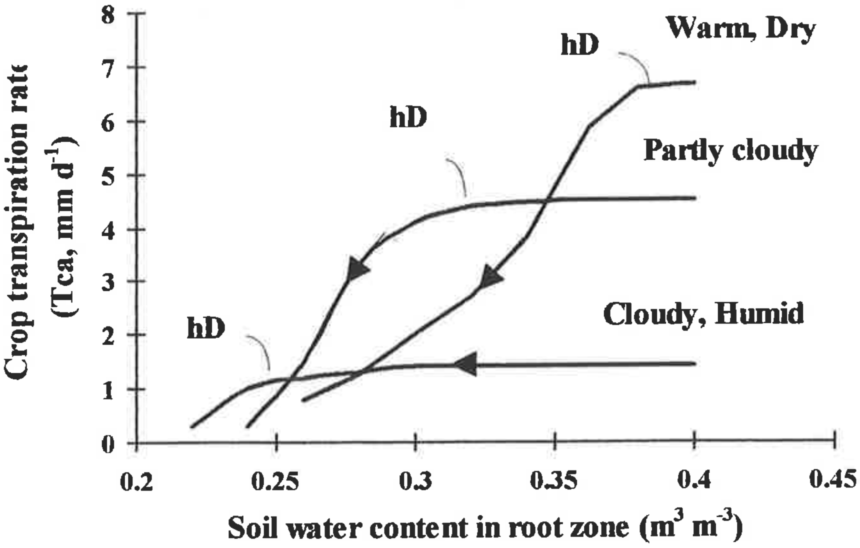

Figure 2.1 The decrease of actual transpiration rate Tca with a decrease of soil water content θi under different climatic conditions, h_D is the critical value of turgor pressure when stomata start to close (Denmead and Shaw, 1962 after Kutilek and Nielsen, 1994).

2.3 The effects of agricultural practices on soil structure and crop growth in dryland farming systems

The upper limit of dryland crop production is set by climatic conditions and the genetic potential of the crop. This limit may be approached by correct management of soil water in order to support the biological needs of the plant. Therefore, optimally efficient use of water in wheat production can be attained when agricultural practices are able to improve soil water storage and availability to the crop. Soil surface management and crop rotation systems have been used in the effort to improve wheat production in relation to water availability for several decades.

2.3.1 Soil structure and plant growth

2.3.1.1 Terminology and definition

(i) Soil structure: Kay (1990) described soil structure in terms of form, stability and resiliency as the following. (1) "Structural form" refers to total porosity, pore size distribution and continuity of the pore system including the arrangement of primary soil particles into hierarchical structure states identified on the basis of failure zones of different strengths. (2) "Structural stability" is the extent to which structural form rearrangement of solid and void space to a less optimal condition when exposed to different stress. (3) "Structural resiliency" is the extent to which degraded structural form will recover optimal condition through natural processes.

(ii) Pore characteristics: Distribution, continuity, stability and resiliency of pores are important in aeration, infiltration, drainage and redistribution of soil water within the soil profile. Thomasson (1978, quoted by Kay, 1990) has defined four classes of structure by using a relative proportion of macro pores (>60 μm diameter) and mesopores (60 - 0.2 μm diameter). The best classes of soil structure has a macroporosity ≥ 15 % and mesoporosity of 20 to 35 %. The worst classes has a macroporosity < 5 % and a mesoporosity of < 35 %. On the other hand, Gibbs and Reid (1988) developed a model using pores greater than 100 μm in diameter to described the change of soil structural characteristics that affect drainage and leaching. These pores are also important for root development in compacted soil (Dexter, 1986; Dexter, 1988; Stypa et al., 1987).

(iii) Soil aeration: Aeration porosity (AP) or "air filled porosity", defined as the relative air filled pore volume at field capacity, is a widely used index of aeration quality. Soil aeration can limit crop growth if the aeration porosity is ≤ 10 % (Doorenbos and Pruitt, 1977). Although most researchers suggested that the minimum limit of aeration porosity in soils for crop growth is about 10 %, no single value of AP can be considered optimum for all situations (Grable, 1966; Stolzy, 1974, quoted by Erickson, 1982).

2.3.1.2 Soil structure and root development

Plant roots require a continuous supply of water and oxygen, supplied via the soil pore system. The flux of water and oxygen to plant roots is controlled by pore size distribution (soil structure), which in turn controls soil water retention, total porosity, soil aeration porosity and soil strength. Bulk density, a surrogate measure of these parameters, is often used to quantify the quality of soil structure for optimum plant growth.

Cassel (1982) stated that the range of bulk density values for optimum plant growth is unknown for most soils. When bulk density is less than an optimum value, soil water retention may be poor while higher bulk density values may restrict aeration and impede root growth through high strength. Rooting depths of a particular plants decrease as soil bulk density increases. Glinski and Lipiec (1990a) asserted that for the average soil bulk density of 1.36 Mg m^{-3}, 90% of wheat roots were found in the soil layer from 0 to 500 mm while for the average soil bulk density of 1.65 Mg m^{-3}, wheat roots were found in the layer from 0 to 150 mm. This restriction of root growth may lead to a reduction of crop growth and yield production. However, the relationship of bulk density and crop yield has been established for some soils (eg., Flocker et al., 1960; Philips and Kirkham, 1962; Singh et al., 1971, quoted by Cassel, 1982).

Dexter (1988) and others have shown that an adequate supply of oxygen to plant roots requires that at least 10 % of the pore space needs to be filled with air in the wettest condition. For freely draining soils this usually occurs when soils are at field capacity. At this water content, gravitational forces will have emptied pores larger than about 30 μm equivalent spherical diameter which corresponds to a matric suction of about 0.01 MPa. or field capacity water suction.

Water supply to roots also depends on the water flow to the root surfaces. Hasegawa and Sato (1987) suggested that soil hydraulic conductivity must be at least 10^{-4} to 10^{-5} mm d^{-1} if water supply is not to restrict plant development. However, the water flow is also controlled by the hydraulic gradient between the root surface and the soil. Such a low K_θ may not restrict root growth under a high hydraulic gradient condition.

Dexter (1988) postulated that plant develops a high density of roots near the surface where plant nutrients, water and oxygen are more available compared with the deeper soil layer. For many crops grown in good soils, normal root density profiles are approximately exponential with the highest density close to surface.

Glinski and Lipiec (1990a) described that when the soil water content decreases, there is often an increase in soil strength and reduced root elongation. Davis (1984) (quoted by Glinski and Lipiec, 1990a) also found that the roots were more sensitive to soil water deficits at higher soil strength values than at lower values in sandy loam soil. On the other hand, Muneer et al. (1982, as quoted by Glinski and Lipiec, 1990a) reported that soybean root length was higher with an increase in soil water content at low soil bulk density values (1.0 Mg m^{-3}). At higher bulk density values (1.4 and 1.6 Mg m $^{-3}$) increasing water content did not produce similar long root systems. These concepts are illustrated in Figure 2.2 which shows a strong interaction between matric suction, bulk density and root elongation rates.

This interaction between water and mechanical properties raises a question mark over the "available water" concept based on the limits of field capacity and permanent wilting point. Letey (1985) proposed an expanded concept which he called "nonlimiting water range" (NLWR). This model characterizes soil physical conditions affecting available water for plant growth in terms of soil aeration and mechanical resistance as well as the conventional limits of field capacity and wilting point.

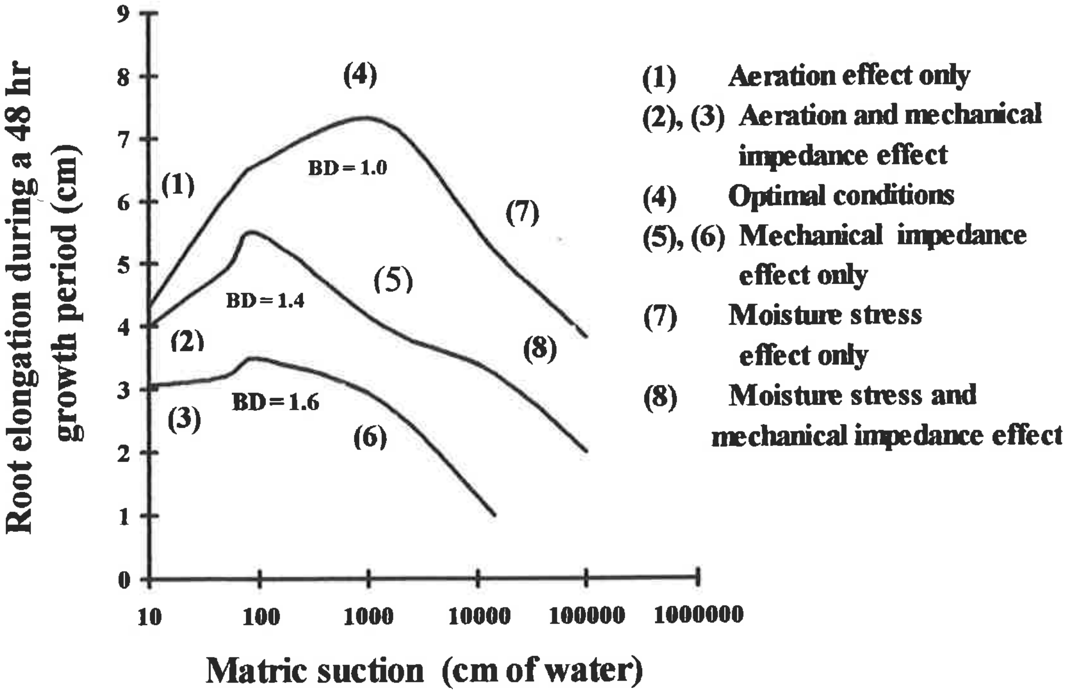

Figure 2.2 Role of mechanical impedance, aeration and moisture stress on pea seedling root elongation in a sandy loam soil held at different matric suction and bulk density values (modified after Eavis, 1972 as quoted by Glinski and Lipiec, 1990a).

2.3.2 Tillage practices affecting soil structure, surface runoff and soil water infiltration

Tillage is defined as the mechanical manipulation of soil to disrupt compact, hard surface layers to create an optimum seedbed for germination, emergence and early growth of crops. Tillage may also serve to control weeds, incorporate plant residues, chemicals and fertilisers. Each tillage operation will alter the soil structure and change soil physical properties because of the loosening, granulation, compaction, crushing, inversion, shearing and shattering that occurs (Gill and Vanden Berg, 1967, quoted by Cassel 1982).

Erickson (1982) and others have made the point that for most soils, tillage can only temporarily correct the hardness and aeration problems of poor soil structure. Many

Australian soils suffer considerable structural deterioration in farming systems that use regular soil tillage. This has led to a strong trend worldwide to reduce tillage to a minimum, very often at sowing only. Coarse textured soils or very well aggregated soils with no aeration problem can generally not be improved by tillage.

Erickson (1982) showed that tillage has an interactive effect with rainfall on plant growth. Tillage can improve soil aeration and root development in seasons of high rainfall because the oxygen supply in the soil increases after tillage operation. In dry seasons a similar level of tillage intensity may have no benefit for crop growth. Dowdell et al. (1979, quoted by Erickson, 1982) found that oxygen concentration affected by tillage practices varied with seasonal rainfall. Direct drilling (tillage only at sowing) resulted in generally higher oxygen concentration in soil (10.2 %) than conventional tillage (7.2%) during wetter seasons. This suggested that direct drilling develops better structural stability and was more durable to rainfall impact compared with conventional tillage.

2.3.2.1 Tillage and soil bulk density

Cassel (1982) showed that bulk density values from tillage studies varied from <1.0 to 1.7 Mg m^{-3}; the significant differences among tillage treatments was as small as 0.07 Mg m^{-3} and the surface soil bulk density is only temporarily changed after the tillage operation. For instance, bulk density of freshly tilled soil may increase after soil settling in response to wetting by rainfall and the kinetic energy associated with rain drop impact (Cassel, 1982; Gusli, 1994). On the other hand this tilled layer may decrease in bulk density due to the loosening action of roots and animal activities (Cassel, 1982).

Chan and Mead (1992) found that a bulk density increased from 1.34 to 1.54 Mg m^{-3} in the top 50 mm of soil between 19 and 98 days after sowing using conventional cultivation methods. The direct drilled treatment showed only a very small increase in bulk density; consequently bulk density of both the cultivated and direct drilled treatments were similar by mid season.

Hageman and Shrader (1979) found that there was no differences in bulk density of the top soil among different tillage practices after 20-year trials because initially the spatial variability of bulk density was large. This suggested that the initial variation of bulk density should be investigated on each field plot before commencing tillage research.

2.3.2.2 Tillage and mechanical impedance

Penetration resistance (mechanical impedance) is defined as the force required to push a metal cone into the soil divided by the basal area of the cone (Davidson, 1965, quoted by Cassel, 1982). This value varied from nearly zero in a subsoil slit to values higher than 9 MPa in a tillage-induced pan (Cassel, 1982). Greacen (1977) showed that resistance by soil to penetration of a metal penetrometer is controlled in a complex way by the strength and compressibility properties of the soil which depend strongly on bulk density and water content. Penetration resistance is often used to predict the impedence offered by soil to root growth. The approach has been criticised because field penetrometers have larger diameters than roots, penetration rates are faster than roots, and are more rigid than roots (Cassel, 1982). However, penetration resistance is a rapid measurement where sufficient data can be obtained allowing use of powerful statistical procedures for evaluating the data.

2.3.2.3 Tillage practices affecting surface runoff, infiltration and soil water conductivity

Tillage operations can alter the water balance of soil (infiltration, runoff, evaporation relationships) by breaking up any surface crust and creating a suite of large pores at the surface. On the other hand tillage may produce a surface crust on bare soil after high intensity rainfall (Cassel, 1982). The type of tillage operation preceding sowing and that used for sowing the crop can have a decisive effect on water relations during the growing season.

Direct drilling of crops produces several conditions that influence infiltration or runoff. The surface ground cover is most important, since cover can slow runoff and decrease the impact energy of raindrops on the soil surface. Direct drilling of seed also favours continuity of pores from the surface down to deeper layers. These continuous pores are important pathways for infiltration. Cassel (1982) showed that direct drilling reduced surface runoff almost every year over a period of 15 years compared with conventional tillage. However, direct drilling failed to increase infiltration in some conditions due to the abnormal weather.

Recently, Malinda (1995) studied the effects of tillage and stubble on surface runoff on a red-brown earth at Tarlee (70 km north of Adelaide) for 10 years. The results showed that runoff was reduced in the zero-tillage treatment and in the stubble retention or stubble x zero-tillage combination. Increasing the average annual stubble retention decreased runoff and soil loss linearly. Crop type also influenced erosion. For example, soil was more vulnerable to erosion after pea than after cereal. The amount of stubble after harvesting was usually greater with cereals than with grain legumes. Similar results were found by Pikul and Aase (1995) and Cassel et al. (1995).

Tillage practices also influence the soil hydraulic potential gradient which may affect the magnitude and direction of water flux in the soil. Ehlers and Baeumer (1974) found that a plough pan induced by tillage operations could impede water infiltration significantly. This was characterised by the reduction of large pores and a lower conductivity at nearly saturation in 20-30 cm soil depth. They observed that the changes in matric suction in the untilled soil occurred at 30-150 cm soil depth after a heavy rain storm. In tilled soil most changes in matric suction were observed at a depth of 0-20 cm, and the wetting front moved down more slowly than in untilled soil (Figure 2.3). They ascribed this difference to better biological activity in direct drilled treatments, rapid infiltration on direct drilled plots occurred through earthworm holes that were open to the soil surface.

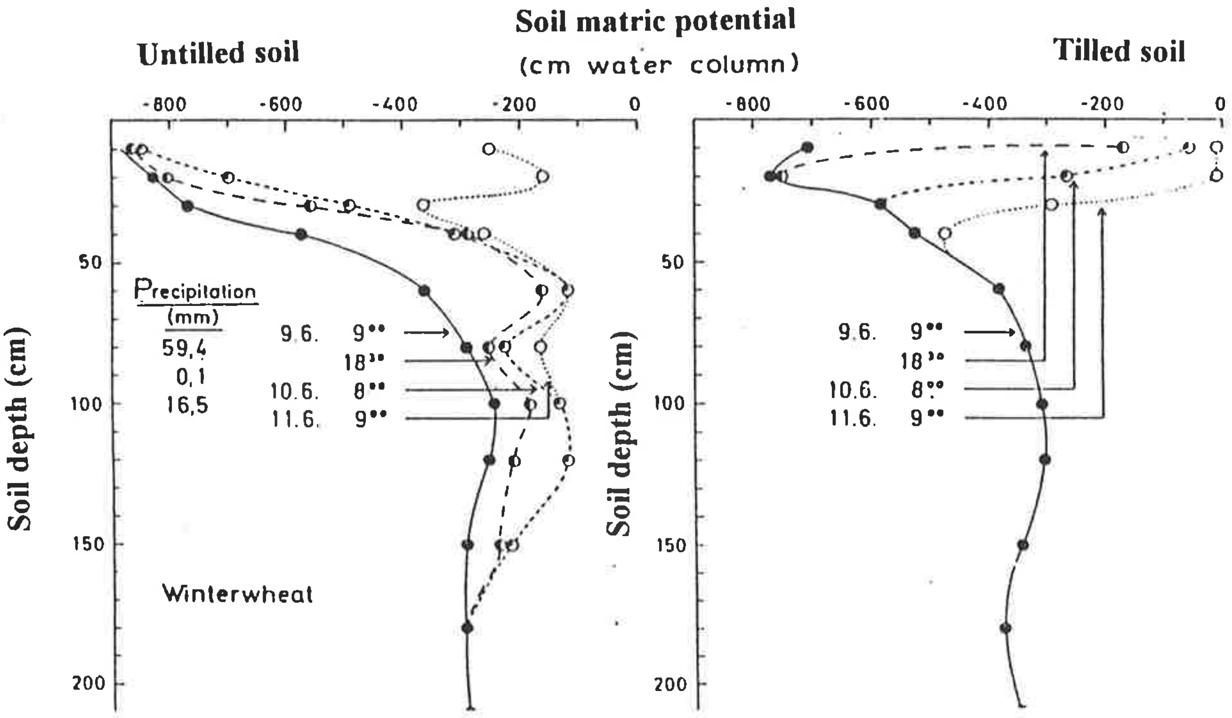

Figure 2.3 Matric suction distribution after infiltration at 11.6 , 10.6 and 9.6 mm hr^{-1} following rainfall of 16.5, 0.1 and 59.4 mm at different times, in tilled and untilled silt loam soil (from Ehlers and Baeumer, 1974).

Cassel (1982) suggested that differences in permeability of subsoil layers may be important in wet seasons or periods when the topsoil is nearly saturated, but subsoil permeability rarely influences infiltration during dry periods or seasons when the water storage capacity of top soil is not filled. Soil crusting, mulching and surface cover are also important factors affecting infiltration.

2.3.3 Effect of agricultural practices on organic matter and stable aggregates

The amount and types of organic matter in the soil can affect soil structural stability differently depending on the rate of decomposition and microbial activity which are caused by tillage operation. Dexter (1988) showed that the organic matter component that stabilises microaggregation may be protected from microbial attack and therefore may persist for a long time. The amount of water stable microaggregation is rather insensitive to tillage and crop rotation systems. On the other hand, the organic matter which stabilises the larger aggregates is constantly renewed by crop growth and is readily accessible to microbial attack. Hence the water stability of large aggregates is therefore sensitive to tillage and crop management.

Tisdall and Oades (1980) found that after fifty years of crop production, most large water stable aggregates (>1000 μm diameter) had broken down into microaggregates (< 250 μm diameter). Aggregates of 50-250 μm diameter were particularly stable in all the treatments studied. They also found that the non-cultivated plots contained the greatest amount (>55 %) of aggregates larger than 250 μm diameter and had the greatest organic carbon (2.3%) contents compared with either the fallowed plots (organic carbon <1.6%) or the cultivated plots (organic carbon > 1.6% and < 2.3%). The explanation for this was that in uncultivated plots plant materials were added to the soil with less disruption and oxidation leading to high percentage of organic matter left in the soil compared with cultivated plots.

Tisdall and Oades (1982) postulated that macroaggregation is controlled by soil management (eg. crop rotations), as management influences the growth of plant roots and the oxidation of organic carbon. The water-stability of microaggregates depends on the persistent organic binding agents and appears to be a characteristic of the soil, independent of management. Edwards and Bremner (1967) suggested that microaggregates are the most stable aggregate component in soil while macroaggregates are readily disrupted when air-dry soil is wetted. Similar results were also found by Carter (1992).

2.3.4 Soil cultivation and root growth

Glinski and Lipiec (1990b) reviewed the effects of conventional and reduced tillage on crop root growth. They concluded that root growth and root density were greatest in the surface horizons of soils under minimum tillage compared to conventional tillage. In wetter seasons this difference was less pronounced. In fine-textured soils, root extension of winter wheat was faster in direct drilled treatments compared to conventional cultivation. In the deeper layers of these soils, the quantity of cereal roots was consistently greater in direct drilling than in cultivated treatments. This suggests that crop water use efficiency in direct drilled crops on fine textured soils will be greater than crops sown by conventional cultivation methods during low rainfall seasons.

Glinski and Lipiec (1990b) reported that in coarse-textured soils the growth of seminal roots was slower under direct drilling or shallow conventional cultivation compared to deeper conventional cultivation. Similar findings had been reported by Ellis and Barnes in 1980. Root growth in sandy and loess soils sown by direct drilling had fewer roots between 100 to 200 mm depths than conventionally cultivated soil because of a traffic pan in the latter treatment at 250 mm depth. The traffic pan had higher bulk density and penetration resistance than any layer in the direct drilled soil. In the direct drilled treatment total water uptake from the 100 to 200 mm depth interval was consequently lower but greater in the 300 to 600 mm depth interval compared to conventionally cultivated soil. This may also lead to higher water use efficiency in direct drilling than in conventional cultivation during drier seasons.

Chan and Mead (1992) found that direct drilled wheat had a greater root length density in the 0-50 mm depth interval compared to wheat sown by conventional cultivation methods. The highest root length density was found in the 50 to 100 mm layer of the conventional cultivation treatment, higher than any root density values found in the direct drilled treatments. Again, as in the work reported by Glinski and Lipiec (1990b), this was probably due to a shallow tillage pan at about 100 mm that was acting as a barrier to downward root extension.

Ellis and Barnes (1980) showed that direct drilled wheat had fewer roots in the 100 to 300 mm depth interval compared with conventionally cultivated treatments. In deeper soil layers (>300 mm), rooting density in direct drilled treatments was not different from cultivated treatments. They also found that after a period of extreme drying, more roots were present in direct drilled treatments than on conventionally cultivated treatments. After a period of prolonged wet soil conditions, fewer roots were present in direct drilled than conventionally cultivated treatments.

Dexter (1988) showed that vertical roots may be deflected to grow horizontally along the top of compacted layers. In this way, roots may be able reach weaker areas in the compacted layer and resume downward growth. Roots with right angle bends are quite commonly observed in cultivated and strongly pedal soils.

Goss et al. (1984) found that root penetration was always deeper after direct drilling than after cultivation, particularly in well drained soil. Regular replenishment of soil water in the surface layers by rainfall would favour direct drilled crops more than conventionally sown crops because of the greater abundance of roots near the surface in the former. Consequently direct drilled crops may have a reduced reliance on deeper water resources. Dexter (1988) suggested that roots in deeper soil layers are important for the supply of water but those in the topsoil layer are important for both water and nutrient supply because plant nutrients are largely confined to the topsoil. This suggests that water use efficiency may be improved in dryland crop production by increasing root density in the topsoil.

However, several researchers showed that surface layers were denser and stronger in direct drilled treatments than conventionally cultivated treatment which might lead to poor early growth of crops in the former treatment (Dexter et al., 1983; Mason and Fischer, 1986; Chan et al., 1987; Chan and Mead, 1992). However, there is little conclusive evidence to support the idea that poor soil physical conditions induced by direct drilling limit root growth and cause poor early growth of wheat. Poorer early wheat growth was caused by biological rather than soil physical factors (Chan et al., 1989; Passioura, 1991).

2.3.5 Effect of rainfall on soil structure

Soil structure in the tilled layer were substantially altered by the amount of rainfall after tillage. Dexter et al. (1983), working with a South Australian Urrbrae fine sandy loam, showed large decreases in porosity with the first 10 mm of rain at all depths in the tilled layer. Further rainfall produced smaller changes but these were still significant at a relative depth (depth/total depth of tilled layer) of 0.25 in the tilled layer. The increases in void size were by factors (the ratio of void size before rainfall and after rainfall) of 1.07, 1.07, and 1.23, and the mean aggregate size increased by factors (the ratio of mean aggregate size before rainfall and after rainfall) 2.1, 1.9, and 1.7 at relative soil depth of 0.25, 0.5, and 0.75 of the tilled layer respectively, with 395 mm of rain (Table 2.1).

Table 2.1 Values of macroporosity (η), void size (δ) and aggregate size (D) at different soil depths of the tilled layer and after different cumulative amounts of rainfall since tillage (after Dexter et al., 1983)

Soil depth as proportion of the depth of the tilled layer	Soil properties	Cumulative rainfall (mm) 0	10	135	395
0.25	η	0.330	0.262	0.241	0.194
	δ (mm)	2.18	2.24	2.25	2.33
	D (mm)	4.64	6.33	7.26	9.67
0.50	η	0.255	0.192	0.208	0.160
	δ (mm)	1.89	1.84	2.19	2.03
	D (mm)	5.53	8.00	8.34	10.63
0.75	η	0.198	0.131	0.151	0.152
	δ (mm)	1.82	1.55	1.85	2.23
	D (mm)	7.63	10.63	10.39	13.03

Kay et al. (1994) showed that the stability and tensile strength of aggregates of a red-brown earth soil declined with the number of wetting events. The variation in these characteristics due to rainfall was often much greater than the variation due to management practices such as crop rotations and tillage operations. Kay and Dexter (1992) concluded that the impact of cropping history on tensile strength of soil aggregates was dependent on climatic conditions.

2.3.6 Crop rotations affecting soil structure and crop growth

It may be possible to improve subsoil structure may be by growing a crop of certain species of crop with strong root systems (by so called biological drilling). Subsequent crops, susceptible to poor soil structural conditions might benefit from the improved structure. Improvement in root growth, water extraction and grain yield could be benefits of biological drilling. Cresswell and Kirkegaard (1995) suggested two possibilities to study the effects of biological drilling in amelioration of subsoil structure. Firstly, specific measurements of soil pores, their size, number and continuity are required to establish that soil structural change has occurred through biological drilling. Secondly, the effect of biological drilling must be isolated from other confounding influences such as disease reduction and improvements in plant nutrition that might occur from crop rotation.

Packer et al. (1994) studied the effect of canola on infiltration and surface soil stability of a red duplex soil (Dr 2.23) with a hard setting sandy loam surface texture in New South Wales. They reported that canola improved surface soil structure as evidenced by a higher infiltration rate, lower runoff, better aggregate stability and higher organic carbon content compared with wheat. These effects were still observable the following season after a crop of faba beans. The reasons for the soil structure improvement by canola were described by Packer et al. (1994) as follows. (i) The extent of surface cover from canola prevented much of the adverse effects of raindrop impact during the vegetative growing stage. (ii) The extensive fine lateral root system of canola at the 100 to 150 mm depth interval encouraged increased biological activity, releasing soil binding agents (carbohydrates and humic substances) and stimulated rhizosphere microflora causing increased aggregate stability.

On the other hand, Cresswell and Kirkegaard (1995) asserted that two seasons of canola did not create any measurable changes to soil structure at the top of the B horizon of a red brown earth (Natric Palexeralf) at Temora, NSW. However, grain yield and water extraction were greater for wheat following canola compared with wheat following wheat due to reduced incidence of root disease. The canola was unable to create new pores due to the high strength of the soil matrix, and thus relied on the pre-existing pores. They also indicated that annual crops with tap roots such as lupins or canola are unlikely to be able to improve B-horizon porosity in dense, duplex soils while perennial species as lucerne might be more effective at biological drilling because of the longer time and wider range of water content conditions in which the plant may establish a deep root system.

Recently, Mckenzie et al. (1995) showed that wheat and canola utilised different mechanisms to obtain their nutrients and influence their root rhizosphere. Rhizosphere changes were a function of interactive effects between plant species, soil type, rainfall and previous soil management history.

Bruce et al. (1995) found that large increases in rainfall infiltration and reduced soil erodibility were associated with direct drilled grain sorghum after crimson clover in comparison to grain sorghum sown by conventional tillage after soybean. The maintenance of a decomposing mulch by crop residue additions of 12 t ha^{-1} yr^{-1} generated high soil C levels in the 0 to 15 mm depth interval and a high water stability of aggregates in the 0 to 80 mm depth interval in comparison to incorporated crop residues. Grain yield of conventional sown soybeans ranged from 30 to 100% greater on the previously direct drilled treatment. This means that the restoration and maintenance of soil productivity were dependent on the previous crop rotations and the soil resources associated with maintenance of decomposing mulch on the soil surface derived from appropriate quantity and quality of crop residues produced in situ.

2.3.7 Cropping systems and available soil water

Larney and Lindwall (1995) found that continuous winter wheat cropping over a period of 10 years greatly depleted soil water reserves in Canada. Averaged over the same period wheat after canola depleted soil water more than either continuous wheat or wheat after fallow. On the other hand, they found that different systems of tillage had no effect on available water during winter wheat production over this time Although direct drilling had no advantage with respect to available water to 1.5 m depth, it did increase available water in the 0 to 150 mm depth interval.

However, Larney and Lindwall (1995) measured soil water contents only twice during each growing season. This probably was not frequent enough to be certain that the available water in the soil profile at these times represented the available water to crop for the whole season. The amount of available water changes daily, depending on evaporative demand, climatic conditions and root distributions. Small but regular differences in water availability in the various rotation treatments may have had significant effects on the observed difference in crop production.

Recently, Brandt and Zentner (1995) reported experimental results from nine rotations of wheat (W), canola (C), barley (B), and alfalfa hay (H) including fallow (F) on a dark brown chernozemic soil. They found that rotations did not affect yield of wheat or canola grown on summer fallow. This meant that available water left in a fallow soil after summer (caused by different crop rotations) did not cause any different yield of wheat or canola. However, wheat grown after canola gave higher yields and better quality than continuous wheat treatment. They noticed that wheat yield reduction in continuous wheat treatments was caused by increased leaf disease compared with growing wheat after canola. The lower incidence of leaf disease could lead to higher water use efficiency and greater yield production. This result was confirmed by Mckenzie et al. (1995) who reported that canola roots caused smaller dehydrogenase activity and frequently lowered pH within their rhizosphere which suppressed microbial activities compared with wheat. Cresswell and Kirkegaard (1995) also found that wheat following canola caused greater grain yield and water extraction compared with wheat following wheat due to reduced incidence of root of root disease.

2.4 Soil water evaporation and tillage

Direct evaporation of soil water from the soil surface will reduce water use efficiency by reducing available water for crop production. The associated upward flow of water in the soil profile transports salts to the surface and causes salinity problems. In the past, tillage was used as a practical strategy to create a "soil mulch" for retarding soil water evaporation. However, this practice has been discredited because it has been shown that excessive, conventional, shallow tillage may cause so much drying of the tilled layer that available water for crop emergence and seedling establishment is reduced during the early growing period (Jalota and Prihar, 1990; Fischer, 1987).

Tillage may affect soil water evaporation in several ways:

(i) increase evaporation of water from the soil surface due to decreased albedo and increased surface roughness of the soil,

(ii) reduce evaporation due to soil mulch which leads to increasing the available water conserved below the tilled layer,

(iii) induce a tillage pan that may increase mechanical resistance to root penetration below the tilled layer,

(iv) decrease the upward flow of water due to increasing discontinuity of soil pores between tillage pan and the tilled layer.

The aim of this section is to discuss the mechanism of the soil water evaporation process, the limiting factors that control evaporation, and the effects of tillage on soil water evaporation losses, in order to understand the effect of tillage on soil water conservation under dryland farming systems.

2.4.1 The mechanism and measurement of soil water evaporation

2.4.1.1 Terminology and definition

Evaporation of soil water (Es) is a hydrological process by which liquid water is transformed to vapour and transported out of the soil to the atmosphere. Kutilek and Nielsen (1994) described the three major stages in evaporation: (i) the transport of liquid water to an evaporating surface, (ii) a phase change from liquid water to vapour, (iii) the transport of water vapour from the soil to the atmosphere. Liquid water transport is influenced by temperature and the hydraulic potential gradient of soil water (Jalota and Prihar, 1990; Marshall and Holmes, 1988; Jury et al., 1991). Vapour pressure and temperature gradient between atmospheric and soil water controls vapour transport (Jensen et al., 1990).

Evaporation from a free water surface or from wet soil surface exposed to the atmosphere where there is no restriction to the rate of evaporation from the surface is denoted as **potential evaporation, Ep** (Ritchie, 1972; Jensen et al., 1990) or **evaporative demand, Eo** (Johns, 1982b) or **evaporativity, Eo** (Jalota and Prihar, 1986; Jalota, 1993). Evaporation from a bare soil or from a soil surface under the crop canopy is named as **soil water evaporation, Es** (Ritchie, 1972; Gardner, 1959) or **actual soil water evaporation**, **Esa** (Kutilek and Nielsen, 1994; Stroosnijder, 1987). This review will define evaporation from a non-restricted surface soil water condition as **potential soil water evaporation (Esp),** and evaporation from any soil surface condition as actual soil water evaporation (Eas). Evaporation from any free water on the soil surface and from a class-A pan are defined as **evaporative demand (Em)** and **pan evaporation (Epan)** respectively. The magnitude of Esp depends primarily on atmospheric conditions, net radiation received by the surface and surface albedo (Jensen et al., 1990). Es from bare soil can be approximately equal to Eo or Esp or evaporative demand as these all have approximately the same albedo and surface roughness.

2.4.1.2 The three stages of soil water evaporation

The rate of soil water evaporation is divided into three stages as presented in Figure 2.4. The three distinct stages are (i) a constant potential rate stage, (ii) a falling rate stage and (iii) a reduced rate stage (Philip, 1957; Idso et al., 1974; Jalota and Prihar, 1990; Kutilek and Nielsen, 1994; Gardner, 1983).

(i) Stage I soil water evaporation

Stage I evaporation occurs at a constant rate from a wet soil surface and high soil water content within the soil profile. This is chiefly limited by the evaporative energy at the soil surface (Ritchie, 1972; Bond and Willis, 1970; Jalota and Prihar, 1990). Jury et al. (1991) described the first stage of soil water evaporation from a wet soil surface as evaporative loss that occurs at the potential rate. At this stage, the upward flow of soil water from deeper soil layers to the soil surface is assumed to match the potential evaporation rate. This balance is maintained by an increase in the hydraulic potential gradient as water is lost from the surface until K_θ decreases. Decreased K_θ decreases the water supply to the surface, causes decreased Es and the first stage of evaporation ends (Figure 2.4) (Kutilek and Nielsen, 1994).

(ii) Stage II soil water evaporation

Stage II evaporation is characterised by a decreasing rate of evaporation because of soil drying. The evaporation rate during second stage is less than the potential evaporation rate. Gardner (1959), Ritchie (1972) and Idso et al. (1974) showed that this stage is regulated dominantly by the soil hydraulic properties that control the rate at which water moves to the soil surface.

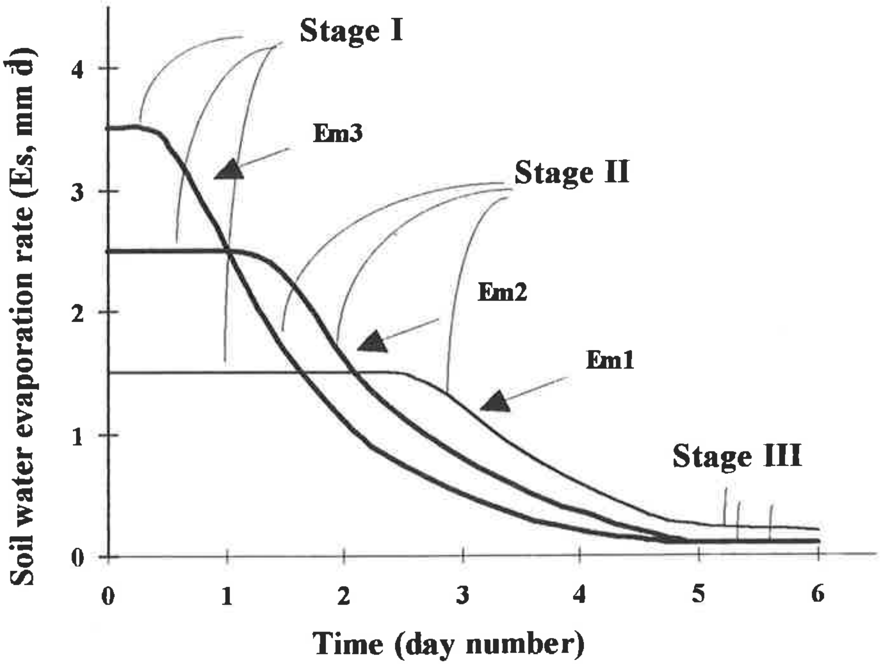

Figure 2.4 Evaporation rate from a soil (Es) as a function of time (t) for three values of a constant evaporative demand (Em1, Em2 and Em3), showing the three stages of evaporation from a soil (Stage I, Stage II and Stage III) during constant atmospheric conditions. (Kutilek and Nielsen, 1994).

Hillel (1971), Jackson et al. (1973) and Jalota and Prihar (1986) agreed that Stage II evaporation rate is determined by soil hydraulic properties but they showed that soil depth, water content of the soil profile and atmospheric conditions are also involved. Therefore, during this stage Es is dominantly limited by the amount of water which can be conducted to the soil surface and evaporative demand at the soil surface. The evaporation rate gradually decreases with time until a dry layer develops at the surface.

(iii) Stage III soil water evaporation

Stage III evaporation is denoted as a reduced-evaporation-rate stage (Jalota and Prihar, 1990) or a water vapour stage (Kutilek and Nielsen, 1994) occurring after the surface soil becomes sufficiently dry and water moves at a slower rate through the drier layer to the surface as vapour. Stage III evaporation (Figure 2.4) is regulated by higher thermal gradients than in the earlier stages (Marshall and Holmes, 1988) and it appears to be initiated at a surface water content that corresponds to a retention of two molecular layers of water surrounding the soil particles (Idso et al., 1974) or when the soil water content of the surface is close to hygroscopic value or atmospheric vapour pressure (Kutilek and Nielsen, 1994).

Idso et al. (1974) asserted that the concept of Stage III evaporation is not clearly understood because the transition between stage II to stage III is not evident when the depth zone of the soil under consideration exceeds a few centimetres. Johns (1982a) stated that the third stage of soil evaporation hardly occurs in the field because diurnal temperature fluctuation and other atmospheric processes can induce diurnal fluctuations of evaporative demand. However, there is some agreement (Jury and Letey, 1979; Kutilek and Nielsen, 1994; Ishihara et al., 1992). that Stage III evaporation occurs as vapour flow from deeper layers to the soil surface by molecular diffusion and turbulent diffusion, but the amount of cumulative evaporation loss at this stage is very small and is relatively unimportant for crop production. Therefore most researchers have confined their attention to evaporation in Stage I and Stage II only, ignoring Stage III evaporation (Philip, 1957d; Ritchie, 1972; Fischer, 1987; Hanks et al., 1967; Lockington, 1994; Marshall and Holmes, 1988; Jensen et al., 1990; Jury et al., 1991; Hanks, 1992b; Kutilek and Nielsen, 1994).

2.4.1.3 The mechanism of soil water transport under evaporation process

Water transport in soil may occur in either the liquid or vapour states depend upon soil hydraulic properties and soil thermal properties. Soil hydraulic properties (hydraulic conductivity, water capacity, water diffusivity, hydraulic gradient and soil water content) influence liquid flow, whereas soil thermal properties (heat conductivity, heat capacity, thermal gradients and soil temperature) influence vapour flow (Hank, 1992a; Jury et al., 1991; Jury and Letey, 1979; Philip, 1957).

(i) Liquid water flow in soil

The upward flow of liquid water through soil to the surface is described by the general theory of water flow for either steady or transient state conditions. Many models for calculating soil water evaporation have basic similarities, having been developed or modified from the general flow equation (Equation 2.11) and Green and Ampt's infiltration equation (Equation 2.12) (Black et al., 1969; Marshall and Holmes, 1988; Jury et al., 1991; Hanks, 1992a; Kutilek and Nielsen, 1994). Equation 2.11 combined with Equation 2.12 gives an equation for predicting soil water evaporation rate (Es) (Equation 2.13). This equation has been modified and is widely used to predict water flux within the soil profile to the soil surface (Gardner, 1959; Black et al., 1969; Kutilek and Nielsen, 1994).

$$\partial\theta / \partial t = \partial (\partial\theta / \partial Z) / \partial Z \qquad (2.11)$$

$$i = \Delta\theta \, (D_\theta / 2\, t)^{1/2} \qquad (2.12)$$

$$Es = (\theta i - \theta s) D_\theta^{1/2} / \pi^{1/2} \, t^{1/2} \qquad (2.13)$$

where θ ($m^3\ m^{-3}$) is the volumetric soil water content, D_θ ($m^2\ sec^{-1}$) is the soil water diffusivity, Z (mm) is the vertical distance of water movement from the deeper soil layer to the soil surface, i is the infiltration rate (mm hr^{-1}), θi is the initial soil water content

(m^3 m^{-3}), and θs is the soil surface water content (m^3 m^{-3}), with $\theta > \theta s$, π is 3.143 and t is time (hr).

(ii) Water vapour flow in soil

Water vapour flow in soil may occur in either upward or the downward direction depending upon soil temperature and vapour pressure gradients. Water vapour can move through the air filled pores when soil has a large air filled porosity during the drying stage.

Hanks (1992a) proposed a simple equation similar to Fick's Law of Diffusion for predicting water vapour flow under steady state conditions:

$$Qv \;=\; Dv\, \Delta\rho v / \Delta z \qquad (2.14)$$

where Qv (g m^{-2} sec^{-1}) is vapour flux density, Dv (mm^{-2} sec^{-1}) is the vapour diffusion coefficient, $\Delta\rho v$ (g ml^{-1}) is vapour density differences between the inflow and outflow boundaries, and Δz (mm) is the distance between inflow and outflow boundaries. (Jury et al., 1991).

Vapour density does not vary greatly over the water potential range from -10 to -1500 kPa. Hanks (1958) showed that water vapour flow in response to differences in temperature within the available water range is very small for the normal temperature range found under field conditions. This strengthened his assertion that isothermal conditions can be assumed to govern evaporation from soil in the wet range and that the error in estimating evaporation will be less than 10 % (Hanks, 1992b). However, Jury and Letey (1979) showed that although the soil moisture content at a relative humidity (RH) of nearly 100% and the salt content do not influence the vapour pressure within the air-filled pore space, water vapour flux can be large enough to transport substantial quantities of soil water if there is sufficient time such as during the fallowing period over summer.

After the soil surface dries, the evaporation rate is equal to the water vapour flux density through the dry surface layer. In this layer, relative humidity is much lower than in the soil just beneath, and there is a large vapour density gradient which can cause substantial loss of water vapour from the soil. Therefore under the high temperature gradients associated with drying , combined with a high air-filled porosity, water vapour flux can be taken as proportional to the temperature gradients. Others have taken a different stance, for example Ishihara et al. (1992). regarded water vapour transfer beneath the soil surface to be a function of molecular diffusion only.

2.4.1.4 Measurement of soil water evaporation

Soil water evaporation can be measured under field condition by using a microlysimetric method which was proposed by Boast and Robertson (1982). A microlysimeter is produced by pushing a thin- walled cylinder of 75 x75 mm into the soil surface, removing it and closing the bottom, weighing and replacing it, then subjecting it to the same evaporative conditions as the surrounding soil for a period of time before reweighing. The amount of evaporation is calculated as the water loss from this undisturbed soil core. This method is applicable to both wet and dry soil surface conditions. This type of microlysimeter was also used by Walker (1983) and Lacasno and Bavel (1986).

Boast (1986) found that for evaporativity ranging from 2 to 9 mm day^{-1}, the microlysimeter containing 70 mm of soil thickness were accurate within 0.5 mm cumulative evaporation for at least 1 to 2 days depending on soil wetness. He suggested that the microlysimeter is valid for use both during Stage I and Stage II evaporation. When the spatial resolution of normal lysimeter is too large such as a crop row under conditions of partial canopy cover, the microlysimeter can provide a reasonable measurement.

2.4.2 The effect of tillage on soil water evaporation

Tillage practices may affect evaporation by causing variation of soil physical properties including: (i) surface properties (roughness, reflectance and soil wetness, porosity); (ii) hydraulic properties (soil water retention characteristic, hydraulic conductivity and liquid diffusivity); (iii) formation of distinct layers (tilled layer and tillage pan) and (iv) mechanical properties (bulk density, texture,, strength and aggregate size distribution). Several factors may interact with tillage in affecting soil water evaporation such as evaporative demand, soil type, depth and time of tillage. Differences in soil properties and their interactions induced by different tillage methods may consequently cause variation in soil water evaporation. These differences may be exploited to develop methods for conserving soil water .

2.4.2.1 Surface roughness, albedo and water content of the soil surface

Increasing soil surface roughness can decrease soil albedo and increased soil water evaporation. Potter et al. (1987) showed that reflectance of solar radiation decreased with increasing surface roughness due to different tillage practices. Linden (1982) asserted that loosening of surface soil by tillage increased surface roughness, which reduced the soil albedo and consequently lead to an increase in potential soil water evaporation. Jalota and Prihar (1990) showed that decreased albedo, increased surface area, and greater penetration of wind into the tilled layer may substantially increase the initial rate of evaporation from tilled soil. Therefore, the top few centimetres of the tilled soil dried more rapidly than the untilled soil. Franzluebbers et al. (1995) also showed that the soil water evaporation from the tilled soil surface was higher than the untilled soil surface due to lower albedo values which may increase evaporative energy at the soil surface. Similar results were also reported by Bowers and Hanks (1965); Idso et al. (1975); and van Bavel (1966).

2.4.2.2 Soil hydraulic properties

The hydraulic properties of soil are altered by tillage. Bulk density and pore size changes associated with loosening of surface soil may cause changes in the soil water characteristic leading to changes in soil water hydraulic conductivity and diffusivity as described in Section 2.4.1

Jalota and Prihar (1990) showed that decreased bulk density caused by tillage increased hydraulic conductivity at low suction (high moisture content) and decreased it at high suction (low moisture content). These changes caused a higher evaporation rate (Es) at high water content in the tilled soil compared to untilled soil because of greater hydraulic conductivity (K_θ) and smaller water capacity (Cw) values causing greater water diffusivity (D_θ) in the tilled layer compared with the untilled soil. This may not be true in the long run because soil pores greater than 30 μm created by tillage may not affect soil hydraulic diffusivity and soil water evaporation at high water contents as described in Section 2.3.

However, Fischer (1987) asserted that the decrease in soil bulk density and changes in unsaturated hydraulic conductivity during evaporation do not significantly cause different Es in Stage I between tilled soil and untilled soil. He showed that the effect of tillage on stage II soil water evaporation was more important because increased soil macroporosity of the tilled layer from tillage leads to a decrease in both unsaturated hydraulic conductivity and thermal conductivity, causing increased water-vapour conductivity.

2.4.2.3 Induction of tillage pans

Kutilek and Nielsen (1994) stated that evaporation from a layered soil profile may be different from a homogeneous profile because soil layering induces resistance to water flow. A tilled soil profile with a plough sole or hard pan below the tilled layer usually has higher hydraulic resistance to water flow compared with an homogeneous soil profile or untilled soil (Kutilek and Nielsen, 1994). The hydraulic resistance (Ri) of layers of different thickness (Zi) and hydraulic conductivity. (Ki), can be calculated if water flow is perpendicular to the layers (Figure 2.5).

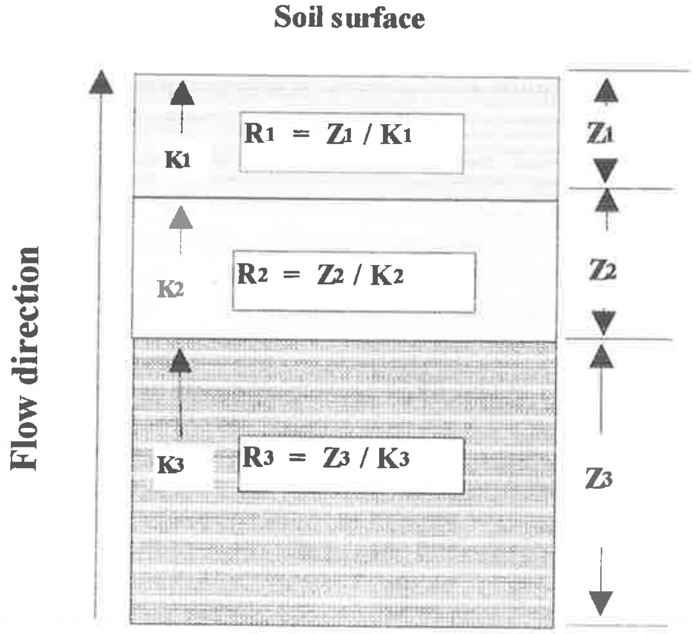

Figure 2.5 Hydraulic resistance (R_1, R_2 and R_3) in a three layered soil (layers 1, 2 and 3) with different hydraulic conductivity values (K_1, K_2 and K_3). (modified from Kutilek and Nielsen, 1994).

The hydraulic resistance of each layer (Ri) is given by:

$$Ri = Zi/Ki \qquad (2.15)$$

and the mean hydraulic resistance (Rs) of all layers is:

$$Rs = \Sigma (Zi/Ki). \tag{2.16}$$

The mean hydraulic conductivity (Ks) of all layers is:

$$Ks = \Sigma Zi / \Sigma (Zi / Ki) \tag{2.17}$$

where Zi and Ki are the thickness and the hydraulic conductivity of each soil layer respectively (Marshalls and Holmes, 1988; Kutilek and Nielsen, 1994).

Equations (2.16) and (2.17) suggest that a layered soil with a decreased hydraulic conductivity (Ki) layer (hardpan below the tilled layer) always has higher mean resistance, Rs, and lower hydraulic conductivity, Ks, than the same soil with a uniform profile and hydraulic conductivity. Therefore, soils without tillage induced layering should conduct water to the surface faster, so providing more water for evaporation compared with layered soils.

Dexter (1988) also suggested that evaporation loss from untilled soil depends on liquid capillary flow to the surface. Tillage can break the capillary pores by producing a "dust mulch" or fine aggregate at the soil surface. Movement of water can only occur through points of contact between aggregates instead of through continuous capillary pores. Therefore, evaporation is reduced.

2.4.2.4 Aeration porosity and aggregate size

Alteration of the air filled porosity within the top soil layer has a direct relation to evaporation loss of water from the soil. Allmaras et al. (1977) found that evaporation increased by 25% with an increase in the total porosity fraction of the tilled layer from 0.5 to 0.64. Jalota and Prihar (1990) also found that the reduction in porosity increased the resistance to vapour flow by making the flow path more tortuous which caused lower evaporation loss.

Ishihara et al. (1992) found that water vapour transfer in porous material with low air filled porosity occurs by molecular diffusion, as well as by turbulent diffusion in conditions where a turbulent wind is blowing across the surface. In porous material with high air filled porosity, water vapour transfer depends on air diffusivity which varied with soil depth as an exponential function.

Jalota and Prihar (1990) reviewed Heinonen's work (1985) by relating components of water flux during evaporation to aggregate sizes as shown in Figure 2.6. They explained that the high Es from fine soil aggregates (< 0.5 mm diameter) is due to the high liquid capillary conductivity associated with fine pores. Increased air porosity occasioned by increasing the aggregate size from 0.5 to 5.0 mm caused slightly increased loss by gas diffusion. Turbulent transport started when the aggregate size increased from 3 to 5 mm. The high Es from large aggregates (5 - 10 mm diameter) was due to the increase in turbulent transport associated with large pores. The maximum drying rate was obtained in aggregates larger than 5 mm. Consequently, the surface area became a limiting factor for evaporation reduction when hydraulic conductivity was low. This suggests that vapour diffusion of water is the main component of water loss from aggregates between 0.5 and 5 mm diameter which can be induced by tillage practices. However the rate of vapour diffusion is lower than either liquid conductance or turbulent transport of vapour. Hence, the aggregate size distribution in this range would minimise soil water evaporation.

Dexter (1988) suggested that if the pores between aggregates is larger than 5 mm diameter, convective flow may occur and accelerate the drying of the soil mulch layer. This could remove significant amounts of water from the surface of the untilled layer beneath the soil mulch. The implication is that the soil mulch needs to be fairly fine. However, this may not be valid because fine aggregate can cause capillary upward flow of soil water by increasing contact points between aggregates of the tilled and untilled layers

(Heinonen, 1985, quoted by Jalota and Prihar, 1990). This will increase evaporation lost from the soil (Figure 2.6).

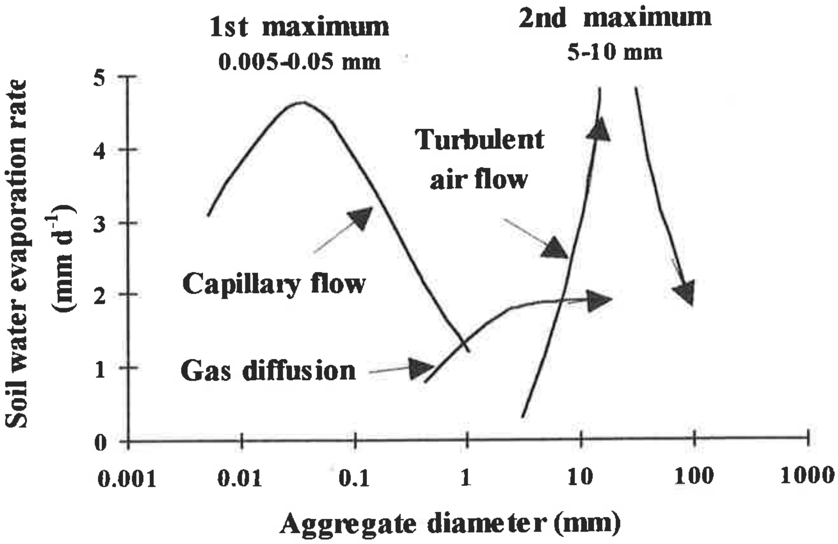

Figure 2.6 Schematic representation of three components of soil water evaporation rate (capillary flow, water vapour diffusion and turbulent air flow) in relation to aggregate size (after Heinonen, 1985, as quoted by Jalota and Prihar, 1990).

2.4.3 Interactive effects of tillage, evaporative demand, soil type and soil water redistribution.

A number of laboratory and field experiments on the effect of a soil mulch on soil water evaporation have been reported (Holmes et al., 1960; Willis and Bond, 1971; Blevins et al., 1971; Gill and Prihar, 1983; Jalota and Prihar, 1986; Jalota and Prihar, 1992; Minhas et al., 1986; Ishihara et al., 1992; Jalota, 1993; Reynolds et al., 1995). All these experiments have shown that the effect of a soil mulch from tillage on soil water evaporation is governed by interactive effects of evaporative demand, soil type, soil wetness, soil water redistribution, depth and time of tillage.

2.4.3.1 Evaporative demand, soil type and soil water redistribution

The rate of soil water evaporation is varied with evaporative demand, soil texture and soil water redistribution. Jalota and Prihar (1990) found that tillage reduced evaporation of soil water (Es) from the surface of all soil types under low evaporative demand (Em), but under high Em, tillage reduced evaporation from fine textured soils only. They also showed that after 2 days of redistribution, tillage of silt loam soil resulted in a higher cumulative soil water evaporation (Esc) over a 30-day period than tillage of a sandy loam. The liquid flux to the soil surface under low Em, was higher than under high Em. The vapour flux contributed less under low Em than under high Em in both soils.

Jalota and Prihar (1986) found that where evaporation commenced immediately after wetting, cumulative soil water evaporation (Esc) under higher Em was always higher than that under lower Em in silt loam and sandy loam. However, in coarse textured soil, such as a loamy sand, Esc under a medium Em value exceeded that under a high Em value after 2 days of evaporation.

2.4.3.2 Atmospheric condition and total porosity interactions

Jalota (1993) found that vapour flux density (Qv) through soil mulch increased with atmospheric temperature and decreased with increasing thickness of soil mulch at a given atmospheric condition. Qv increased with increasing soil porosity of a thin soil mulch (5 mm) and under high Em value (>8 mm d^{-1}) only. Qv was also dependent upon atmospheric temperature more than wind speed. More porous soil surface structure caused higher cumulative evaporation than less porous structure during Stage I of evaporation (Mwendera and Feyen, 1994).

The above interactive effects between several factors show that evaporative demand and soil type dominantly control soil water evaporation under tillage practices.

Furthermore, evaporative water loss from the tilled soil of different soil types is also dependent upon depth and time of tillage. Willis and Bond (1971) found that the deeper tillage gave the greater amount of soil water evaporation compared with the shallower tillage. Similar result was also found by Jalota and Prihar (1990).

2.4.4 The effect of tillage on soil water conservation

The effect of tillage on soil water conservation under the field conditions is not clearly understood because of the interactive effects between soil properties, environmental conditions and tillage operation. Linden (1982) stated that soil tillage in humid regions is a mechanism for enhancing soil water evaporation and thus speeding soil drying. On the other hand, tillage is considered as a means for conserving soil water in arid regions. Tillage has been shown to increase short- term evaporation losses but decrease long-term soil water evaporation losses (Allmaras et al., 1977; Holmes et al., 1960; Gill et al., 1977; Willis and Bond, 1971; Jalota and Prihar 1990; Jones et al., 1994). However, Fischer (1987) considered that there was no data from Australia which supported the notion of moisture conservation by creating a tilled layer at the soil surface. He asserted that tillage failed to conserve soil water in eastern Australia where frequent rain cycles negated the dry soil mulch effect during the growing season.

Jones et al. (1994) found that direct drilling improved water conservation due to reduced evaporation and caused 18 % and 10 % greater amount of total plant available soil water than tillage during fallow after sorghum and wheat respectively. On the other hand, Blevins et al. (1971) found that zero-tillage caused higher volumetric moisture contents of a silt loam soil only to a depth of 600 mm. Beyond 600 mm soil depth, there was no significant difference between the two tillage systems. They asserted that the decrease in evaporation and the greater ability to store moisture under no-tillage produces a greater water reserve which leads to more efficient water use of corn compared with the conventional tillage treatment.

Mwendera and Feyen (1994). have found that more evaporation occurred from the more open surface structures of tilled soil at higher evaporative demands during Stage I evaporation. At low evaporative demand during Stage II evaporation (30 days of drying), cumulative evaporation from the untilled soil was higher than that from the tilled soil. Tillage can reduce soil water evaporation more effectively at lower than at higher evaporative demands. These results agree with those obtained by Jalota and Prihar (1990) and Johns (1982a). Jalota and Prihar (1990) suggested that in medium and fine textured soil, where surface layers remain wet for a long period after rain or irrigation, shallow tillage is likely to reduce soil water evaporation.

These agreements showed that under conditions of the limited soil depth as in the uniform disturbed soil columns (Jalota and Prihar, 1990), soil monoliths (Johns, 1982a) and undisturbed soil cores (Mwendera and Feyen, 1994), the cumulative upward flow of soil water at high Em is dominantly controlled by evaporative demand rather than by the hydraulic gradient. Mwendera and Feyen (1994) also suggested that the results from the laboratory may differ from the field because the limited core length of soil samples stops any capillary rise from a deeper soil layer. However, Minhas et al. (1986) conducted the experiment under field conditions and found that tillage effectively reduced evaporation loss under low evaporative demand only. There was no effect of tillage method under high evaporative demand. They also found that the evaporation rate was dominantly controlled by the soil water potential of the tilled layer.

2.4.5 Predicting evaporation from the tilled soil

Many evaporation models are not sensitive to the changes of soil properties under tillage condition or tillage variables. Only models which take account of hydraulic properties, the initial conditions and the soil surface boundary surface condition are likely to be of use in predicting tillage effects on soil water evaporation. However, at present, data on hydraulic properties of tilled soil are rather scarce.

Linden (1982) presented a model for predicting the soil water evaporation of tilled soil. He utilised a well known soil water model created by Dutt et al. (1972) and Hanks and Bowers (1962) with some modification. He took account of the soil surface boundary and some initial soil properties which are affected by tillage. The model required the following input information: (i) a soil water retention curve (soil water content (θ) versus soil water potential (φ)) covering the range of soil water encountered in the field, (ii) the bulk density (ρ_b) of the soil profile and the maximum hydraulic conductivity (K_θ), and (iii) a roughness index of the soil surface and the albedo of the soil in a smooth dry condition

The model output indicated that higher evaporation losses of water stored in the tilled layer can be expected from tilled soils, but the flow of water below the tilled zone to the surface would be retarded by hydraulic resistance of the tilled layer. Hence, tillage can conserve water. Linden (1982) also concluded that the depth of soil water distribution after infiltration has a large influence on subsequent evaporation. A review of model and experimental systems by Linden (1982) revealed several tillage related results: (i) low unsaturated hydraulic conductivity of the surface soil layer reduces soil water evaporation, (ii) structural features of a soil such as cracks and variation in clod size distribution influence evaporation processes by affecting the movement of water vapour within the soil, such as increased large pores may enhance vapour movement by increasing both diffusion and by mass flow of air, and (iii) distribution of water at the start of an evaporation cycle also significantly affects soil water evaporation. Linden also suggested that soil surface roughness is of some significance, but the hydraulic properties of the soil are major concern for the effect of tillage on soil water evaporation.

2.5 Use of modelling in quantifying evapotranspiration and water use efficiency

The utility of using models to quantify the components of water balance in dryland farming systems may help to explain the results obtained from field experiments to isolate the effect of each component in the soil water balance and its potential contrtibution to improvement of dryland crop production in the future. Weaich (1993) noted two distinct advantages in using models. (i) For a researcher or scientist, models can be used to interpret observations, design the experiments and increase the intuitive understanding about the behaviour of the system. (ii) Models can be used by decision makers to improve the quality of their decisions based on the research results. Furthermore, models can also be used to 'package' complex sets of rules in a form that can be easily used.

Soil water balance models are mainly concerned with water use or evapotranspiration and differ in their complexity and details. They vary from the simple models of Reddy (1983), French and Schultz (1984), Campbell and Diaz (1988) and Lhomme and Katerji (1991) to the more complex models of Ritchie (1972); Tanner and Jury (1976), Greacen and Hignett (1976), Saxton et al. (1974), Shanholtz and Younos (1994), Stockle and Campbell (1985), Shouse et al. (1982) and Monteith (1980). Although these models differ in detail, they all are similar in using soil and environmental data as input, and various empirical or numerical equations to estimate the water loss from the soil water budget. The specific components such as runoff, drainage, soil water evaporation and soil water storage can all be modelled.

Many soil water balance models address soil water evaporation (Es) and crop evapotranspiration (ETc) from a crop canopy because these two components directly relate to each other and substantially affect water use efficiency of the crops (Lhomme and Katerji, 1991; Campbell and Diaz, 1988; Tanner and Jury, 1976; Shanholtz and Younos, 1994).

There are many empirical and numerical formulas including several measurement techniques for evaluating potential evapotranspiration (ETp) and soil water evaporation (Es). To estimate water used by the crop (ETc), reference crop evapotranspiration (ETo) must be estimated from micrometeorological variables measured above the evaporative surface such as temperature, humidity, wind velocity and radiation. ETp can be estimated from the product of ETo and crop coefficient.

The actual crop water used (ETa) is dependent on available soil water content and the water supply to the root zone. Direct estimation of actual water use by a crop is possible by using lysimetry. However, ETa can be estimated by the model using the available soil water deficit factor (Doorenbos and Kassam,1979). Several models are available to calculate the ETp from climatic data. Some are simple, giving only approximate results and are suitable for specific conditions only. Some are more complicated and provide more accurate and more precised results. For instance, Shouse et al. (1982) tested five different models for predicting potential evapotranspiration (ETp) from a well-watered crop during the full cover stage in southern California. They found that only those models which included a vapour deficit correction for advection gave results close to the measured ETp values.

The purpose of this section is to develop an information base for incorporating crop evapotranspiration into water balance models of dryland wheat production. The review addresses: (i) terminology and fundamentals of potential evapotranspiration (ETp) and actual crop evapotranspiration (ETa) prediction, (ii) the models and methods used to predict soil water evaporation (Es), crop water requirement or potential evapotranspiration (ETp) by concentration on Class A-pan evaporation, Ruche' s model, Stroosnijder' s model and the Penman-Monteith combination model.

2.5.1 Definitions and factors affecting evapotranspiration

2.5.1.1 Terminology and definitions

(i) **Potential evapotranspiration** (ETp) is defined as the amount of water lost through evapotranspiration of a disease-free crop, growing in large fields under non-restricted soil conditions including soil water and chemical fertility and achieving full production potential under the given growing environment. This term is also defined as **crop water requirement** (Doorenbos and Pruitt, 1977)

Monteith (1980) explained that the concept of ETp was an attempt to characterize the micrometeorological environment of a field in terms of evaporative demand. It defines the soil-vegetation unit under a given set of meteorological conditions and depends on climatic factors as well as soil properties and vegetative factors.

(ii) **Reference crop evapotranspiration** (ETo) is defined as the rate of evapotranspiration from an actively growing, extensive, uniform cover of green grass or alfalfa or lucerne of 80 to 150 mm height, completely shading the ground surface and not short of water (Doorenbos and Pruitt, 1977).

(iii) **Actual crop evapotranspiration** (ETca) is the water used by the crop under a specific soil water content and evaporative demand which will vary with climatic conditions and crop growth (Doorenbos and Pruitt, 1977). The daily ETca can vary from nearly zero to the same amount as potential crop evapotranspiration depending on available soil water and climatic conditions.

Normally, ETca of a dryland crop is less than the crop water requirement because the soil water may not be fully available to the crop. Particularly in dry conditions, soil water is not supplied at the full rate of the crop evapotranspiration because of the flux of available water towards roots may limit uptake.

2.5.1.2 Limiting factors and the calculation of evapotranspiration

Evapotranspiration of plants may be restricted by three main factors:

(i) **Weather Conditions:** These are the products of net radiation, wind speed, humidity, temperature and vapour pressure of the air surrounding the crop. Net radiation at the surface of a crop can be partitioned into **sensible heat flux** to the air (H) and to the soil (G), and **latent heat flux** for evaporation of water from the soil surface and plant (λE). Jensen et al. (1990) showed that total heat required for evapotranspiration (λE) is equal to the supplied heat from the air to the surface for evaporation ($\lambda E1$, sensible heat) plus the heat required to change liquid water to vapour ($\lambda E2$, latent heat). The energy balance can be written in form of vapour pressure and temperature relationships as

$$\begin{aligned}\lambda E &= \lambda E1 + \lambda E2 = Cp\,(Tz-Twz)/Ra + [\Delta / (\Delta + \gamma)]\,(Rn - G) \\ &= Cp\,(es-ed) / Ra\,(\Delta + \gamma) + (Rn - G)\,\Delta/ (\Delta + \gamma) \qquad (2.18)\end{aligned}$$

where Cp is heat capacity, Tz and Twz is the dry and wet bulb air temperature at height z above the crop canopy, Ra is aerodynamic resistance, Δ is the slope of saturation vapour pressure and temperature relationships, γ is psychrometric constant.

(ii) **Soil factors:**These are soil wetness and soil water potential. When the soil water is not limiting, it does not affect crop evapotranspiration and evapotranspiration of the crop occurs at a constant rate which is almost the same rate as potential evaporation from the soil surface during the first growing stage of the crop. When the crop is fully developed, evapotranspiration rate is constant and equal to the potential evapotranspiration without limitation of available soil water; the soil water content does not affect crop evapotranspiration. As the soil water decreases, loss of soil water by evaporation from the soil surface below the crop canopy is decreased and water use efficiency of the crop is increased due to an increase in transpiration. Both soil depth and hydraulic properties of the soil can have considerable effects on the actual evapotranspiration rate (Gardner and Hillel, 1962).

(iii) **Crop factors:** These are the crop characteristics and the leaf area index (LAI) which limit the crop water requirement or potential evapotranspiration (ETc or ETp). As leaf area increases and the crop develops more shading, the potential soil water evaporation decreases due to a decrease in net radiation below the crop canopy (Ritchie, 1972). The crop factor is given by the crop coefficient (Kc) which presents the relationship between reference crop evapotranspiration (ETo) and crop water requirement (ETc) or potential evapotranspiration.

The crop coefficient or the crop factor (Kc) is determined by the type of crop and crop growth stage. Generally, Kc for the particular crop, the stage of development and the climatic region is selected from a table of crop coefficients which have been established by previous research. Then ETp or ETc is calculated as (Doorenbos and Pruitt, 1977):

$$\mathrm{ETc} = \mathrm{Kc}\,\mathrm{ETo}. \qquad (2.19)$$

The Kc value is an empirical constant for each crop at each growing stage under a certain climatic environment. To have a precise prediction of ETc, ETo and Kc should be investigated for a specific crop and area. Values of Kc vary with the crop types, growing stage, growing season and weather conditions and ranges from a value near zero to more than unity. The variations are due to the resistance to transpiration of different plants, stomatal behaviour during the day (pineapple) and extent of wax coatings on the leaves (citrus), as well as differences in crop height, crop roughness, reflection and ground cover.

Equation 2.19 may be used to calculate ETc provided the available soil water is not less than 50% and the crop is never in extreme moisture stress. If the soil surface is wet or if the crop is under extreme moisture stress or if the available water is less than 50%, the available soil water content must be included in the equation to determine the actual crop evapotranspiration (ETa).

(iv) **Calculation of actual evapotranspiration**

The available soil water factor (Ks) is required to calculate the available soil water fraction (AWf) in order to obtain actual evapotranspiration (ETa). Ks is calculated from the available soil water (AW) as:

$$Ks = 1 \quad \text{for } AWf \geq 0.5 \qquad (2.20)$$

$$Ks = 2\,AWf \quad \text{for } AWf < 0.5 \qquad (2.21)$$

after Boonyatharokol and Walker (1979). This corresponds to the general crop water use depletion curve and can be calculated as recommended by Jensen et al. (1990).

$$Ks = \ln(AW+1)/\ln(101) \qquad (2.22)$$

The actual crop water use or evapotranspiration (ETa) is calculated as:

$$ETa = Ks\,ETp \qquad (2.23)$$

Furthermore, Shouse et al. (1982) asserted that local conditions and agricultural practices such as climatic variation, advection, salinity, cultivation methods and crop management can substantially affect actual crop evapotranspiration (ETa). These effects are mainly influenced by the interaction of evaporative demand with plant and soil factors

(Gates and Hanks, 1967, quoted by Shouse et al., 1982). The dominant soil factors are hydraulic properties of the soil which govern the flux of water to plant roots and to the soil surface. The dominant hydraulic property determining the rate of ETa is dependent on the available soil water content.

Ritchie (1974, quoted by Jensen et al., 1990) proposed a concept of "extractable water fraction" (available water fraction, AWf in this thesis) which is the amount of water in the root zone above a field wilting point. Ritchie measured extractable limits by field observation of the root zone and noted the highest and the lowest water contents attained over an extended time. Soil water between maximum and minimum field water content was defined as " the maximum extractable water" (available water capacity, AWC in this thesis). The ratio of the remaining extractable water to the maximum extractable water is termed "extractable water fraction (AWf)". AWf has a range of $0 < Wf < 1$ depending on leaf area index (LAI). This available water fraction concept was similar to that used by Greacen and Hignett (1976) (Section 2.2).

2.5.2 Model for predicting evapotranspiration

A common procedure for predicting evapotranspiration from a crop canopy. (ETc) is to first estimate reference crop evapotranspiration (ETo) from a mature standard reference crop such as grass or alfalfa (*Medicago sativa L.*). Then apply an empirical crop coefficient, which depends on crop characteristics, to estimate potential crop evapotranspiration.

Most models are based on the Penman combination model (1963) which has been derived from the energy balance between sensible heat and latent heat and which includes a wind function above the crop canopy. Monteith (1965) modified the Penman model by adding aerodynamic and crop resistance functions. or Ritchie (1972) adopted a different approach, adding a crop factor such as leaf area index. These two models have been widely tested and are regarded as the most reliable evapotranspiration models currently available.

2.5.2.1 The Penman model

Jensen et al. (1990) presented the general form of The Penman equation which combines the energy shared by latent heat from net radiation $[(\Delta(Rn - G) / (\Delta + \gamma)]$ and sensible heat from the moving air or wind function $[Wf\, \gamma\, (es - ed), / (\Delta + \gamma)]$. This model is written as:

$$\boldsymbol{\lambda ETo = \Delta(Rn - G)/ (\Delta + \gamma)] + 6.43\, Wf\, \gamma\, (es - ed)/ (\Delta + \gamma)} \qquad \textbf{(2.24)}$$

where λETo is latent heat flux density from a well watered grass reference crop, Rn is the net radiation, G is soil heat flux density, Δ is the slope of the saturation vapour pressure-temperature curve, γ is the psychrometric constant, and Wf is the wind speed function. Units of λETo, Rn and G are in MJ m^{-2} d^{-1}, es and ed in kPa., and Uz, in km d^{-1}. Wf is dependent on wind speed at 2 m above ground (Wf = 1.0 +0.53Uz). This equation is known as the Penman Combination Equation because it has combined the effects of sensible heat, latent heat and the wind function. However, the Penman Combination Equation is not a complete model because crop characteristics such as leaf cuticle and stomata-aperture can reduce transpiration. The crop resistance to transpiration should be included as a parameter in the equation.

2.5.2.2 The Penman-Monteith model

Sharma (1985), Allen et al. (1989) and Jensen et al. (1990) suggested that the most acceptable equation for calculating potential evapotranspiration is the Penman-Monteith Combination expression which is based on a combination of energy balance, crop resistance to transpiration and aerodynamic transport considerations.

The Penman-Monteith model was proposed by Monteith (1965) by adding aerodynamic (Ra) and canopy resistance (Rc) terms into the Penman equation (Equation 2.24). The combined form of psychrometric constant (γ^*) and the resistance ratio (Rc/Ra) is given as (Jensen et al., 1990):

$$\gamma^* . = \gamma(1 + Rc/Ra) \qquad (2.25)$$

Ra affects the rate at which air can supply heat to the surface as well as specific heat (c_p) and density (ρ_a) of the air. The form of sensible heat in Equation 2.24 is transformed to $\rho_a\ c_p(es - ed)/\ [Ra\ (\Delta + \gamma)]$ and substituting γ^* for γ, Equation 2.24, is written as

$$\lambda ETo = \frac{\Delta\ (Rn - G) + Cp\ (es - ed)\ /\ Ra}{\Delta + \gamma^*}. \qquad (2.26)$$

From Equation 2.25, and 2.26, the Penman-Monteith model is written as

$$\lambda ETo = \frac{\Delta\ (Rn - G) + \rho_a\ c_p(es - ed)\ /\ Ra}{(\Delta + \gamma\ (1 + Rc/Ra)} \qquad (2.27)$$

where λETo is evapotranspiration from a well watered grass reference crop as latent heat flux density (λETo, kPa $^oC^{-1}$), Δ is slope of the saturation vapour pressure - temperature curve (des / dT), Rn and G are the net radiation and the heat flux density to the ground respectively (MJ $m^{-2}day^{-1}$), ρ is the air density (kg m^{-3}), (es-ed) is the daily vapour pressure deficit (kPa) at mean height of crop canopy, and Ra and Rc are aerodynamic and canopy resistance (s m^{-1}) respectively.

Allen et al. (1989) suggested that Ra can be calculated from the height of wind (Zw), air and humidity (Zh) measurement above the ground surface (m) and wind speed

(U_z, m s^{-1}) as

$$Ra = \frac{\ln [(Zw - D) / Zom] \ln [(Zh-D)/Zov]}{(0.41)^2 Uz} \qquad (2.28)$$

D is the zero plane displacement of wind profile (m) calculated as 0.67 Hc; Hc is the mean height of a crop canopy (m); Zom is the roughness length for momentum transfer (m) (Zom = 0.123 Hc, when Hc is < 2 m); Zov is the roughness length for vapour transfer from vegetation; (Zov = 0.0123 Hc).

Rc is the surface resistance to vapour transfer (s m^{-1}) which is estimated as

$$Rc = R_l / 0.5\ LAI \qquad (2.29)$$

where R_l is an average minimum day time value of stomatal resistance for a single leaf, which is approximately 100 s m^{-1} for alfalfa and grass canopies (Monteith, 1981; Sharma, 1985; Allen et al., 1989). LAI is leaf area index is approximated for a tall grass and alfalfa as (Allen et al., 1989)

$$LAI = 5.5 + 1.5 \ln(Hc)\ . \qquad (2.30)$$

2.5.2.3 Pan evaporation method

Doorenbos and Pruitt (1977) asserted that the pan evaporation method was a measurement of the integrated effect of radiation, wind, temperature and humidity on evaporation from a specific open water surface. Latent heat energy used for evaporation from a pan is similar to that used for evapotranspiration from the soil and plant community. Reference crop evapotranspiration (ETo) can be calculated from

$$ETo = Kp\ Epan \qquad (2.31)$$

where Epan is mean value of pan evaporation in mm d^{-1}, and Kp is pan factor, which varies between 0.6 and 0.9 according to types of pan, environment and locations of pan setting (Doorenbos and Pruitt, 1977).

An evaporation pan is an economical method of determining the evaporative demand, provided local calibration does not vary from season to season (Shouse et al., 1982). Monteith (1981) suggested that the empirical 'pan factor' or 'pan coefficient' works well enough for many practical purposes when the pan factor is almost constant. However he disagreed with the idea of using a pan to estimate the evaporation loss from a crop canopy under periodically dry conditions, because of negative correlation between evaporation from a pan and from a crop canopy can occur significantly. As the evaporation rate from the crop canopy decreases, the atmosphere becomes drier and pan evaporation increases.

However, evaporation from a shallow pan (4 feet in diameter, 10 inches deep and mounted above grass level for the Class-A pan) cannot represent the energy exchange, heat storage and aerodynamic condition for the crop canopy. Watts et al. (1985) suggested that all evaporation pan data should be regarded as untrustworthy. Several factors may produce significant differences in water loss between crop evapotranspiration and pan evaporation:

(i) Reflection of solar radiation from vegetative surface is 20-25 % but from a free water surface is only 5-8 % (Doorenbos and Pruitt, 1977).

(ii) Heat capacity of the crop canopy (soil and crop) is different from the evaporating pan. Soil depth, crop density and crop height are largely varied during growing season.

(iii) Stored heat within the pan may cause equal evaporation during night and day while transpiration from the crops occur only during daytime.

(iv) The siting of the pan, types of pan and the pan environment such as wind speed, air humidity, temperature and climate can influence the measured data, especially when the pan is placed in fallow rather than crop fields (Watts et al., 1985).

(v) Thermal property variations of the soil below pan due to variation of soil wetness, surface tension problems when refilling to the needle point and possible shade at low sun angle (Watts et al., 1985).

These effects may cause a large variation in pan coefficient and impractical use of Equation 2.31 which provides poor prediction of crop water requirement. (Doorenbos and Pruitt, 1977; Watts et al., 1985).

The methods presented above, provide the same criteria to calculate the reference crop evapotranspiration (ETo) by using the mean climatic data for 10 to 30 day- periods. ETo is expressed in mm per day and represents only the mean value over the period. However, the ETp varies from day to day. To obtain more precision, the shorter period should be more preferable. The choice of method is dependent on the type of climatic data available and on the accuracy required in determining crop water requirement.

Doorenbos and Pruitt (1977) stated that the Penman Combination equation offered the best results with minimum possible error of approximately 10 % in summer and up to 20 % under low evaporative conditions. The pan method is the second best method with an error of 15% depending on the location of the pan. The radiation method involves a possible error of up to 20 % in extreme conditions such as in summer.

None of the models for predicting the potential evapotranspiration or crop water requirement are perfectly accurate. This arises because they have been developed from various environments which are different from an environment of a specific applied location, Furthermore, all of the models are based on empirical formulas. Most micrometeorogical models give slightly conservative estimates of ETo in humid regions. (Doorenbos and Pruitt, 1977). On the other hand, over-estimation of ETo by 10 to 15 % may be possible at some mid latitudes and in semi-arid locations and under-estimation of ETo by 5 to 10 % can occur in very hot dry desert locations with light wind. Sharma (1985) asserted that at present, most methods can be applied only in large, flat areas with a uniform vegetative cover. Under conditions of advection, the models must be used with care.

2.5.3 Model for predicting crop transpiration

Most transpiration models are based on the available soil water fraction within the root zone, root length density in each soil layer, evaporative demand and crop growth function or leaf area index. A model for predicting crop transpiration for dryland wheat production proposed by Greacen and Hignett (1976) may give a good results because it includes each component of soil water balance and the water supply index for crop growth. Input data for this model are rainfall (P), pan evaporation (Ep), rooting depth (RD), field capacity (FC), wilting point (WP) or total available water with in the root zone or available water capacity (AWC). The output results are the actual available water at each growing period and cumulative evapotranspiration from a crop canopy. The water supply index was given as the quantity of water stored in the soil at peak anthesis divided by the mean weekly evaporation for the following two weeks. This indicates the number of weeks that the available water supply would last or crop growth would be limited by soil water. Potential crop evapotranspiration (ETc) was predicted using pan evaporation (Epan) multiplied by a crop factor (Kc). Crop factor varied from 0.3 to 1.0 depending on number of weeks (N) from sowing to full crop cover stage or can be calculated as

$$Kc = 1.22\,N / (3.55 + N) \qquad (2.32)$$

$$ETc = Kc\,Epan\,. \qquad (2.33)$$

ETc was used to estimate weekly actual crop transpiration (Tca) rate based on cumulative potential transpiration (ΣTcp) and the available soil water fraction (AWf) of the subsoil horizon. Tcp is a function of ETc and root length density, in the subsoil layer when available soil water is fully supplied. The actual crop transpiration (Tca) was calculated as

$$\mathbf{Tca} \quad = \quad \mathbf{0.000045\,(\Sigma Tcp)^2\,AWf\,.} \qquad (2.34)$$

Greacen and Hignett's model is appropriate for drying conditions because it uses the soil water supply index which can show the crop water stress and the amount of available water within the root zone at a specific time. However, this model may not predict ETc precisely for heavy textured soils with shallow rooted crops because a significant proportion of the available water may be supplied by capillary rise from deep soil layers below the root zone.

Campbell and Diaz (1988) calculated daily crop transpiration (Tca) using the fraction of maximum root depth in terms of the fraction of time from planting to maturity date and the soil water potential between field capacity and wilting point. Tca from each soil layer is assumed directly proportional to the difference in water potential between the soil and the xylem, and inversely proportional to the root resistance in that layer.

On the other hand, Tanner and Sinclair (1983) proposed a transpiration model for a crop canopy based on atmospheric conditions (atmospheric pressure, the vapour pressure gradient between the leaf and the atmosphere, and the boundary layer and stomatal resistances) and the leaf area index (LAI). Their model is a simple expression of daily crop transpiration. It may not be suitable for dryland crop transpiration because the transpiration is also limited by soil water content (Figure 2.2), net radiation received by the crop canopy and root distributions in the soil profile. Using only leaf area index and vapour pressure gradient between atmosphere and leaves for predicting transpiration may not give a valid result.

However, Ritchie and Burnett (1971a) also found that the ratio of crop transpiration to potential evapotranspiration (Tc/ETo) was closely related to the leaf area index (LAI). The non linearity of the relationship between LAI and Tc/ETo can be written as $Tc/ETo = -0.21 + 0.70\, LAI^{1/2}$ for $(0.1 < LAI < 2.7)$

$$\text{or } \mathbf{Tc = ETo\,(-0.21 + 0.70\, LAI^{1/2})}. \qquad (2.35)$$

Equation 2.36 shows that Ep is larger per unit of leaf area for smaller plants than for larger plants with LAI approaching 2.7. Sensible heat was a significant source of the total energy contributing to ETp. Ritchie and Burnett (1971b) suggested that using higher plant populations and closer row spacings would improve water use efficiency of dryland crops. However, Yunusa et al. (1993) found that using agronomic approaches by increasing plant population and decreasing row spacing failed to improve water use efficiency and grain yield of wheat in a dry Mediterranean environment. This implies the possibility for improving water use efficiency using closer row spacing to decrease Es may not be possible for spring wheat in dryland agricultural systems.

The actual transpiration at each stage of crop growth may be calculated directly by subtracting the actual soil water evaporation (Esa) from the measured evapotranspiration under field conditions (Ritchie, 1972).

$$\mathbf{Tca = ETa - Esa} \qquad (2.36)$$

where Tca is crop transpiration, ETa is predicted actual evapotranspiration or total water loss by evaporation together with transpiration from the soil surface and crop canopy.

2.5.4 Models for predicting soil water evaporation

2.5.4.1 Diffusivity base model

The evaporation rate (Es) can be obtained from Green and Ampt's infiltration equation combined with general flow equation which was derived by Crank (1956 quoted by Black et al., 1969) as shown in Section 2.4.1.3 and is rewritten as:

$$\mathbf{Es = (\theta i - \theta s)D^{1/2}/\pi^{1/2}\,t^{1/2}} \qquad (2.37)$$

where θi is the initial soil water content, and θs is the soil surface water content, D is the soil water diffusivity, t is time.

The soil water diffusivity D is not a constant, it varied as soil water content varied. Hence, Gardner (1959) introduced "weighted-mean diffusivity, D*" as a mean soil water diffusivity.

$$\mathbf{D^* \quad = \quad \pi Ds/4\,(dc/dy)^2\,.} \qquad (2.38)$$

By substituting D in Equation 2.37 for D* from Equation 2.38 yields

$$\mathbf{Es = Ds^{1/2}/2t^{1/2}\,(\theta i - \theta s)\,(dc/dy)} \qquad (2.39)$$

where Ds (m^2 sec^{-1}) is the diffusivity value when $\theta = \theta s$, $\pi = 3.1416$, c is reduced soil water content ratio which is calculated as $c = (\theta - \theta s)/ (\theta i - \theta s)$, θi is the initial soil water content (m^3 m^{-3}), and θs is the soil surface water content (m^3 m^{-3}), with $\theta i > \theta s$ and

$y = Z / 2Ds^{1/2}\,t^{1/2}$, Z is soil depth. Z (mm) is the vertical distance of water movement from the deeper soil layer to the soil surface.

2.5.4.2 Ritchie's model

Ritchie (1972) presented a model for predicting evaporation from a row crop with incomplete cover. The model was used for calculating the daily evaporation rate from a crop surface of a row crop canopy in which the soil water supply to the plant roots is not limited. The model covers evaporation from the soil surface (Es) and plant surface (Ep, transpiration), the rainfall (P), the potential evaporation (Eo), leaf area index (LAI), and the net radiation at the soil surface below the canopy (Rns) and above the canopy (Rno). The evaporation from the soil surface is divided into two stages :

(i) Stage I evaporation

The evaporation rate is constant when the soil water starts drying at field capacity and evaporation rate is limited only by the energy supply to the surface. Ritchie's model incorporated The Penman Combination Equation (Penman, 1963) to define Potential evaporation or evaporative demand (Em).

$$\mathbf{Em = [\Delta / (\Delta + \gamma)]\, Rno + 0.262\,(1 + 0.0061U)\,(es\text{-}ed)\,[\gamma/(\Delta + \gamma)].} \quad (2.40)$$

The soil heat flux (G) is neglected and the wind speed (U) is measured at 2 m height above the soil surface. The net radiation at the soil surface below the canopy was calculated from leaf area index (LAI) and net radiation above the canopy

$$\mathbf{Rns = Rno\,exp\,(-\,0.398\,LAI).} \quad (2.41)$$

If the vapour pressure deficit and the wind function is assumed to be negligible, soil evaporation when the surface is freely evaporating or the potential evaporation below the canopy (Eso) can be calculated as,

$$\mathbf{Eso = [\Delta / (\Delta + \gamma)]\, Rno\,exp\,(-\,0.398\,LAI).} \quad (2.42)$$

(ii) Stage II evaporation

The falling rate of evaporation when the soil water is drying continuously from the first stage and the evaporation rate is limited by the capillary rise or hydraulic properties of the soil.

Ritchie (1972) suggested a simple equation for calculating evaporation rate during Stage II, which is identical to Philip's infiltration equation and is written as:

$$\mathbf{Es = \alpha /2t^{-1/2}} \quad (2.43)$$

The cumulative soil water evaporation during time t and t-1 is calculated as:

$$\Sigma Es = \alpha t^{1/2} - \alpha (t-1)^{1/2} \qquad (2.44)$$

where α (m^2 sec^{-1}) is desorptivity and is regarded as remaining constant during Stage II evaporation (Ritchie, 1972; Shouse et al., 1982).

Calculation of cumulative soil water evaporation (ΣEs) by Equation 2.44 can be continued on subsequent days by updating time and Es. The calculation is dependent on rainfall (P) and soil water content near the soil surface. If P is greater than Es during falling rate stage, then Es will be equal to Eso due to high surface soil water content. When P has evaporated, the evaporation mechanism returns to falling rate stage.

Equation 2.44 is the most widely tested and used in the calculation of soil water evaporation during Stage II evaporation with a constant desorptivity. (Johns, 1982b; Novak and Black, 1982; Stroosnijder, 1987; Yunusa et al., 1994, Brutsaert and Chen, 1995). Many studies have shown that α in Ritchie's model is sensitive to evaporative demand (Jalota and Prihar, 1986; Yunusa et al., 1994; Stroosnijder, 1987). Jackson et al. (1973) reported that α increases linearly with seasonal temperature while Johns (1982b) found that α is inversely proportional to evaporative demand.

However, Jalota and Prihar (1986) asserted that the magnitude and pattern of evaporation loss from a soil depends upon a combination of evaporative demand, (Eo), initial surface soil water content, (θi) and water transmission characteristics of soil. Therefore, a diffusivity based model, Equation 2.38 may give more accurate results than the modified Philip's infiltration equation or Ritchie's model Equation 2.45. This is because Equation 2.38 was developed based on soil water diffusion during the drying stage of soil water evaporation which is mainly governed by diffusivity and the boundary conditions. Even in a nonuniform soil profile such as dryland cultivated soil, the different soil layers can be divided into discrete layers, with different depths and initial water contents (boundary conditions), the weighted-mean diffusivity of each layer can be calculated. (Gardner, 1959).

2.5.4.3 Stroosnijder's model

Measurement of soil water diffusivity in 2.4.3.1 under field conditions is not practical and Ritchie's model is not appropriate because of diurnal fluctuation of evaporative demand (Em) and soil water evaporation (Es). Jackson et al. (1973) found that the soil water flux in the 0 to 9 cm layer is very dynamic and the flux at all depths continually change in magnitude and may change direction from 1 to 4 times a day. Therefore, calculation of soil evaporation rate or cumulative evaporation based on time intervals of many days or many hours may not be appropriate. Instead of using time intervals as a variable in Equation 2.44, Stroosnijder (1987) proposed an equation based on potential evaporation (Ep) for calculating soil water evaporation (Es) under semiarid conditions as

$$\mathbf{\Sigma Es} = \mathbf{\Sigma Ep} \quad \text{for stage I} \qquad (2.45)$$

$$\mathbf{\Sigma Es} = \boldsymbol{\beta} \, \mathbf{(\Sigma Ep)}^{1/2} \quad \text{for stage II} \qquad (2.46)$$

$$\mathbf{\Sigma Es} = \mathbf{\Sigma Es,n} - \mathbf{\Sigma Es,n\text{-}_1} \qquad (2.47)$$

where n is the day number on which evaporation takes place and β is an experimental parameter of evaporation characteristic.

Equation 2.46 is similar to Equation 2.44 and may be more practical because time does not enter as an independent variable. Time used in Equation 2.44 has been transformed into the variable ΣEp. Stroosnijder (1987) stated that Equation 2.46 can be used to estimate Es in situations with strongly varying daily Ep values whereas equation

2.44 fails. Moreover, β is independent of Ep which makes Equation 2.46 more practical compared with Equation 2.44.

Stroosnijder has found that β varied little for different soils and different climates (β ranged from 1.65 to 2), equation 2.46 may be appropriate for a bare soil conditions without a crop only. How this equation perform under the crop canopy with different evaporative demands has not been verified yet; β values must vary greatly during the growing season because variation of the crop canopy would cause large variations of Es under the crop.

The main differences between Ritchie' s model and Stroosnijder' s models for Stage II evaporation are the variable, time (t) and evaporative energy (Eo). In general, time controls soil water content (θ) but energy controls both soil water content (θ) and evaporation rate (Es). Energy should dominate evaporation process more than time. However if θ is very low, Stroosnijder' s model may not be valid. Therefore, soil water content and evaporative energy should be taken into account in modelling soil water evaporation.

Using infiltration models to represent evaporation process may not be valid because the infiltration process is controlled by the soil water potential gradient only while evaporation is regulated by both soil water potential gradient and energy supplied at the soil surface.

2.6. Summary

Crop production in many dryland farming systems is limited by rainfall and soil properties which control the crop water use efficiency for both biomass and grain production. The pathway to increasing dryland crop productivity lies in improving soil properties via improved soil tillage and crop rotation systems and thence water use efficiency. The important points that have emerged from this review of the literature related to soil properties and water use efficiency in dryland farming systems are listed below.

(i) The dryland agricultural water balance system is the balance between water gain from rainfall (P) and water loss through the interception of the crop canopy (I), surface runoff (R), deep drainage (D), total stored water change within the soil profile (ΔS) and crop water use (soil water evaporation, Es, and crop transpiration, Tc). Improvement of water use efficiency is to increase grain production, decrease I, R, D and Es and optimise ΔS and Tc via agricultural practices under different rainfall conditions.

(ii) Improved tillage practices (eg direct drilling as opposed to conventional cultivation) and crop rotation systems as opposed to monoculture, are practical strategies to improve surface and subsurface soil structure. Direct drilling ameliorates both surface and subsurface soil structure by increasing aggregate stability and aeration porosity, decreasing soil bulk density and mechanical impedance compared to the other tillage methods. Improved soil structure reduces surface runoff, decreases soil water evaporation rate, increases infiltration rate and increases the available soil water and crop transpiration. Consequently root development, crop growth, grain production and water use efficiency are improved compared to the other tillage methods. The effect of tillage practices on soil structure may also depend on climatic factors such as energy, intensity and distribution of rainfall during the growing season.

(iii) Crop rotations improve subsoil structure by raising the biological activity of different plant root systems leading to increases in soil water storage capacity, water extraction and grain yield. Canola can reduce root diseases and improve surface soil structure by improving aggregate stability and infiltration and reducing runoff compared with wheat. These effects are (1) canola, a broadleaf crop, can prevent raindrop impact and protect the surface soil structure from disruption by rainfall energy and (2) the root system of canola can encourage increased soil biological activity, and release soil binding agents which cause increased aggregate stability..

(iv) Soil water evaporation is controlled by two factors, (1) external meteorological conditions (net radiation, wind speed, air temperature and relative humidity) which influence conversion of liquid water to vapour and flow of vapour into or out of the soil, (2) soil properties which control water movement from deeper layers to the soil surface (water content, soil water retention, hydraulic conductivity and soil water diffusivity).

(v) Soil water evaporation occurs in three stages. Stage I is a constant evaporation rate from a high soil water content which is chiefly limited by the atmospheric evaporative demand, Stage II is a falling rate stage which is controlled by both evaporative demand and soil hydraulic properties, and Stage III is a reduced rate stage which dominantly occurs at low soil water content through vapour flow process. Soil water transport to the soil surface can be either a liquid flow process or a vapour movement process depending upon soil hydraulic gradient, soil water diffusivity, soil and air temperature gradient and vapour pressure conditions. The energy balance and mass conservation concepts are used to predict Stage I soil evaporation, while the laws of soil water movement and soil hydraulic properties are applied for predicting Stage II evaporation. However, all three stages of soil water evaporation are influenced by both atmospheric conditions and soil physical properties depending upon soil water content and time of evaporation.

(vi) Tillage causes variation of soil physical properties and consequently affects soil water evaporation by (1) increasing soil surface roughness and macroporosity which leads to increased soil water evaporation rate, (2) inducing a tillage pan with a decreased upward water flow from the deeper layer to the soil surface due to increased pore discontinuity between the tilled layer and the tillage pan, leading to a decrease in soil water evaporation, and (3) consequently increasing soil water conservation by creating a dry soil mulch. Several factors (evaporativity, soil type, soil wetness, depth and time of tillage) may interact with tillage in affecting soil water evaporation.

(vii) Use of modelling in quantifying evapotranspiration and water use efficiency is an effective tool to improve the quality of the research, and to describe the behaviour of soil management affecting dryland water use efficiency under the interactive effects of tillage practices and climatic conditions. Modelling of soil water evaporation (Es) and crop evapotranspiration (ETc) using several numerical and empirical formulas has been addressed by many researchers. Most models use equations that characterise the micrometeorological environment of a crop canopy in terms of evaporative demand to evaluate the reference crop evapotranspiration (ETo) and the potential crop evapotranspiration or crop water requirement (ETp) at each growth stage. The growth stage is quantified by a crop characteristic and/or crop factor.

(viii) The actual crop evapotranspiration (ETca) is evaluated based on ETp and the actual available soil water within the root zone (AWa). To have a better prediction of the water use efficiency, soil water evaporation (Es) and crop transpiration (Tc) must be separately evaluated. Models for predicting crop transpiration (Tc) are based on the available soil water fraction, evaporative demand, and crop growth function (Greacen and Hignett, 1976) or leaf area index (Ritchie and Burnett, 1971b).

(ix) The more recently calibrated Penman method (which includes the wind function) and the Penman-Monteith method (which uses an approximate canopy resistance) give the most accurate estimates of reference crop evapotranspiration. Normal meteorological data required for estimating reference crop evapotranspiration using the Penman-Monteith model are solar radiation, actual air temperature (dry bulb air temperatures), dewpoint temperature (wet bulb temperature), wind speed, air humidity or actual vapour pressure, and soil temperature or heat flux density of soil. To obtain the crop water requirement (ETc) or potential evapotranspiration (ETp), the crop coefficient (factor) of each crop at each growing stage must be known. Crop water requirement or ETp is the product of the crop coefficient and reference crop evapotranspiration (ETo).

(x) Predicting soil water evaporation requires models which take account of soil hydraulic properties, soil surface roughness, and some initial soil physical properties which are affected by soil management such as tillage practices. The soil hydraulic properties are a major requirement for predicting the effect of tillage on soil water evaporation. The diffusivity-based model with a weighted mean soil water diffusivity parameter (Gardner 1959) is one of the widely used numerical models that can predict soil water evaporation.

(xi) The most widely used of the semi-empirical soil water evaporation models is the Ritchie (1972) model. In this model soil water evaporation is evaluated in two stages, each with a different function. Stage I models constant evaporation from a wet soil surface, using a fraction of the net radiation at the soil surface below the canopy (estimated from leaf area index) and the Penman Combination Equation to define the evaporative demand at the soil surface. Stage II evaporation is identical to Philip' s infiltration equation based on time and desorptivity which is controlled by soil hydraulic properties.

(xii) Many results of research on soil water evaporation, conducted under different environmental conditions, often give conflicting results. Particularly, Stage I of soil evaporation does not dominantly exist under field conditions and the Stage II is not limited only by the soil water content but also by the evaporative energy at the soil surface. The change from Stage I to Stage II is not clearly defined nor the factors in modelling evaporation which can trigger the change. Therefore, the most fruitful modelling approach may be to derive a single function that deals with both Stage I and Stage II conditions.

CHAPTER 3

EXPERIMENTAL METHODS

3.1 Introduction

The experimental work was conducted at two levels: a field experiment and supporting laboratory work. A modelling component support was also included. Field work was commenced in 1992 and continued through to 1995. Tillage practices such as direct drilling and conventional cultivation were used to prepare a seed bed for different crop rotation systems. Crops grown were rotations of wheat (*Triticum aestivum L.*), canola (*Brassica napus*) and faba bean (*Vicia faba L.*).

Studies of water use efficiency were based on measurement of water used by the crop to produce dry matter and grain. Only soil water evaporation and total stored water changes within the soil profile at each growing stage of the crop were taken into account as the soil water balance components, deep drainage, surface runoff and interception were not measured due to exceptionally dry years in 1993 and 1994. This work was commenced 4 months after sowing in 1992, but methodology for measurement of all the soil water balance components were not completely set up until after the 1993 season and this was continued in 1994.

The cropping seasons in 1992, 1993 and in 1994 were unusual for climatic conditions in SA with abnormal rainfall during the effective growing period (from May to October). The 1992 season was very wet (428 mm), the 1993 and 1994 season were exceptionally dry (292 and 181 mm respectively). The 1995 season was more typical of the Southern Australia climate. Therefore in 1995 the research was continued in a reduced form to take advantage of more typical climatic conditions after two dry seasons in 1993 and 1994.

The aim of this section is to describe the locations, experimental design and methodology used to study the effects of tillage practices and crop rotation systems on soil properties and water use efficiency of wheat, faba bean and canola under rainfed conditions.

3.2 Experimental location and soil description

The experiment was established in May 1992 by Prof. Tim Reeves at the Roseworthy Agricultural Research Center (RARC), University of Adelaide, in field North 3 located at altitude 114 m, latitude 34° 30' South and longitude 138° 44' East. The experimental area was approximately 2.5 ha and had been used for growing wheat with no farm traffic for 3 years before being set up. The climate is semi-arid to sub-humid Mediterranean type. Monthly distribution of the average rainfall and evaporation including the long-term average rainfall and evaporation at the experimental site are shown in Figure 3.1.

The soil is classification is Great soil group, Red-brown earth, with Factual Key classification of Dr2.13 (Northcote, 1981), or Rhodoxeralfs (Soil Taxonomy, 1975, quoted by Northcote, 1981) or calcic luvisols mixed with Orthic solonetz (World Soil Map, 1970 quoted by Northcote, 1981) (Figure 3.2). The soil profile consisted of three horizons described in Table 3.1. Soil physical properties are presented in Table 3.2. The soil texture and the soil water characteristic at different soil depths are presented in Figure 3.3 and 3.4. respectively.

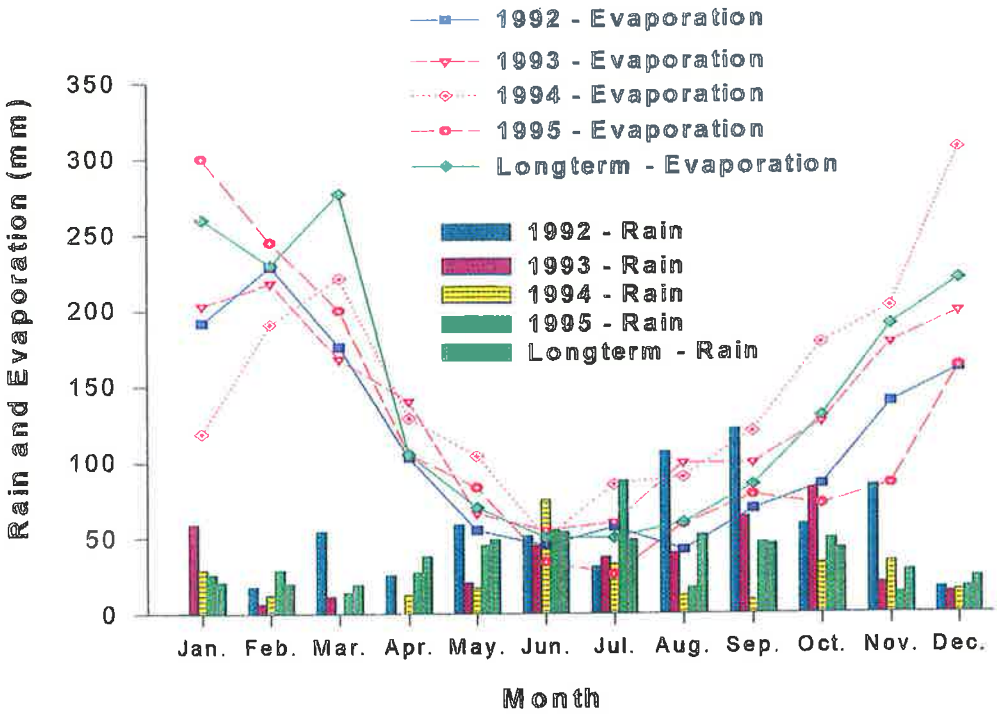

Figure 3.1 Monthly distribution of rainfall and pan evaporation for 1992-1995 and the longterm averages (20 years) at Roseworthy Agricultural Research Center (RARC), University of Adelaide (Data from the weather station of RARC).

Figure 3.2 The soil profile morphology of the Red-brown earth at Roseworthy Agricultural Research Center (RARC), University of Adelaide.

Table 3.1 Soil profile description for the Red-brown earth at RARC.

Horizon Depth (mm)	**Description**
A-horizon, 0-200	Dark reddish brown (5YR3/3 moist), fine sandy loam; granular to sub angular blocky; soft and friable, many roots
B1-horizon, 200-400	Brown (5-7.5YR4/4 moist), clay loam, moderate subangular blocky, soft and friable; many roots, many calcareous nodules
B2-horizon 400-800	Red brown, (5YR4/4 to 2.5 YR4/6 moist), clay; subangular; blocky, plastic (moist); many roots, many limestone nodules
C-horizon, 800-1000	Yellow brown (10 YR5/6 moist) clay, soft friable, weakly subangular blocky; soft friable to firm; coarse mottling, few limestone nodules

Table 3.2 Average soil physical properties of three profile pits located in field North 3, Roseworthy, University of Adelaide. The standard errors for each soil properties was small and is not presented.

Soil physical properties	**Soil depth interval (mm)**				
	0-100	**100-200**	**200-400**	**400-800**	**800-1000**
Bulk density (Mg m^{-3})	1.25	1.50	1.45	1.50	1.55
Particle density (Mg m^{-3})	2.45	2.55	2.50	2.50	2.50
Total porosity (m^{3} m^{-3})	0.490	0.412	0.420	0.420	0.380
Aeration porosity (m^{3} m^{-3})	0.240	0.092	0.040	0.020	0.030
Field capacity (m^{3} m^{-3})	0.250	0.330	0.380	0.400	0.350
Wilting point (m^{3} m^{-3})	0.130	0.180	0.200	0.250	0.180
Total available water (mm)	12	15	36	60	34
Soil reaction (pH)	7.10	7.50	7.40	8.36	8.00
sand-silt-clay (% mass)	52-24-24	45-10-45	26-16-58	25-17-58	35-22-43
Soil texture	**Sandy clay loam**	**Clay**	**Clay**	**Clay**	**Clay**

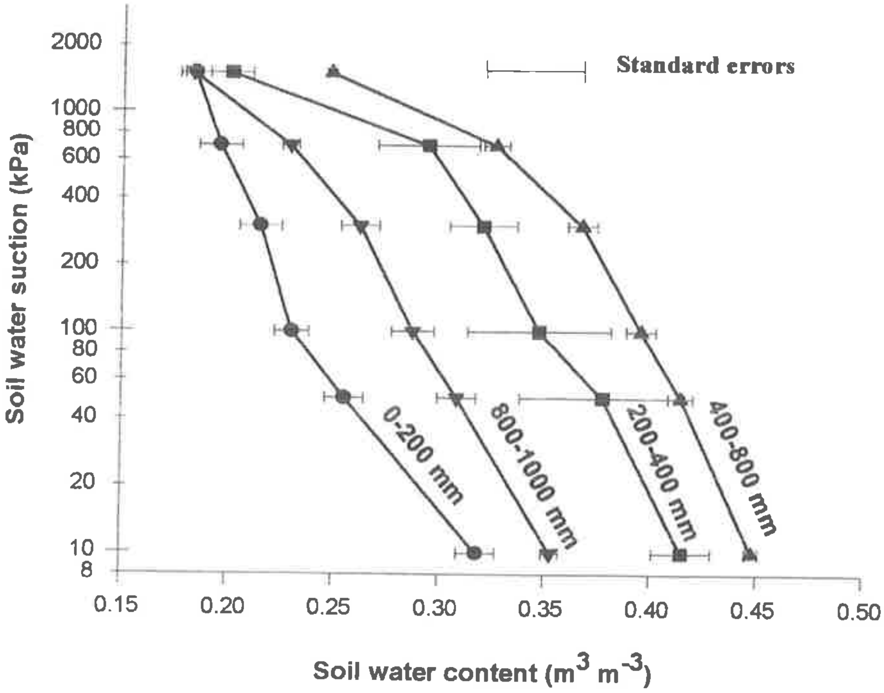

Figure 3.3 Average soil water characteristic of the Red-brown earth at Roseworthy Agricultural Research Center (RARC), University of Adelaide.

3.3 Experimental design

The experimental area was divided into eight 15x122 m main plots which carried the main tillage treatments with a 9 m lane between each plot. Each main tillage plot was divided into twenty seven 4x15 m sub-plots separated by a 0.5 m wheel track. The treatments of tillage practices and crop rotation systems were assigned to each plot according to the experimental design in Table 3.3 and plot layout, Figure 3.4.

The statistical design is a randomized split-plot with repeated measure. The treatments comprised 4 replications of two tillage practices (T) and five crop rotation systems (S). The outline of Analysis of Variance is shown in Table 3.4.

Tillage practice	**Direct drilling (DD)**
	Conventional Cultivation (CC)
Cropping System :	**Wheat *(Ttiticum aestivum L.*, W)**
	Canola (*Canola cache L.*, C)
	Faba bean *(Vicia faba L.*, B)

Table 3.3 The treatment combinations for the experiment from 1992 to 1995.

Year		* Tillage (T)	* Crop rotation systems (S)				
1992	(1)	DD	W		C		B
		CC	W		C		B
1993	(2)	DD	WW	WC	WB	CW	BW
		CC	WW	WC	WB	CW	BW
1994	(3)	DD	WWW	WCW	WBW	CWB	BWC
		CC	WWW	WCW	WBW	CWB	BWC
1995	(4)	DD	WWWW	WCWC	WBWC	CWBW	BWCW
		CC	WWWW	WCWC	WBWC	CWBW	BWCW

*** DD**	Direct drilling	**W**	Wheat
*** CC**	Conventional Cultivation	**C**	Canola
		B	Faba bean

In total there were 216 experimental plots with a plot size of 4x15 m. A subset of the full crop rotation experiment chosen for these studies were equal to 40 plots (2 tillage practices x 5 crop sequences x 4 replicates). The combinations of tillage practices and crops chosen for this project are outlined in Table 3.3.

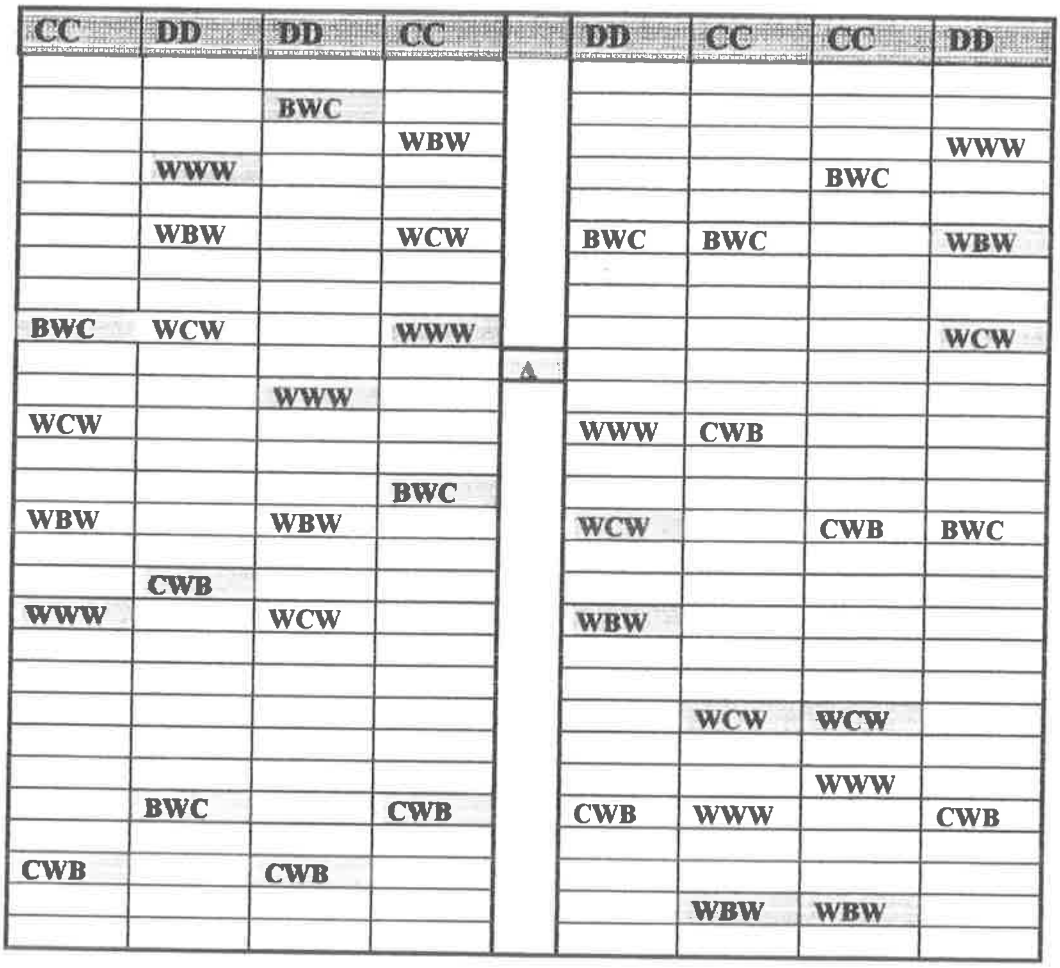

Figure 3.4 Plan of the experimental blocks, comprising of 2 mainplots (direct drilling, DD and conventional cultivation, CC) and 5 subplots (cropping systems, wheat, W, Faba bean, B and canola, C) with 4 replications. A is the weather station. The plots with shading were divided into two subplots in 1995 in order to maintain the four replications for each treatment.

In 1992, wheat (W), canola (C), and faba bean (B) were sown as sub-plots in direct drilling (DD) and conventional cultivation (CC) main plots. In 1993, The soil was prepared similarly to 1992. Each crop was sown under direct drilling (DD) and conventional cultivation (CC) using the following crop sequence.

WW: wheat in 1993 after wheat in 1992.
WC: canola in 1993 after wheat in 1992
WB: faba bean in 1993 after wheat in 1992

CW: is growing wheat in 1993 after canola in 1992

BW: is growing wheat in 1993 after faba bean in 1992.

Table 3.4. Outline of Analysis of Variance.

Source of Variation	**Degree of Freedom**			
	1992	**1993**	**1994**	**1995**
Replication	**3**	**3**	**3**	**3**
Treatment	**5**	**9**	**9**	**9**
Tillage practice (T)	1	1	1	1
Cropping system (S)	2	4	4	4
Interaction (TxS)	2	4	4	4
Error	**15**	**27**	**27**	**27**
Total	**23**	**39**	**39**	**39**

In 1994, the following crop sequences were sown (Table 3.3):

WWW:	wheat in 1994 after wheat in 1993.
WCW:	wheat in 1994 after canola in 1993
WBW:	wheat in 1994 after faba bean in 1993
CWB:	faba bean in 1994 after wheat in 1993
BWC:	canola in 1994 after wheat in 1993.

In 1995, the following crop sequences were sown (Table 3.3):

WWWW:	wheat in 1995 after wheat in 1994.
CWBW:	wheat in 1995 after faba bean in 1994
BWCW:	wheat in 1995 after canola in 1994.
WBWC:	canola in 1995 after wheat in 1994.
WCWC:	canola in 1995 after wheat in 1994

Six treatment combinations were studied in 1992 and ten treatments were monitored each year from 1993 to 1995 as shown in Table 3.3. Analysis of variance was done as shown in Table 3.4 for all years except 1995 where the replications for growing wheat and canola were reduced by half. Faba bean was not grown in 1995. Each plot was divided into two equal subplots in order to maintain the number of 4 replications. Soil properties and crop development were measured in each divided main plot in order to retain 4 blocks for each crop rotation. Only 2 replications of each crop rotation were monitored with soil moisture meter.

3.4 Soil preparation, seeding and management

3.4.1 1992 Experiment

Stubble from the previous year's wheat crop was burnt on 29 April 1992 in order to control weeds and pests. Wheat (*Triticum aestivum L.*, RAC 698), Canola (*Canola cache L.*, Barossa) and Faba bean (*Vicia faba L.*, Fiord) were sown on 30 and 31 May 1992 by conventional cultivation (CC) and (DD) (Figures 3.5 and 3.6 respectively).

The conventional cultivation (CC) treatment was scarified with a cultivator 3 times followed by harrowing to level the soil surface (Figure 3.5). All the direct drilled plots were sprayed with 1.0 L/ha of Trifuralin, 2.0 L/ha of Paraquat and 1 L/ha of Reglone to control weeds on 30 May 1992. Sowing on direct drilled plots was carried out by a seeder with 20 mm opening duck foot tynes attached to a gantry with 4 m wheel spacing in order to restrict traffic to wheel tracks (Figure 3.6).

Faba bean (Fiord) was inoculated with rhizobium inoculant before sowing. The sowing rate for faba bean was 96 kg/ha, canola (Barossa) 10 kg ha^{-1}. and wheat (Trident) 63 kg ha^{-1}. All plots received 60 kg ha^{-1} of triple super phosphate.

Figure 3.5 Conventional cultivation (CC) using scarified cultivator.

Figure 3.6 Direct drilling (DD) using direct seeder with a gantry of 4 m wheel spacing.

During the growing season in 1992, methods for measuring micrometeorological data, soil properties, soil water content and some components of the soil water balance were investigated in order to obtain information about soil, crop responses and climate at the growing site. Steel access tubes of 2 m depth for soil water measurement by the neutron scattering method were set in the center of each sub-plot before sowing.

Calibration of the neutron water meter was done in situ for different soil horizons in the three profile pits adjacent to the experimental plots. The calibration was conducted during the dry period after harvesting (February-March 1993) using the method of Greacen (1981a). Two readings were made using a Campbell Pacific Nuclear neutron probe (CPN 503 DR) set to 16 s counts at 100, 300, 450 and 1000 m below the soil surface in each access tube. A tank of water (200 L) was used as a standard during the calibration and for each day of measurement. All readings were expressed as a ratio of the standard. The volumetric soil water content was measured simultaneously at the corresponding depth around the access tube (5 replications per depth). The calibration curves for each soil horizon are shown in Figure 3.7.

The data of Figure 3.7 were fitted as the following equations for each soil depth interval:

(i) 0-200 mm : $\theta = 0.5636 N + 0.0297$ $R^2 = 0.96$ (3.1)

(ii) 200-600 mm : $\theta = 0.9705 N - 0.1686$ $R^2 = 0.90$ (3.2)

(iii) 600-800+ mm : $\theta = 1.7858 N - 0.5611$ $R^2 = 0.99$ (3.3)

where θ is the volumetric soil water content ($m^3 m^{-3}$) and N is the ratio of the actual neutron count to the standard count for the indicated depth interval.

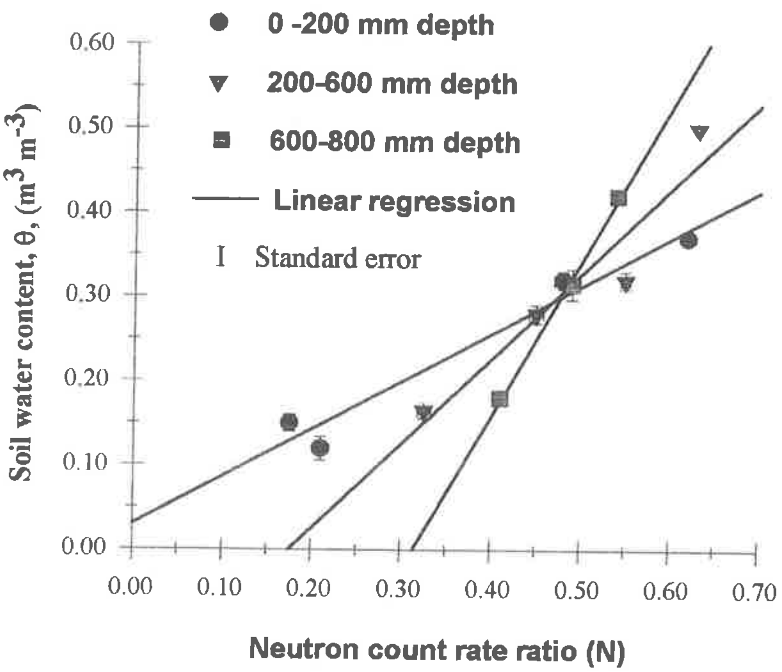

Figure 3.7 The calibration curves of soil water content (θ) and relative counts (neutron count rate ratio) for 3 soil horizons averaged in 3 locations on Roseworthy Red-brown earth at RARC, University of Adelaide.

Soil water content was measured several times before and after rainfall throughout the growing season. Soil samples were taken one month before harvesting, Undisturbed soil cores were sampled at 0-75 and 75-150 mm depth using cylindrical metal rings of 75 x 75 mm pressed into the soil. The samples were removed and cut to have the same volume as the core, then transfered to laboratory to determine the soil physical properties.

3.4.2 1993 Experiment:

Tillage treatments were prepared as in 1992. Cultivation was carried out on 15 June 1995. Weed control by herbicide, seed inoculation and fungicide treatment were carried out 2 days before sowing using the same chemicals and inoculant and procedures as in 1992.

Wheat, canola and faba bean were sown as sub-plots after the 1992 crops according to the experimental design in Table 3.3, using the same seeding rate as in 1992. The sowing dates were on 18 to 19 June 1993. Fertilizer was applied to all plots as diammonium phosphate grade 18-20-0 at a rate of 100 kg ha $^{-1}$. Measurement of soil water content, soil physical properties, soil evaporation, soil hydrological properties, micrometeorological data and root growth are described in Section 3.5

3.4.3 1994 Experiment:

The soil preparation was conducted by the same procedure used in 1993. The sowing date was on 28-29 June 1994. Wheat, canola and faba bean were sown as rotating cropping systems according to Table 3.3 for 1994. Seeding rate, herbicide application, seed inoculation, fertilizer application and fungicide treatment were similar to the 1993 experiment.

3.4.4 1995 Experiment:

The experiment was continued in 1995, at a reduced level because the climatic conditions in 1992, 1993 and 1994 were unusual. The 1992 season was very wet (428 mm, including 1 in 100 year rainfall events), the 1993 and 1994 season were exceptionally dry (292 and 181 mm, the driest for 25 years) These three years did not provide data which represented a typical climate and did not address the main aim of the work. Therefore, monitoring soil water content and soil physical properties under some treatments were carried out in 1995 in order to obtain a more comprehensive set of information. Only wheat and canola rotations were monitored.

In 1995, the soil was cultivated with scarifier 2 times on 22 June 1995. Soil levelling, weed control and fertilizer application were conducted by the same method as done in 1993.

3.5 Field measurements

3.5.1 Soil properties

During growing seasons from 1992 to 1995, bulk density, available water capacity, aeration porosity, aggregate stability, mean weight diameter of stable aggregates, penetration resistance, steady infiltration rate, soil water characteristic, total nitrogen and organic matter content were measured at 0- 75 mm and 75-150 mm depths. The soil was sampled approximately one month before harvesting (2 November 1992, 1 November 1993, 2 November 1994 and 4 November 1995) as shown in Table 3.5. The soil properties were measured as follows.

(i) **Bulk density (BD)** at field capacity moisture content (2 days after rainfall) was measured at 0-75 mm (ploughed or tilled layer) and 75-150 mm soil depth. The soil sample was taken (2 replications per plot) by using undisturbed soil core sampler of 75 mm diameter and 75 mm height core size (McIntyre and Loveday, 1974).

(ii) **Particle density (PD)** of the surface and sub-surface soil were measured from composite samples taken from each treatment for each soil using 250 ml volumetric flasks and direct weighing methods (modified from Blake and Hartge, 1986).

(iii) **Total porosity (TP)** was calculated from BD and PD obtained in (i) and (ii) and calculated as TP = 1-BD/PD.

(iv) **Soil water content at field capacity (FC) and permanent wilting point (WP)** were measured as volumetric soil water content at soil water suction of 10 and 1500 kPa by using a porous pressure plate with a hanging water column, and with the pressure extractor apparatus respectively.

(v) **The available soil water capacity (AWC)** was calculated from field capacity (FC) and wilting point (WP) obtained in (iv) as AWC = FC-WP.

Table 3.5 Soil properties and soil water content were measured by using the standard methods.

Soil properties	Unit	Methods of measurement
(i) Bulk density (BD)	**Mg m^{-3}**	Undisturbed soil cores in 75x75 mm stainless steel rings.
(ii) Particle density (PD)	**Mg m^{-3}**	Pycnometer and gravimetric method.
(iii) Total porosity (TP)	**m^3 m^{-3}**	Calculated as 1-BD/PD.
(iv) Field capacity (FC) and P wilting point (WP)	**m^3 m^{-3}**	Soil water content at soil water suction of 10 kPa and 1500 kPa respectively.
(v) Available water capacity (AWC)	**m^3 m^{-3}**	Calculated as FC-WP.
(vi) Aeration porosity (AP)	**m^3 m^{-3}**	Calculated as TP-FC.
(vii) Soil water characteristic	**m^3 m^{-3} vs kPa**	Gravimetric metric method and pressure extractor apparatus at high pressure (≥ 100 kPa) and hanging column at low pressure (≤ 60 kPa).
(xiii) Aggregate stability and mean weight diameter of stable aggregate (SAD, SAT, MWD)	**% w/w and mm**	Wet sieving method. (Kemper and Chepil, 1965).
(ix) Soil penetration resistance	**MPa**	Pocket or micro- penetrometer.
(x) Infiltration rate	**mm hr^{-1}**	Disk permeameter method using 0.25 kPa suction. (White et al., 1992)
(xi) Organic matter content	**% w/w**	Wet oxidation by Walkley-Black Procedure (Nelson and Sommers, 1982)
(xii) Total nitrogen content	**% w/w**	Kjeldahl's method.(Bremner and Mulvaney., 1982)

(vi) **Soil aeration porosity (AP)** was calculated in (iii) and (iv) by subtracting the volumetric soil water content at field capacity from total porosity and calculated as AP = TP-FC.

(vii) **Soil water characteristic** for both surface and subsurface soil layers were measured using pressure plate extraction apparatus at a high suction (≥ 100 kPa) and hanging water column under the pressure plate at low suction (≤ 60 kPa). The soil water characteristics was measured on undisturbed core samples collected one month before harvesting. This procedure provided a general description and a measure of changes of soil hydraulic properties under soil tillage practices and crop sequences.

(viii) **Aggregate stability** was measured by the wet sieving method using a set of four 50 mm diameter sieves with opening of 0.5, 1.0, 2.0 and 5 mm. and the air dry aggregates of ≤ 9.5 mm diameter. The soil samples were taken as a composite sample from 0-50 mm soil depth. Wet sieving was carried out for 25 min according to Yoder's method (Kemper and Chepil, 1965). Data obtained were calculated as mean weight diameter (MWD), percentage of stable aggregates (SA) in total dry soil (SAT) and in dry aggregates (SAD) for the surface soil (0-50 mm).

(ix) **Soil penetration resistance (PR)** obtained from the soil sample taken as an undisturbed core of the surface soil (0-75 mm) and sub-surface soil (75-150 mm). Measurement was done at the soil matric suction of 60 kPa using a pocket penetrometer in the laboratory.

(x) **Steady state infiltration rate (IR)** was measured 1 month before harvesting (6 November 1994) by using disk permeameter (White et al., 1992)) The steel infiltrometer ring was pressed 200 mm into the soil to prevent horizontal flow of soil water over the plough pan, and the disk permeameter was placed on a pad of fine sand

(Figure 3.8) on the soil surface within the ring. Cumulative infiltration under a suction of 0.25 kPa was recorded against time. The steady (final) infiltration rate was calculated by plotting the cumulative infiltration as a function of time. The slope of the linear part of this relation is the steady state flow rate or final infiltration rate.

(xi) **Organic carbon content (OC)** was analysed by wet oxidation according to Walkley-Black procedure (Nelson and Sommers, 1982) for composite samples taken at grain filling stage for root analysis for 0-100 and 100-200 mm soil depth respectively.

(xii) **Total nitrogen content (N)** in soil was analysed using Kjeldahl's method (Bremner and Mulvaney, 1982).

3.5.2 Soil water

(i) **Soil water content (θ)** was measured nearly every fortnight during the growing season using a neutron water meter (Figure 3.9) at depth of 100, 250, 400, 600, 800, 1000, 1350 and 1750 mm. Readings were divided by a standard count from a 200 L water drum set near the plots to obtain the count ratio (n). Volumetric soil water content (θ) was calculated using the calibration curves obtained in Section 3.4.1. The surface soil (0-75 mm) water content measurement was supplemented by Time Domain Reflectometry (Dalton, 1992) and hand sampling.

(ii) **Total stored soil water (TSW)** at each growing stage was calculated as equivalent depth of water (mm) within the soil profile to 2 m depth, the amount of stored water was calculated as,

$$\mathbf{SW} = \sum_{i=1}^{n} \boldsymbol{\theta} \mathbf{i}\, \mathbf{Zi} \qquad \mathbf{(3.1)}$$

where i is the number of horizons or soil layers which were measured by the neutron moisture meter, θi and Zi are the volumetric water content and thickness of the i^{th} horizon respectively.

(iii) **The changes in total stored water within the root zone (ΔSW)** during a period of crop growth was accounted for water used by the crop, losses by evaporation from the soil surface and added by infiltration of rainfall. The changes of stored water during a period of time from time t_1 to t_2 can be written as,

$$\Delta SW = \sum_{i=1}^{n} \theta_i t_2 Z_i t_2 - \sum_{i=1}^{n} \theta_i t_1 Z_i t_1 \qquad \textbf{(3.2)}$$

3.5.3 Micro-meteorological data

The CR10 weather station (Campbell Scientific, Inc.) was set at the centre of the experimental site in 1993 and 1994. All sensors for rainfall, relative humidity, wind speed, air temperature, net radiation, soil moisture, soil heat flux density and soil temperature were set at the same location and soil depths in both years of experiment. All micrometeorological data were recorded by the Campbell data logger. These data were measured every 3 min, averaged every hour and stored. The following data were collected during the growing seasons in 1993 and 1994.

(i) **Rainfall (P)** The amount of rainfall was measured by the TE525 tipping bucket rain gauge (Campbell Scientific, Inc.) calibrated against a normal gauge located on the plots. The data were recorded in data logger located with a weather station at the centre of the experimental site (Figure 3.10). A comparison was made with daily rainfall at the weather station of Roseworthy campus 3 km away as a check.

Figure 3.8 Infiltration measurement using disk permeameter and infiltrometer ring to control vertical downward movement of water through the soil surface

Figure 3.9 Soil water content measurement using neutron moisture meter and access tubes in monitoring plots

Figure 3.10 Overview of the experimental plot during flowering stage of canola. Weather station with a data logger connected to net radiometer, anemometer, hygrometer, air temperature, automatic tipping rain gauge and all underground sensors.

(ii) **Relative humidity (RH) and air temperature (Ta):** were measured by automatic exchange mechanism (AEM) electronic sensors (Campbell Scientific, Inc.) set at 1.5 m above the crop. The data were recorded in data logger (CR10).

(iii) **Soil temperature (Ts)** at 50, 100, 200, 1000 mm soil depth were measured by thermistors (Campbell Scientific, Inc.).

(iv) **Soil heat flux density (G)** at 200 mm soil depth was measured by heat flow transducers (HFT3, Campbell Scientific, Inc.).

(v) **Albedo** or the reflection coefficient of plant canopy and soil surface were measured at intervals by an albedo meter (Campbell Scientific, Inc.).

(vi) **Net radiation (Rn)** measured by total hemispherical radiometer (THRDS-5, Campbell Scientific, Inc.) above wheat canopy at 2 m height from the ground level.

(vii) **Wind speed (W)** was measured by anemometer (Campbell Scientific, Inc.) set 2 m above the soil surface over wheat, at the ground surface as well as at crop height for each of wheat, canola and faba bean.

(viii) **Evaporation (Epan)** from a free water surface or evaporative demand over the crop canopy was measured by Class-A pan set near the weather station. Data were read manually every week.

3.5.4 Estimation of deep drainage and surface runoff

(i) **Deep drainage (D)** was not measured in this trial. The only year in which the profile may have drained was 1992 with saturated hydraulic conductivity (Ks) varying from 5.8×10^{-4} to 2.4×10^{-3} m d^{-1} for the 200-800 mm soil depth (Ks was measured in the laboratory using undisturbed soil core samples of 75 x 75 mm taken from the profile pit in 1992). Deep drainage was negligible due to the unsaturated soil water content throughout the growing seasons from 1993 to 1995, and because the vertical downward unsaturated flux beyond 800 mm hardly occurred as soil water suction at 600 mm was always higher than that at 800 mm according to the soil water characteristics of these two horizons (Figure 3.3). Furthermore, the evidence from neutron moisture meter reading showed that soil water content at 1.5 m depth did not vary significantly throughout the growing seasons, implying that deep drainage could be negligible during the 4 years of the experiment.

(ii) **Surface runoff (R)** was not measured because the slope of the experimental area was very low (varied from 0.5-to 2 %) and saturated infiltration rate (varied from 29 to 117 mm hr^{-1}) was higher than rainfall intensity in 1993, 1994 and 1995. In 1992, surface runoff was assumed to be negligible because surface water was observed on the soil surface for many days after rainfall and there was no indication of runoff from the plots.

3.5.5 Crop growth and root distribution

(i) **Crop growth** was measured as total dry matter at different stages of crop growth and grain or seed yield. Crop development was based on wheat phenology which varied from year to year depending on sowing date, rainfall and temperature. In 1992, dry matter was not measured, only grain and seed yield at harvesting. The stages of crop development from sowing date to harvesting are shown in Table 3.6.

From 1993 to 1995, dry matter was obtained by cutting all plant materials above ground level from two, 2 m lengths of row. Samples were dried at 55 °C for three days. Crop yields (grain and seed) were harvested several days after the complete ripening stage which occurred within 185, 138, 138 and 140 days after sowing in 1992, 1993, 1994 and 1995 respectively. Crop yields were taken from the whole plot (180 m^2) in 1992 and from two representative areas of 1 m^2 in 1993, 1994 and 1995.

(ii) **Root length density** was measured once a year during crop yield formation. Three random, composite soil samples of 50 mm diameter were taken from each plot at depths of 0-100, 100-200, 200-400 mm and then in 200 mm increments to maximum root depth. This varied from year to year (from 1000 to 1600 mm) according to rainfall and crop height. Subsampling and preparation of samples for root length estimation were carried out using the method of Hignett (1976).

Root length determinations were carried out using a video based perimeter detection algorithm running on a computer. The apparatus was calibrated by direct root counts using a microscope and a dish marked with a grid of intersection- reference points were for 10 samples at each soil depth according to Newman's method (Newman, 1966). These data were used to calibrate those obtained by video based perimeter detection.

Table 3.6 Crop development and numbers of days from sowing to each growing stage approximately for each measurement from 1992 to 1995.

Crop development from sowing to....	**Number of days from sowing to each growth stage**			
	1992	**1993**	**1994**	**1995**
Sowing date	**30-31 May**	**18-19 June**	**29-30 June**	**5 July**
Seedling	40	38	36	36
Tillering	75	75	68	58
Heading	95	85	87	78
Flowering	115	110	100	97
Yield formation	145	115	105	107
Grain and seed filling	160	123	114	118
Ripening	185	138	138	140
Harvesting	195	163	155	158
Harvesting date	**12 Dec.**	**29 Nov.**	**2 Nov.**	**10 Dec.**

3.5.6 Calculation of crop water use and water use efficiency

(i) **Crop water use** was determined as soil water evaporation (Es) and crop transpiration (Tc) calculated from the soil water balance equation by assuming deep drainage (D), surface runoff (R) and canopy interception (I) were zero. Therefore, soil water balance is written as

$$\mathbf{Es + Tc} \quad = \quad \mathbf{P - \Delta S} \qquad (3.4)$$

where P is rainfall and ΔS is the changes of stored soil water within the soil profile of 2 m depth. Es and Tc were calculated together as cumulative water use or cumulative actual crop evapotranspiration (ETc) during different growing stages. The 5 crop growing stages were based on those for wheat which were approximately, from sowing to seedling (20 days), seedling to tillering (30 days), tillering to flowering (30 days), flowering to yield formation (30 days) and from yield formation to ripening or harvesting (30 days) (Table 3.6). Therefore, cumulative crop evapotranspiration (ETc) was calculated for each stage from rainfall (P) and the changes of total stored soil water (ΔS) data as

$$\mathbf{ETc} \quad = \quad \mathbf{Es + Tc =} \quad \mathbf{P - \Delta S} \qquad (3.5)$$

(ii) **Water use efficiency** of each crop was calculated based on cumulative dry matter at each growing stage and grain (seed) yield using corresponding cumulative water use or evapotranspiration, dry matter and grain or seed yield of wheat, canola and faba bean. The water use efficiency of each crop was expressed as dry matter and grain or seed weight production per mm of water use for actual crop evapotranspiration.

3.6 Soil water evaporation

3.6.1 Field measurement of soil water evaporation

Soil water evaporation (Es) was measured by a lysimetric method using a microlysimeter (Boast, 1986) as described in Section 2.4.1.4, Chapter 2. Cylindrical stainless steel rings of 75 mm diameter and 75 mm height were pressed into the soil when the soil moisture content was approximately at field capacity. At least 5 of these soil cores per plot were left in the field for at least 1 week before measurement (Figure 3.11a). On the day chosen for measurement, the core was removed and the plastic base attached to isolate it from the soil below. The core was weighed and reinserted into the original location by mid morning. The core was left to evaporate through the day and removed and weighed in the evening. The soil evaporation loss was calculated as mm of soil water loss per 10 hr which was assumed to be total loss per day.

The measurements in 1993 were done with a single replication on the 10 treatments around the weather station. In 1994 and 1995. Evaporation studies focused on soil water evaporation and water balance modelling for a continuous wheat crop rotation sown by direct drilling or conventional cultivation.

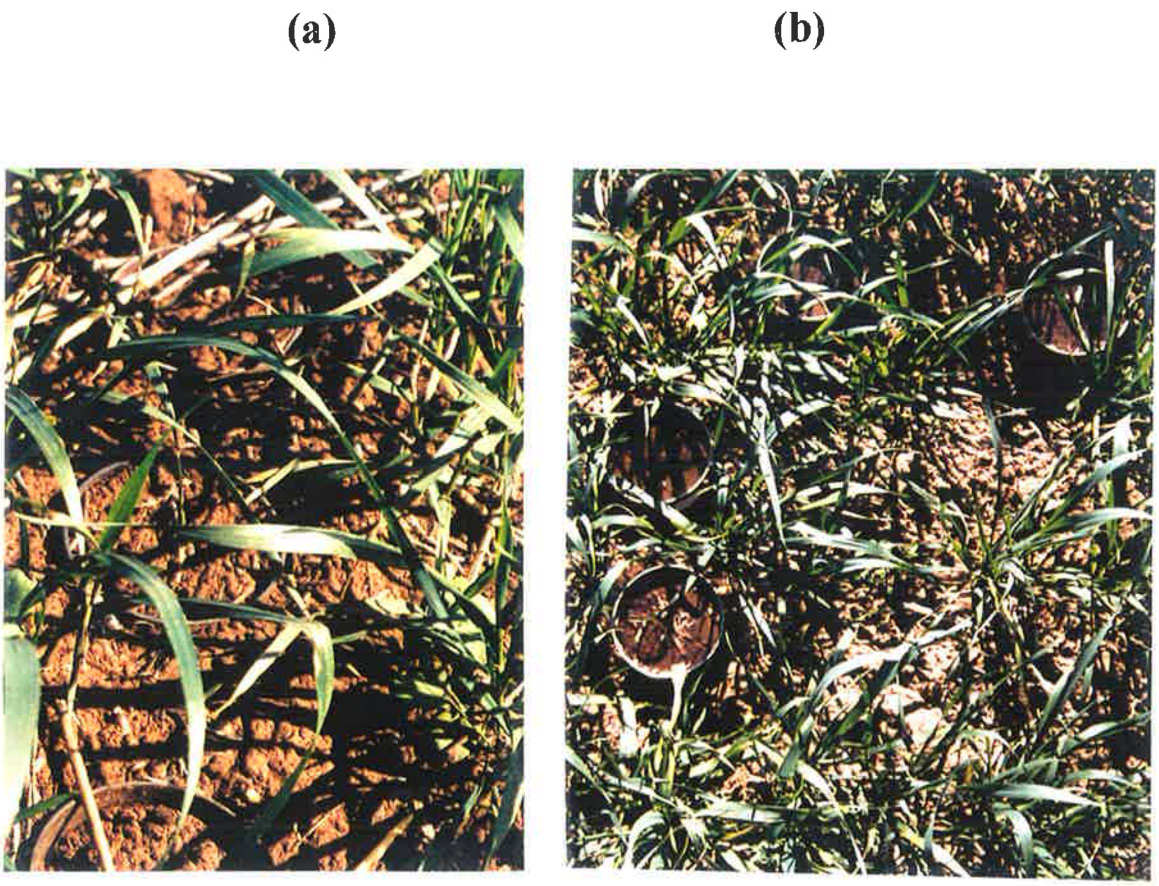

Figure 3.11 Measurement of **(a)** soil water evaporation and **(b)** evaporative demand using a microlysimeter and a microevaporimeter respectively.

.3.6.2 Evaporative demand (Em)

The potential soil water evaporation or evaporative demand under the crop canopy was measured by a microevaporimeter (Figure 3.11b) in order to represent the environmental condition such as air temperature, relative humidity, net radiation, and soil albedo over the soil surface under the crop canopy. A small can 80 mm diameter and 60 mm height was 2/3 filled with top soil and covered with 20 mm of water. It was placed in a hole of equivalent size near the microlysimeters and weighted at the same time as the microlysimeters periodically during the day in order to estimate the potential soil evaporation or evaporative demand under the crop canopy. Five replications of evaporative demands were measured for each set of soil evaporation measurement. The measurements were repeated several times during the growing season from 1993 - 1995.

3.7 Summary

Methods for studying the effects of tillage practices and crop rotation systems on soil properties and water use efficiency of dryland crop production were conducted from 1992 to 1995 at the RARC-experimental field. The methods used were as follows:

(i) The field experimental design was a split plot randomized block with 4 replications. The treatments consisted of 2 main plots comprising tillage practices, direct drilling (DD) and conventional cultivation (CC), and 3 sub-plots for crop rotation systems of wheat (W), canola (C) and faba bean (B). Crops were sown by direct drilling or conventional cultivation in the same main plots every year. Wheat (W), canola (C) and faba bean (B) were rotated in different sub-plots each year. In 1992, being the first year of experimentation, all 3 crops were monitored. In 1993 and 1994, 5 crop rotations were studied (WW, BW, CW, WB and WC in 1993, and WWW, WBW, WCW, CWB and

BWC in 1994). In 1995, only wheat and canola were sown and 5 crop rotations (WWWW, CWBW, BWCW, WBWC and WCWC) were studied.

(ii) Soil profile descriptions and soil properties (pH, soil texture, bulk density, field capacity, wilting point, aeration porosity and soil water characteristic) for each soil horizon were investigated and measured during growing season in 1992 in order to have general information about soil at the experimental site. A neutron water meter was calibrated for the site during the dry period after the first year experiment.

(iii) Soil properties (bulk density, aeration porosity, field capacity, wilting point, aggregate stability, penetration resistance, infiltration rate, organic carbon and total nitrogen) of surface soil (0-75 mm depth) and subsurface soil (75-150 mm depth) were measured 1 month before harvesting each year.

(iv) Samples for root distribution were taken during yield formation every year. Soil water content at different soil depths was measured regularly using neutron water meter and crop development as total dry matter was monitored at different growing stages during the cropping season.

(v) Micrometeorological data (rainfall, wind speed, atmospheric pressure, air humidity and temperature) some soil thermal properties and soil moisture retention were measured by electronic sensors. These data were measured automatically at 1 hour intervals and stored in a data logger located with the main weather station sensors at the center of the experimental plots.

(vi) The soil water balance study focused on rainfall, total stored soil water within the soil profile, soil water evaporation and evapotranspiration. Deep drainage, surface runoff and interception were assumed negligible. Soil evaporation (Es) were measured using microlysimetric method under field conditions in 1993, 1994 and 1995. Es was also measured using large soil cores evaporating under natural conditions outside the laboratory (50km from the field).

(vii) The statistical analysis of all measured data (soil properties, soil water content and crop development) were completed for each year in order to compare the effects of treatments on water use efficiency of each crop under each climatic condition. Micrometeorological data were used to test some available water balance models in order to interpret the effects of the agricultural practices on dryland crop production.

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CHAPTER 4

EFFECTS OF TILLAGE PRACTICES AND CROP ROTATION SYSTEMS ON SOIL PROPERTIES

4.1 Introduction

Dryland soil management practices such as the methods and frequency of tillage and use of crop rotation systems may influence the structure of both surface (0-75 mm) and a subsurface soil (75-150 mm) differently under different climatic conditions. Tillage is often used to disrupt soil physical barriers such as crusts, hardset layers and pans. Bulk density is reduced, porosity increased and the aggregate size distribution changed in ways which improve the soil physical quality of the seed bed. This usually promotes higher germination rates and better early seedling development. The literature supporting these assertions have been reviewed in Chapter 2.

Erickson (1985) and others confirm the benefits of tillage but point out that, for example, tillage only had a temporarily benefit on aeration problems associated with poor soil structure. These benefits were clear during a season of high rainfall by loosening the surface soil layer and improving drainage. Tillage during drier seasons may not benefit crop growth because the soil surface structure was not disrupted by rainfall. In any event, the work of Erickson and many others (see Chapter 2) has shown that for many poorly structured and structurally fragile soils, intensive tillage benefits are transient and chronically debilitative to long term structural stability.

This recognition of the limitations to traditional intensive tillage has led to the development of reduced tillage systems, so-called zero tillage or direct drilling of crops into undisturbed soil (see Chapter 2). For example, Dowdell et al. (1979) showed that direct drilling techniques develop better structural stability which is more durable to rainfall impact than conventional tillage techniques.

Crop rotation systems are also perceived to have beneficial effects on soil physical properties. The level of benefits probably depends on crop types, crop development and crop rotation systems which may interact with climate, particularly rainfall as well as tillage practices. For example, Packer et al. (1994) reported that canola improved the surface soil structure of a hardsetting sandy loam surface soil. After a crop of canola this soil had a higher infiltration rate, lower runoff rate, higher aggregate stability and higher organic carbon content compared with the soil on which wheat was cultivated. This area of work is contentious, for example, Cresswell and Kirkegaard (1995) asserted that canola did not create any measurable changes to soil structure at the upper layers of the subsoil of a red-brown earth. They claimed that the root system of canola was unable to create new pores due to the high strength of the soil matrix and showed that root development of canola was dependent only on the pre-existing pores (Section 2.2.4).

The accumulation of organic matter and total nitrogen from a previous crops may also induce improved soil structure by improving aggregate stability to rainfall impact and tillage-induced disruption. For example, Tisdall and Oades (1980) found that longterm crop rotations caused a decrease in stable macroaggregates (>1000 μm diameter) and an increase in stable microaggregates (< 250 μm diameter). They also found that zero tillage gave the greatest amount of aggregates larger than 250 μm diameter and had the highest amount of organic carbon compared with other tillage treatments. This is because zero-tillage caused larger amounts of plant materials to be added continually to the soil with less disruption and oxidation which led to a higher percentage of organic matter in the untilled soil compared with the tilled soil.

The aim of the work reported here is to show the effects of tillage practices and crop rotations systems on soil physical properties under different rainfall condition. The tillage practices studied were direct drilling (DD) and conventional cultivation (CC). Crop rotation systems were wheat (W), faba bean (B) and canola (C) grown in rotation every year. Direct drilling was done by direct sowing with a seeder with duck foot tynes attached to a gantry with 4 m wheel spacing. In conventional cultivation, the soil was scarified 2 to 3 times by a scarifier - cultivator followed by harrowing twice to give a uniform tilled surface. Sowing in conventional cultivation treatment was then done by the same procedure as direct drilling (Section 3.4)

4.2 Materials and methods.

The experiment was commenced in 1992 as a split plot design comprising of main plots of tillage practices (direct drilling, DD and conventional cultivation, CC) and subplots of crop rotation systems (wheat, W, faba bean, B and canola, C). The 1993, 1994 and 1995 experiments were conducted using the same main plots with different subplots of crop rotations as described in Section 3.3.

Soil properties such as bulk density, available water capacity, aeration porosity, aggregate stability, penetration resistance, soil infiltration rate, soil nitrogen and soil organic matter content were measured 1 month before harvesting every year. Soil water evaporation was measured several times during crop growth in 1993 in order to study the effects of direct drilling and conventional cultivation on soil water evaporation. The methods for soil properties and soil water evaporation measurements were described in

Section 3.5.1 and 3.6.1 respectively. Details of these materials and methods are described in Chapter 3.

4.3 Results and discussion

Monthly rainfall distribution during the growing season (April-October) and cumulative weekly rainfall (from January to October) during the four year experiment from 1992 to 1995 are presented in Figure 4.1. The F-values from statistical analysis of the effects of tillage practices (T) and crop rotation systems (S) on soil physical properties in 1992, 1993, 1994 and 1995 are presented in Table 4.1. The average values and the least significant differences (l.s.d.) of the means for soil physical properties are presented in Table 4.2 to 4.10. The main effect of tillage practice (T) and crop rotation system (S) on soil properties for each year from 1992 to 1995 are presented in Table 4.2, 4.4, 4.6 and 4.8 while the interaction effects of T and S (TxS) on the same soil properties are shown in Table 4.3, 4.5, 4.7 and 4.9 respectively. Results obtained for each year from 1992 to 1995 are plotted in Figures 4.2 to 4.8. The combined results for the whole experiment from 1992 to 1995 are presented in Figures 4.9 to 4.14 respectively.

4.3.1 Rainfall

The variation of rainfall from season to season had important effects on the results of the experiment. Rainfall differences were particularly marked in the grain filling period. Rainfall data are shown as the cumulative weekly rainfall and the monthly rainfall in Figure 4.1. Distributions of weekly rainfall data are also shown in Appendix 1.

(a)

(b)

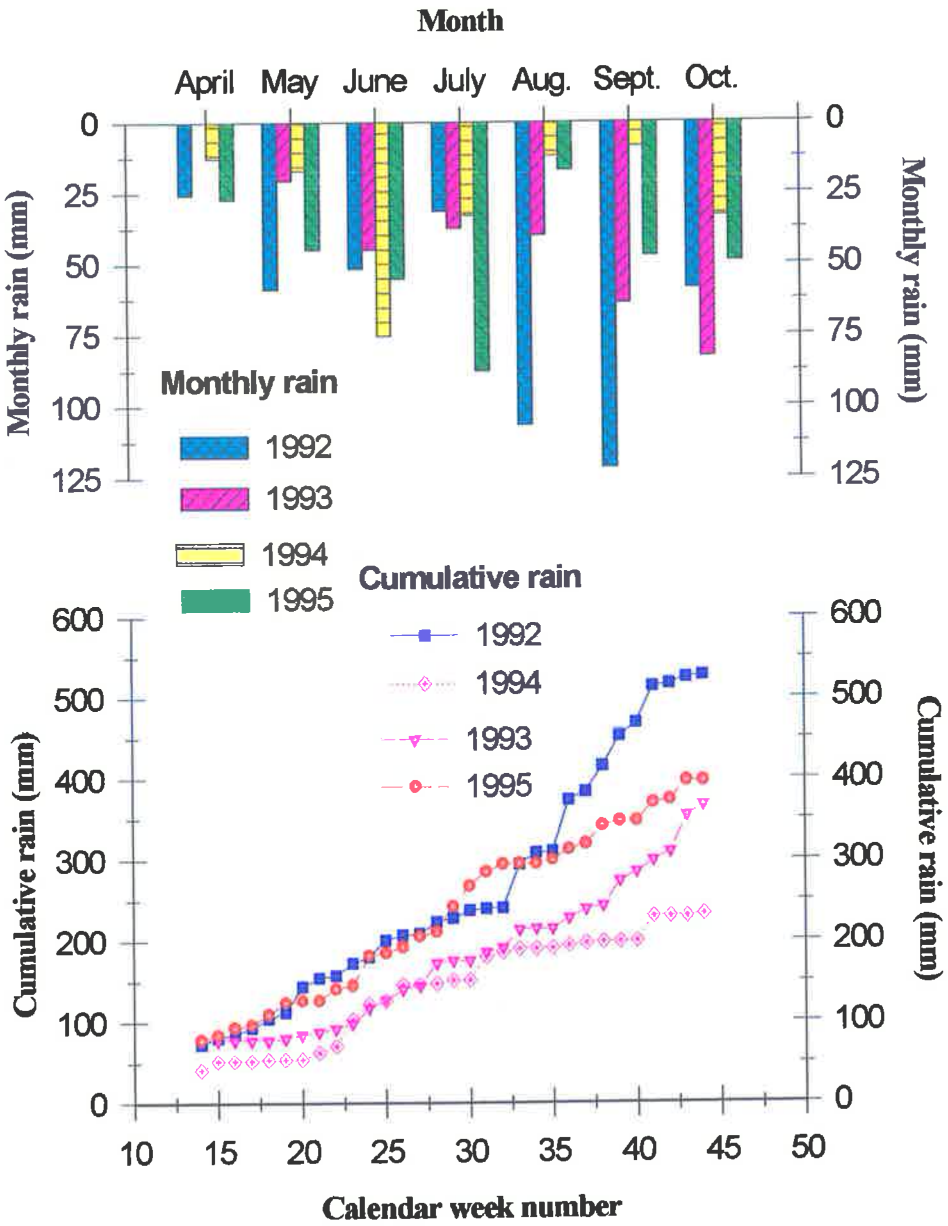


Figure 4.1 **(a)** Monthly distribution of rainfall during the growing season (April-October) and **(b)** cumulative rainfall (January - October) from 1992 to 1995 at Roseworthy Campus, The University of Adelaide.

4.3.2 Overall effects of tillage practices and crop rotation systems

The F-values in Table 4.1 (at a $p \leq 0.05$ significance level) show that interactive effects of tillage practices and crop rotations (TxS) on soil physical propert were not significant in 1992 and 1994. The total rainfall in these two exceptionally and dry years was 628 and 279 mm respectively. The growing seasonal rainfall (from to October) was 454 and 192 mm respectively (Figure 4.1).

In general, tillage practices (T) affected soil physical properties more significa than crop rotations during the four years of the experiment. Crop rotations (S) sho more significant effects on soil properties in 1993 and 1995 than in 1992 and 1993. variation in results from year to year (Table 4.1) may have been caused by variatio both amount and distribution of rainfall during 1992 to 1995 (Figure 4.1).

However, the interactive effects of tillage practices and crop rotations (significantly influenced some soil physical properties in 1993 and 1995. These years more normal climatic conditions with total rainfall of 401 and 410 mm and growing se rainfall of 290 and 329 mm respectively. Interactive effects from the treatments sh particularly significant effects on soil properties in 1993 but significance was more n in 1995. This difference might be due to the different distribution of rainfall during growth in 1993 compared to 1995.

4.3.3 1992 experiment

Table 4.2 shows that direct drilling (DD) resulted in significantly lower valu bulk density (BD = 1.377 Mg m^{-3}) of the subsurface soil layer (75-150 mm depth, higher values of stable aggregate (SAD = 50.40 %) and mean weight diameter (MW 1.39 mm) of surface soil layer (0-50 mm depth) than the conventionally cultiv treatment (CC) (BD = 1.446 Mg m^{-3}, SAD = 44.70 % and MWD = 1.17 mm) as presented in Figure 4.2a.

These results corresponded to the higher value of aeration porosity (AP) of both surface and subsurface soil layers in the direct drilled plots (AP = 0.266 and 0.141 m^3 m^{-3} respectively) which were higher than in the conventional cultivated plots (AP = 0.226 and 0.100 m^3 m^{-3} respectively) as shown in Figure 4.2 b.

The main effects of crop types in the first year are also presented in Table 4.2. Wheat (W) and faba bean (B) gave significantly larger values of available water capacity (AWC) in the subsurface soil layer (75-150 mm depth) than canola treatment (C) as shown in Figure 4.2 c.

The interactive effects of tillage practices and crop types (TxS) in Table 4.3 indicated that faba bean grown under conventional cultivation (CC-B) resulted in the lowest value of organic carbon and total nitrogen content (OC = 1.156 % and N = 0.917 %) in the surface soil layer (0-100 mm depth) and tended to cause the lowest aeration porosity (AP = 0.085 m^3m^{-3}) in the subsurface soil layer (75-150 mm) compared with the other interactive effects of tillage practices and crop types. This could have been caused by poor soil aeration during this season of high rainfall (Figure 4.1). In turn this could have caused the symbiotic nitrogen fixation process to become inactive. In general, nitrogen requirement of faba bean is higher than wheat or canola. Insufficient supply of nitrogen to faba bean might lead to decreasing soil nitrogen. Therefore, faba bean sown by CC caused the lowest value of soil nitrogen compared with either faba bean or canola.

Table 4.1 The statistical significance of F values obtained from analysis of variance of the effects of tillage practices (T) and crop rotation systems (S) on soil properties in 1992, 1993, 1994 and 1995

Soil properties	**Soil Depth**	**1992**			**1993**			**1994**			**1995**		
		T	**S**	**T x S**	**T**	**S**	**T x S**	**T**	**S**	**T x S**	**T**	**S**	**T x S**
Bulk density	**0-75**	0.14	0.08	2.86	2.48	**8.22****	**2.90***	**18.55***	**5.60***	1.80	1.73	2.24	0.01
(BD, Mg m^{-3})	**75-151**	**75.15****	2.83	1.60	**17.20****	0.47	2.08	**16.92***	0.83	0.48	**36.47****	0.74	1.89
Available water capacity	**0-75**	1.99	1.21	1.62	**109****	**53.82****	**15.81****	0.48	0.49	0.57	**8.73***	0.71	0.63
(AWC, m^3 m^{-3})	**75-151**	0.03	**9.17****	3.71	0.02	1.82	**5.60****	7.98	1.40	1.62	**6.82***	**3.84***	**2.85***
Aeration porosity	**0-75**	**3.19***	0.06	4.08	**15.50***	**5.70***	**3.61***	**13.51***	2.64	0.95	3.15	**2.75***	0.12
(AP, m^3 m^{-3})	**75-151**	**12.61***	2.39	2.00	**21.01***	**4.80****	**5.44****	**37.76****	1.63	0.52	**109.96****	2.03	1.07
Stable aggregate (a) (SAT, % of total dry soil)	**0-50**				**44.9****	**8.6****	1.71	0.24	0.87	1.18	0.06	**4.28****	**4.86***
Stable aggregate (b) (SAD, % of dry aggrgate)	**0-50**	**84.26****	1.26	0.94	**3.4***	**3.88***	1.42	0.11	0.63	1.01	0.54	**4.00***	2.31
Mean weight diameter (MWD, mm)	**0-50**	**22.01***	2.31	0.72	**5.2***	**8.30****	1.91	0.01	1.05	0.662	0.05	**3.70***	3.29
Penetration resistance	**0-75**	-	-	-	-	-	-	**1204****	1.82	0.51	-	-	-
(PR, MPa)	**75-150**	-	-	-	-	-	-	**86.84****	2.28	3.36	-	-	-
Infiltration rate (IR, mm min^{-1})	**0**	-	-	-	-	-	-	**11.08***	**20.32****	2.57	0.49	**2.92***	1.57
Organic carbon	**0-100**	1.81	**11.43****	**6.03***	0.06	2.04	**3.25***	0.5	0.99	1.09	x	x	x
(OC, %)	**100-200**	0.15	3.05	0.02	1.71	**3.69***	2.60	**17.95***	0.51	0.64	x	x	x
Total nitrogen (N, %)	**0-100**	4.63	**8.91****	**11.78****	2.52	1.77	0.68	1.56	**2.59***	1.1	x	x	x

(a) and (b) are the percentage of stable aggregates in total dry soil (SAT) and in total dry aggregates (SAD) of the soil respectively.

* represent the significant F- values at probability (P) of 0.05 :

** represent the significant F- values at probability (P) of 0.01 :

-, Soil properties were not measured, x : no analysis of varience

Table 4.2 The 1992 main effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop types were wheat (W), faba bean (B) and canola (C)

Soil properties	**Depth (mm)**	**Tillage practices**		**l.s.d***	**Crop rotation systems**			**l.s.d***
		DD	**CC**	**T**	**W**	**B**	**C**	**S**
Bulk density	**0-75**	1.221	1.240	ns	1.251	1.230	1.232	ns
(BD, Mg m^{-3})	**75-150**	**1.377b**	**1.446a**	0.026	1.369	1.415	1.450	ns
Available water capacity	**0-75**	0.118	0.141	ns	0.138	0.130	0.120	ns
(AWC, $m^3 m^{-3}$)	**75-150**	0.151	0.148	ns	**0.151a**	**0.178a**	**0.119b**	0.031
Aeration porosity	**0-75**	**0.266a**	**0.226b**	0.040	0.240	0.248	0.248	ns
(AP, $m^3 m^{-3}$)	**75-150**	**0.141a**	**0.100b**	0.038	0.120	0.108	0.134	ns
Stable aggregate (b)	**0-50**	**50.40a**	**44.70b**	1.91	44.00	49.30	49.40	ns
(SAD, % of dry aggregate)								
Mean weight diameter	**0-50**	**1.39a**	**1.17b**	0.15	1.11	1.24	1.47	ns
(MWD, mm)								
Organic carbon	**0-100**	1.473	1.384	si	1.439	1.297	1.55	si
(OC, %)	**100-200**	0.773	0.737	ns	0.794	0.672	0.801	ns
Total nitrogen (N, %)	**0-100**	1.032	1.194	si	1.238	0.979	1.122	si

(b) is the percentage of stable aggregates in total dry aggregates (SAD) of the soil.

l.s.d* T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)

a , b represent differences between the means, values followed by different letters, within any row are significantly

ns is non-significant differences between different tillage practices, and among different cropping systems

si: is significant as interaction effect

Table 4.3 The 1992 interactive effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop types were wheat (W), faba bean (B) and canola (C)

Soil properties	Depth (mm)	Interaction of tillage practices and crop rotation systems						l.s.d* (1) TxS	l.s.d* (2) TxS
		DD			CC				
		W	B	C	W	B	C		
Bulk density	0-75	1.201	1.191	1.290	1.300	1.271	1.172	ns	ns
(BD, Mg m^{-3})	75-150	1.365	1.350	1.415	1.372	1.482	1.485	ns	ns
Available water capacity	0-75	0.120	0.113	0.120	0.155	0.148	0.120	ns	ns
(AWC, $m^3 m^{-3}$)	75-150	0.138	0.200	0.115	0.165	0.155	0.123	ns	ns
Aeration porosity	0-75	0.288	0.280	0.225	0.193	0.215	0.270	ns	ns
(AP, $m^3 m^{-3}$)	75-150	0.128	0.130	0.165	0.113	0.085	0.103	ns	ns
Stable aggregate (b)	0-50	46.50	55.01	49.81	41.50	43.60	49.00	ns	ns
(SAD, % of dry aggregate)									
Mean weight diameter	0-50	1.17	1.47	1.52	1.06	1.43	1.06	ns	ns
(MWD, mm)									
Organic carbon	0-100	**1.397a**	**1.438a**	**1.584a**	**1.481a**	**1.156b**	**1.516a**	0.244	0.204
(OC, %)	100-200	0.808	0.696	0.815	0.779	0.648	0.786	ns	ns
Total nitrogen (N, %)	0-100	**1.001b**	**1.039bc**	**1.054b**	**1.473a**	**0.917c**	**1.19b**	0.281	0.236

(b) is the percentage of stable aggregates in total dry aggregates (SAD) of the soil.

l.s.d* T and S are the least significant differences of the means caused by interaction effects of tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)

(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practices respectively

a, b and c represent differences between the means, values followed by different letters, within any row are significantly different.

ns : interaction effects were not significant

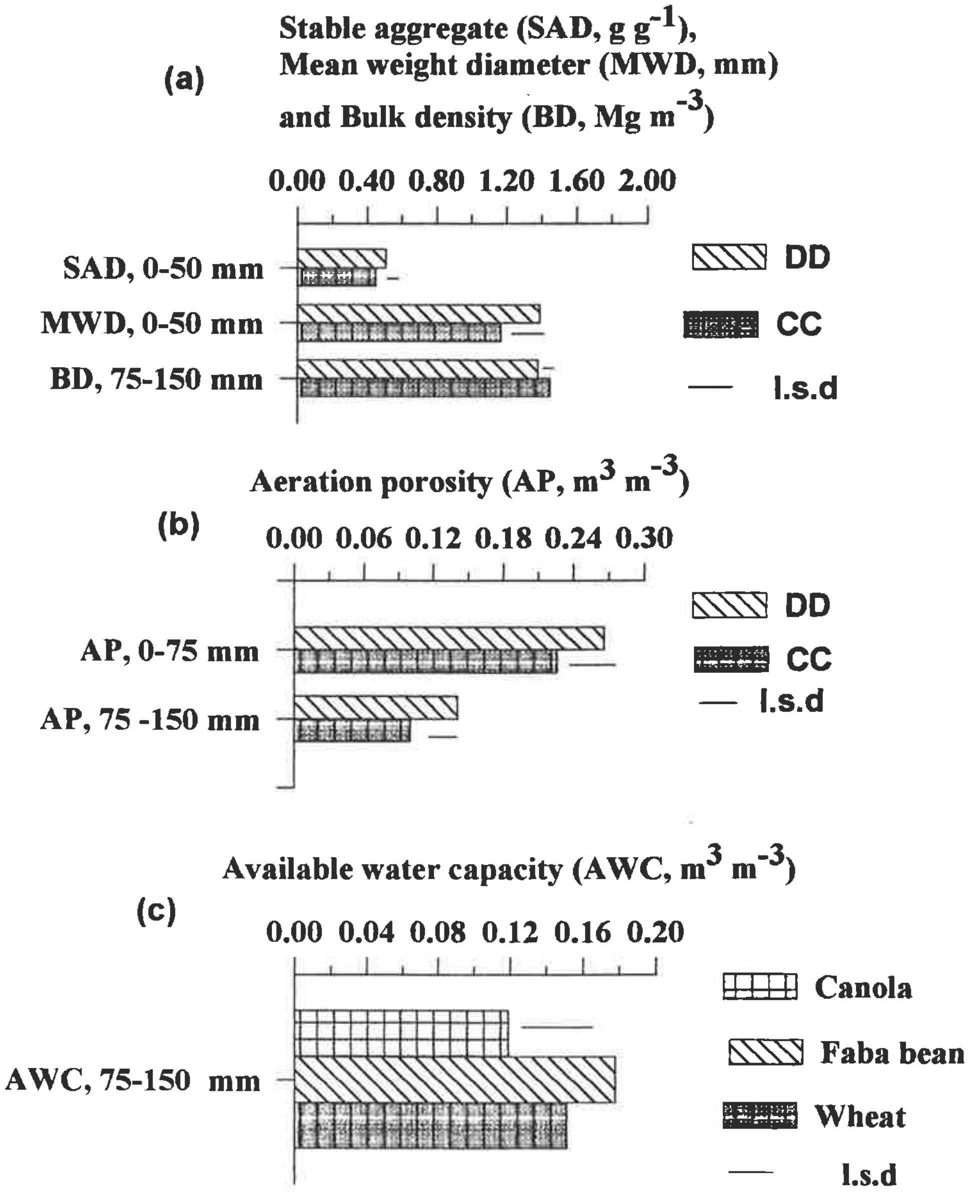


Figure 4.2 The effects of direct drilling (DD) and conventional cultivation (CC) on surface soil (0-75 mm) and subsurface soil (75-150 mm) properties **(a)** stable aggregate (SAD), mean weight diameter (MWD) and bulk density (BD), **(b)** aeration porosity (AP), and **(c)** the effects of wheat, faba bean and canola on available water capacity (AWC) of subsurface soil layer (75-150 mm) in 1992.

4.3.4 1993 experiment

4.3.4.1 Soil properties

Table 4.4 shows that direct drilling resulted in larger values of stable aggregates (SAT = 14.42 %, SAD = 40.82 %) and mean weight diameter (MWD = 1.30 mm) of the surface soil and a smaller value of bulk density (BD = 1.312 Mg m^{-3}) in subsurface soil layers compared to the conventional cultivation treatment (SAT = 11.51%, SAD = 36.00 %, MWD = 1.04 mm, and BD = 1.452 Mg m^{-3}) as presented in Figure 4.3 a.

Table 4.4 also showed that crop rotations of canola grown after wheat (WC) caused the lowest values of stable aggregates as a percentage of total dry soil (SAT) and as a percentage of dry aggregates (SAD) and the mean weight diameter (MWD) of the surface soil layer (0-50 mm depth), but CW gave the highest organic carbon content in the sub-soil layer (100-200 mm depth) compared with the other crop rotations as presented in Figure 4.3 b. These results might be explained by poor growth of canola during the drought period two months after sowing in 1993. The lower surface cover resulted in more destruction of soil aggregates by raindrop impact compared with the other crops which had denser canopies at that time.

The interactive effects of tillage practices and crop rotation systems (TxS) shown in Table 4.5 indicated that every crop rotation (WW, BW, CW, WB and WC) sown by direct drilling (DD) tended to have lower values of bulk density (BD) and available water capacity (AWC) in the surface layer (0-75 mm depth) than those sown by conventional cultivation (CC). These results are presented in Figure 4.4a and b respectively.

Table 4.4 The 1993 main effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop rotations were wheat after wheat (WW), canola after wheat (WC), faba bean after wheat (WB), wheat after canola (CW) and wheat after faba bean (BW).

		Tillage practices		**l.s.d***	**Crop rotation systems**					**l.s.d***
Soil properties	**Depth**	**DD**	**CC**	**T**	**WW**	**BW**	**CW**	**WB**	**WC**	**S**
Bulk density	**0-75**	1.141	1.198	si	1.166	1.209	1.086	1.180	1.204	si
(BD, Mg m^{-3})	**75-150**	**1.312b**	**1.452a**	0.108	1.365	1.380	1.375	1.386	1.403	ns
Available water capacity	**0-75**	0.111	0.146	si	0.154	0.108	0.145	0.101	0.134	si
(AWC, $m^3 m^{-3}$)	**75-150**	0.145	0.143	si	0.135	0.143	0.131	0.151	0.161	si
Aeration porosity	**0-75**	0.31a	0.248b	si	0.255	0.280	0.304	0.299	0.258	si
(AP, $m^3 m^{-3}$)	**75-150**	0.192a	0.119b	si	0.178	0.158	0.173	0.138	0.13	si
Stable aggregate (a)	**0-50**	**14.42a**	**11.51b**	2.851	**13.79a**	**14.11a**	**13.83a**	**12.35a**	**10.76b**	2.22
(SAT, % of total dry soil)										
Stable aggregate (b)	**0-50**	**40.82a**	**36.00b**	3.208	**38.74ab**	**36.90bc**	**41.04a**	**41.42a**	**33.86c**	3.52
(SAD, % of dry aggregate)										
Mean weight diameter	**0-50**	**1.30a**	**1.04b**	0.204	**1.19bc**	**1.02bc**	**1.27ab**	**1.46a**	**0.90c**	0.30
(MWD, mm)										
Organic carbon	**0-100**	1.548	1.528	si	1.552	1.607	1.473	1.452	1.609	si
(OC, %)	**100-200**	0.855	0.908	ns	**0.898b**	**0.889b**	**0.986a**	**0.835c**	**0.800d**	0.034
Total nitrogen (N, %)	**0-100**	1.064	1.107	ns	1.081	1.143	1.131	1.049	1.025	ns

(a) and (b) are the percentage of stable aggregates in total dry soil (SAT) and in total dry aggregates (SAD) of the soil respectively.
l.s.d* T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)
a, b and c represent differences between the means, values followed by different letters, within any row are significantly different.
ns : is non-significant differences between different tillage practices, and among different cropping systems
si: is significant as interaction effect

Table 4.5 The 1993 interactive effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S).
The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop rotations were wheat after wheat (WW), canola after wheat (WC), faba bean after wheat (WB), wheat after canola (CW) and wheat after faba bean (BW).

Soil properties	**Depth**	**Interaction of Tillage practices and Crop rotation systems**										**l.s.d***	**l.s.d***		
		DD					**CC**					**(1)**	**(2)**		
		WW	**BW**	**CW**	**WB**	**WC**	**WW**	**BW**	**CW**	**WB**	**WC**	**TxS**	**TxS**		
Bulk density	0-75	1.158bc	1.138bc	1.093bc	1.148ab	1.170ab	1.175a	1.280a	1.080c	1.213a	1.24a	0.127	0.093		
(BD, Mg m^{-3})	75-150	1.265	1.303	1.333	1.350	1.308	1.465	1.458	1.418	1.423	1.498	ns	ns		
Available water capacity	0-75	0.115c	0.093d	0.133c	0.095d	0.12c	0.193a	0.123c	0.158b	0.118c	0.148b	0.016	0.014	0.025**	0.021**
(AWC, $m^3 m^{-3}$)	75-150	0.115b	0.130b	0.130b	0.158ab	0.193a	0.155ab	0.155ab	0.133b	0.145b	0.128b	0.051	0.043	0.082**	0.070**
Aeration porosity	0-75	0.298a	0.333a	0.310a	0.320a	0.288a	0.213b	0.228b	0.298a	0.278ab	0.228b	0.059	0.048		
(AP, $m^3 m^{-3}$)	75-150	0.248a	0.203ab	0.205ab	0.150b	0.153b	0.108c	0.113bc	0.140bc	0.125bc	0.108c	0.059	0.044	0.096**	0.072**
Stable aggregate (a) (SAT, % of total dry soil)	0-50	15.88	14.72	14.28	15.92	11.31	11.70	13.50	13.37	8.77	10.20	ns	ns		
Stable aggregate (b) (SAD, % of dry aggregate)	0-50	41.02	40.49	38.07	50.25	34.29	36.46	33.30	44.01	32.60	33.42	ns	ns		
Mean weight diameter (MWD, mm)	0-50	1.31	1.16	1.16	1.87	0.90	1.06	0.87	1.38	1.04	0.89	ns	ns		
Organic carbon	0-100	1.494ab	1.758a	1.428b	1.395b	1.667ab	1.609ab	1.455b	1.518ab	1.509ab	1.551ab	0.319	0.262		
(OC, %)	100-200	0.904	0.917	0.860	0.804	0.790	0.893	0.860	1.111	0.866	0.809	ns	ns		
Total nitrogen (N, %)	0-100	1.013	1.092	1.151	1.038	1.027	1.148	1.169	1.134	1.061	1.022	ns	ns		

(a) and (b) are the percentage of stable aggregates in total dry soil (SAT) and in total dry aggregates (SAD) of the soil respectively.
l.s.d* T and S are the least significant differences of the means caused by interaction effects of tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)
(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practices respectively
a and b represent differences between the means, values followed by different letters, within any row are significantly different.
ns : interaction effects are not significant

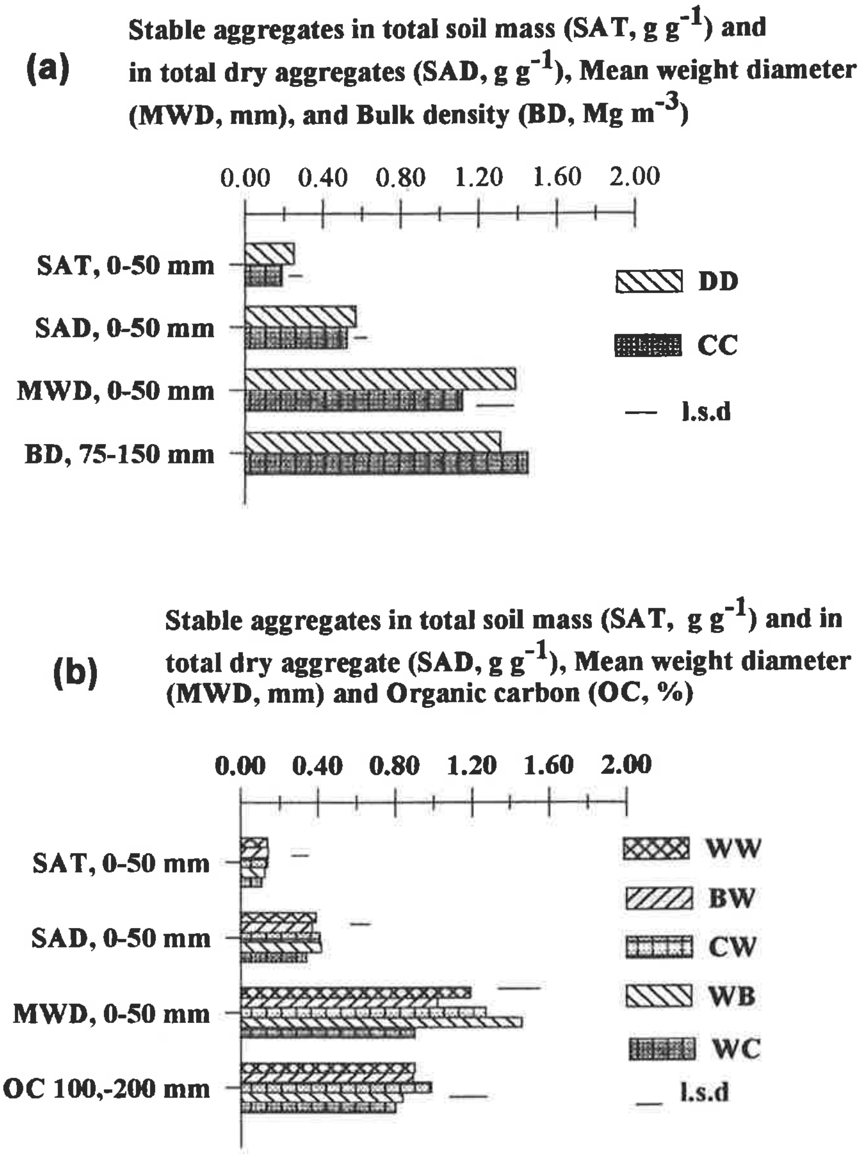


Figure 4.3 The effects of direct drilling (DD) and conventional cultivation (CC) on surface soil (0-75 mm) and subsurface soil (75-150 mm) properties **(a)** stable aggregate as fractions of total soil mass (SAT) and dry aggregate(SAD), mean weight diameter (MWD) and bulk density (BD), and **(b)** the effects of crop rotations as wheat after wheat (WW), wheat after faba bean (BW), wheat after canola (CW), faba bean after wheat (WB) and canola after wheat (WC) on SAT, SAD, MWD and organic carbon (OC) in 1993.

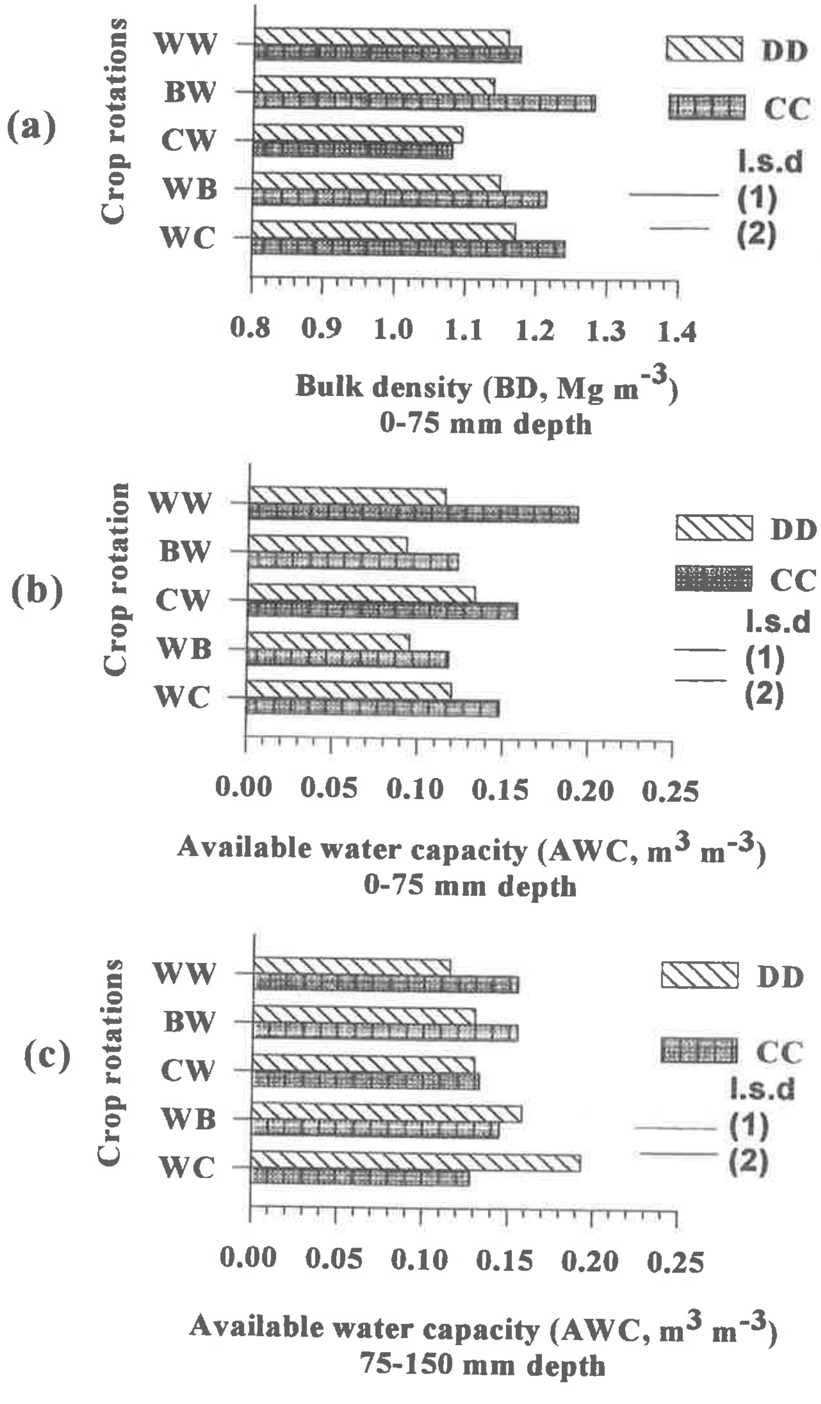


Figure 4.4 The interactive effects of tillage practices (DD and CC) and crop rotation systems (WW, BW, CW, WB and WC) on **(a)** bulk density of the surface soil (0-75 mm), **(b)** available water capacity (AWC) of the surface soil (0-75 mm) and **(c)** AWC of subsurface soil (75-150 mm) respectively, at grain filling in 1993.

Figure 4.4 a shows that wheat after faba bean (BW) in conventional cultivated plots (CC-BW) resulted in the highest BD value while wheat after canola caused the lowest value of BD in both tillage practices (DD-CW and CC-CW). On the other hand, wheat following wheat (WW) with CC resulted in the highest value of available water capacity (AWC). Wheat after faba bean (BW) and faba bean after wheat (WB) caused the lowest values of AWC in both DD plots compared with the other treatments as shown in Figure 4.4 b. Canola following wheat (WC) tended to have the highest AWC value of the subsurface soil layer (75-150 mm depth) compared with the other treatments as presented in Figure 4.4 c.

The inconsistency of the interactive effects were not only caused by the interaction of tillage practices and crop rotations but also influenced by the effects of rainfall and crop growth. The nonuniform distribution and the low amount of rain during early crop growth (Figure 4.1) might have caused different root development (root densities and root distributions) in the surface and subsurface soil (Chapter 5). This effect consequently may have caused the differences in BD and AWC values.

4.3.4.2 Soil water evaporation between the crop rows (Esa)

The average values and standard error of the actual soil water evaporation (Esa) during the seedling stage to yield formation (20 to 120 days after sowing respectively) as affected by direct drilling (DD) and conventional cultivation (CC) are presented in Figure 4.5 a. The mean values of the water content of the top soil (0-75 mm) and subsurface soil layer (75-150 mm) corresponding to the soil water evaporation are presented in Figures 4.5 b and c. The data set of soil water evaporation and soil water content in the surface and subsurface soil layers are also presented in Appendices 2 and 3 respectively.

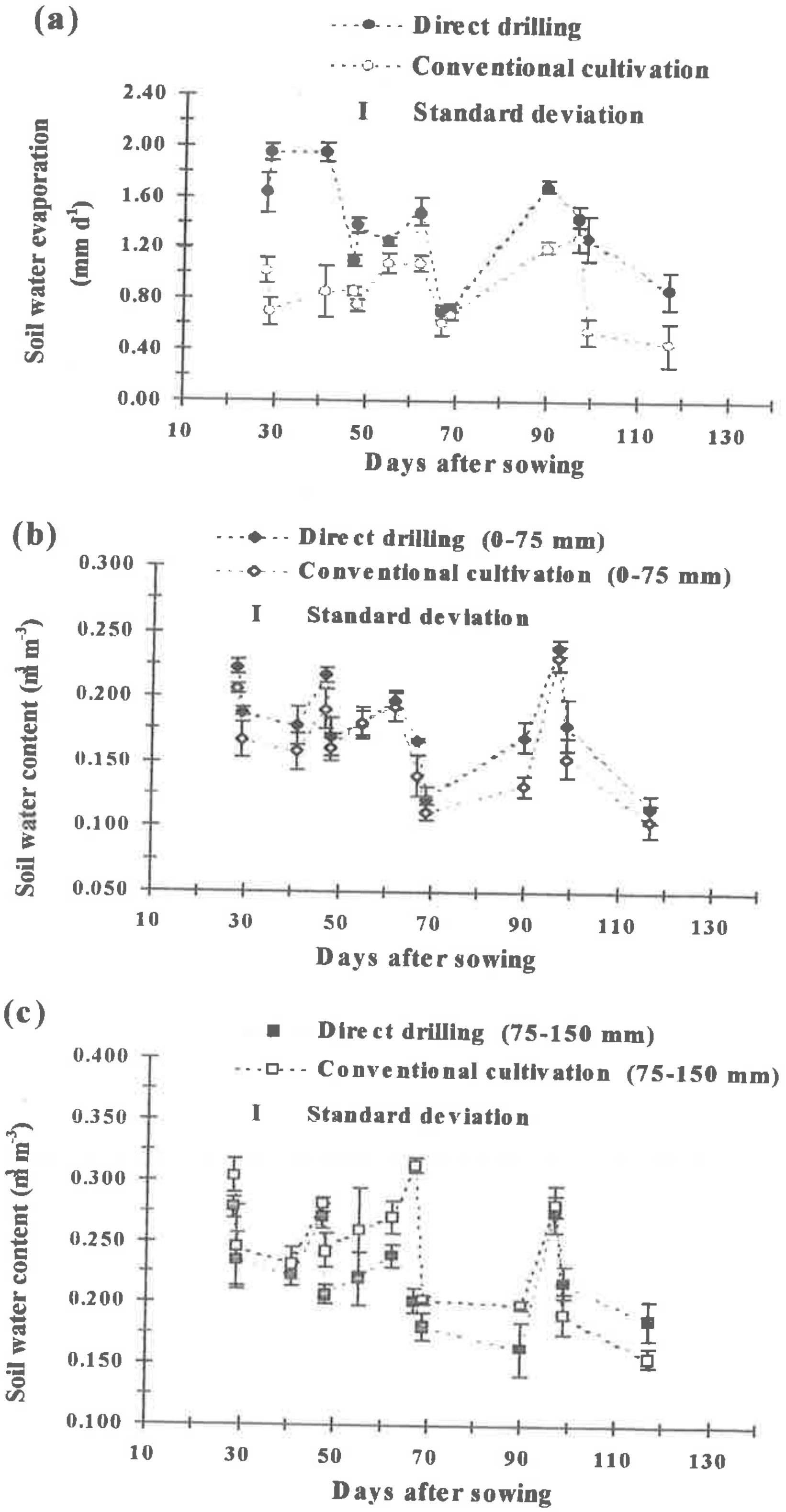


Figure 4.5 The effect of direct drilling and conventional cultivation treatments on **(a)** actual soil water evaporation rate, **(b)** surface soil (0-75 mm) water content and **(c)** subsurface soil (75-150 mm) water content on specific days of measurement during crop growth in 1993.

Figure 4.5a showed that direct drilling resulted in higher actual soil water evaporation rate (Esa) than conventional cultivation. The result varied with the soil water content at the 0-75 mm depth (Figure 4.5 b) during early crop growth (20 to 60 days after sowing). However, the soil water evaporation rate during tillering to yield formation was not governed only by the topsoil water content (θ, 0-75 mm), but also by the evaporative demand (Em) at the soil surface. This assertion is supported by Ritchie (1974) and Jalota and Prihar (1986). On the other hand, soil water suction, which varied as the surface soil structure and texture varied, should be a dominant factor governing the evaporation from the soil surface. Therefore the fluctuations of soil water evaporation and soil water content relationships were obtained during the active growing stage of the crop.

Figure 4.5 b and c showed that conventional cultivation had a drier surface soil layer and a wetter subsurface soil layer compared to direct drilling. This result suggested that conventional cultivation may have reduced the continuity of capillary pores between the surface and the subsurface soil layer. This would reduce capillary rise of soil water to the surface soil layer in CC.

Figure 4.5 c shows that the subsurface soil (75-150 mm) water content in conventional cultivated plots was always higher than in direct drilled plots. This result indicated that the subsurface soil water did not transmit to the surface soil (0-75 mm) in conventional cultivation treatment due to discontinuity of pores between the tilled layer and the tillage pan (plough sole) layer. This assertion is supported by a significant difference in bulk density and different aeration porosity between the two layers in CC (Table 4.4). On the other hand, upward flow of soil water from the sub-soil layer (75-150 mm) occurred in the direct drilled treatment more than in the conventionally cultivated plots due to more continuity of capillary pores. However, the upward flow from a deeper soil layer (>150 mm depth) during active crop growth should be negligible because soil water within a deeper soil layer would be used by the active root growth during active crop development. Therefore, soil water evaporation determination should account for only the top-soil layer in both tilled and untilled soil.

It was not possible to compare the effects of crop rotation systems on Esa because only one plot for each crop rotation treatment was measured.

4.3.5 1994 experiment

4.3.5.1 Soil properties

Table 4.6 shows that conventional cultivation caused lower values of bulk density, BD (1.05 Mg m^{-3}), penetration resistance, PR (0.70 MPa) and infiltration rate, IR (1.20 mm min^{-1}) and greater values of aeration porosity AP (0.32 m^3 m^{-3}) of the surface soil layer (0-75 mm) than direct drilling. On the other hand, conventional cultivation resulted in higher values of bulk density, BD (1.43 Mg m^{-3}) and penetration resistance (2.68 MPa) of subsurface soil layer (75-150 mm) compared with direct drilled treatments (which gave the values of BD, PR, AP and IR of surface soil equal to 1.16 Mg-m^{-3}, 1.07 MPa and 0.27 m^3-m^{-3} and 1.63 mm min^{-1} respectively and gave BD, AP, and PR of subsurface layer equal to 1.26 Mg m^{-3}, 0.24 m^3 m^{-3} and 1.46 MPa respectively (Figure 4.6a and b).

Crop rotations wheat-wheat-wheat (WWW), wheat-faba bean-wheat (WBW) and wheat-canola-wheat (WCW) did not affect any soil physical property significantly. However, wheat-canola-wheat (WCW) and faba bean-wheat-canola (BWC) gave lower IR (1.13 mm min^{-1}) than either WWW (1.63 mm min^{-1}) or WBW (1.55 mm min^{-1}) (Table 4.6 and Figure 4.6c).

Table 4.6 The 1994 main effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop rotations were (wheat-wheat-wheat (WWW), wheat-faba bean-wheat (WBW), wheat-canola-wheat (WCW), canola-wheat-faba bean (CWB) and faba bean-wheat-canola (BWC).

Soil properties	**Depth**	**Tillage practices**		**l.s.d ***	**Crop rotation systems**					**l.s.d ***
		DD	**CC**	**T**	**WWW**	**WBW**	**WCW**	**CWB**	**BWC**	**S**
Bulk density	**0-75**	**1.163a**	**1.050b**	0.083	**1.109a**	**1.151a**	**1.135a**	**1.012b**	**1.127a**	0.068
(BD, Mg m^{-3})	**75-150**	**1.258b**	**1.427a**	0.131	1.344	1.373	1.352	1.331	1.313	ns
Available water capacity	**0-75**	0.132	0.137	ns	0.140	0.127	0.130	0.142	0.133	ns
(AWC, $m^3 m^{-3}$)	**75-150**	0.128	0.149	ns	0.140	0.130	0.138	0.147	0.138	ns
Aeration porosity	**0-75**	**0.268b**	**0.319a**	0.051	0.289	0.276	0.288	0.325	0.292	ns
(AP, $m^3 m^{-3}$)	**75-150**	**0.242a**	**0.146b**	0.048	0.184	0.183	0.191	0.194	0.220	ns
Stable aggregate (a) (SAT, % of total dry soil)	**0-50**	13.29	14.54	ns	13.87	13.72	16.64	13.51	11.86	ns
Stable aggregate (b) (SAD, % of dry aggregate)	**0-50**	29.90	31.60	ns	31.30	27.20	35.30	31.30	28.60	ns
Mean weight diameter (MWD, mm)	**0-50**	1.009c	1.03	ns	1.04	0.76	1.35	1.01	0.95	ns
Penetration resistance	**0-75**	**1.065a**	**0.704b**	0.178	1.440	1.827	1.880	1.592	1.613	ns
(PR, MPa)	**75-150**	**1.455b**	**2.682a**	0.42	2.035	2.265	2.228	1.985	1.828	ns
Infiltration rate (IR, mm min^{-1})	**0**	**1.63a**	**1.20b**	0.41	**1.55b**	**1.55b**	**1.13c**	**1.94a**	**0.92c**	0.260
Organic carbon	**0-100**	1.428	1.393	ns	1.366	1.38	1.402	1.455	1.449	ns
(OC, %)	**100-200**	**0.790a**	**0.724b**	0.051	0.725	0.749	0.757	0.773	0.78	ns
Total nitrogen (N, %)	**0-100**	1.141	1.236	ns	1.178	1.067	1.178	1.221	1.298	ns

(a) and (b) are the percentage of stable aggregates in total dry soil (SAT) and in total dry aggregates (SAD) of the soil respectively.
l.s.d* T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)
a b and c represent differences between the means, values followed by different letters, within any row are significantly different.
ns : is non-significant differences between different tillage practices, and among different cropping systems

Table 4.7 The 1994 interactive effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop rotations were (wheat-wheat-wheat (WWW), wheat-faba bean-wheat (WBW), wheat-canola-wheat (WCW), canola-wheat-faba bean (CWB) and faba bean-wheat-canola (BWC).

		Interaction of Tillage practices and Crop rotation systems										
		DD					**CC**					
Soil properties	**Depth**	**WWW**	**WBW**	**WCW**	**CWB**	**BWC**	**WWW**	**WBW**	**WCW**	**CWB**	**BWC**	**(TxS)** ^{ns}
Bulk density	**0-75**	1.153	1.234	1.217	1.020	1.189	1.064	1.067	1.052	1.003	1.064	-
(BD, Mg m^{-3})	**75-150**	1.263	1.308	1.253	1.259	1.212	1.426	1.437	1.455	1.403	1.414	-
Available water capacity	**0-75**	0.141	0.116	0.130	0.148	0.127	0.140	0.138	0.131	0.135	0.140	-
(AWC, m^3 m^{-3})	**75-150**	0.119	0.121	0.133	0.141	0.128	0.162	0.140	0.143	0.154	0.148	-
Aeration porosity	**0-75**	0.276	0.244	0.252	0.310	0.258	0.301	0.307	0.323	0.340	0.326	-
(AP, m^3 m^{-3})	**75-150**	0.235	0.217	0.240	0.244	0.277	0.133	0.149	0.142	0.145	0.163	-
Stable aggregate (a) (SAT, % of total dry soil)	**0-50**	11.31	11.95	16.26	16.06	11.09	16.63	15.49	17.63	10.95	12.63	-
Stable aggregate (b) (SAD, % of dry aggregate)	**0-50**	25.7	25.44	35.44	36.12	27.1	37.44	28.93	36.44	26.42	30.04	-
Mean weight diameter (MWD, mm)	**0-50**	0.83	0.72	1.32	1.25	0.93	1.26	0.79	1.41	0.77	0.97	- -
Penetration resistance	**0-75**	1.108	1.237	1.025	0.684	1.273	0.546	0.966	0.825	0.515	0.666	-
(PR, MPa)	**75-150**	1.737	1.842	1.52	1.125	1.096	2.38	2.688	2.936	2.844	2.559	-
Infiltration rate (IR, mm min^{-1})		1.61	1.95	1.41	2.18	1.00	1.48	1.14	0.85	1.70	0.84	-
Organic carbon	**0-100**	1.382	1.367	1.393	1.46	1.539	1.350	1.394	1.411	1.449	1.359	-
(OC, %)	**100-200**	0.730	0.788	0.765	0.829	0.836	0.719	0.710	0.718	0.724	0.725	-
Total nitrogen (N, %)	**0-100**	1.082	0.968	1.124	1.201	1.330	1.274	1.166	1.232	1.243	1.267	-

(a) and (b) are the percentages of stable aggregates in total dry soil (SAT) and in total dry aggregate (SAD) of the soil respectively.

(T x S)^{ns} : all interaction effects of tillage practices and crop rotation systems are not significant at $P < 0.05$

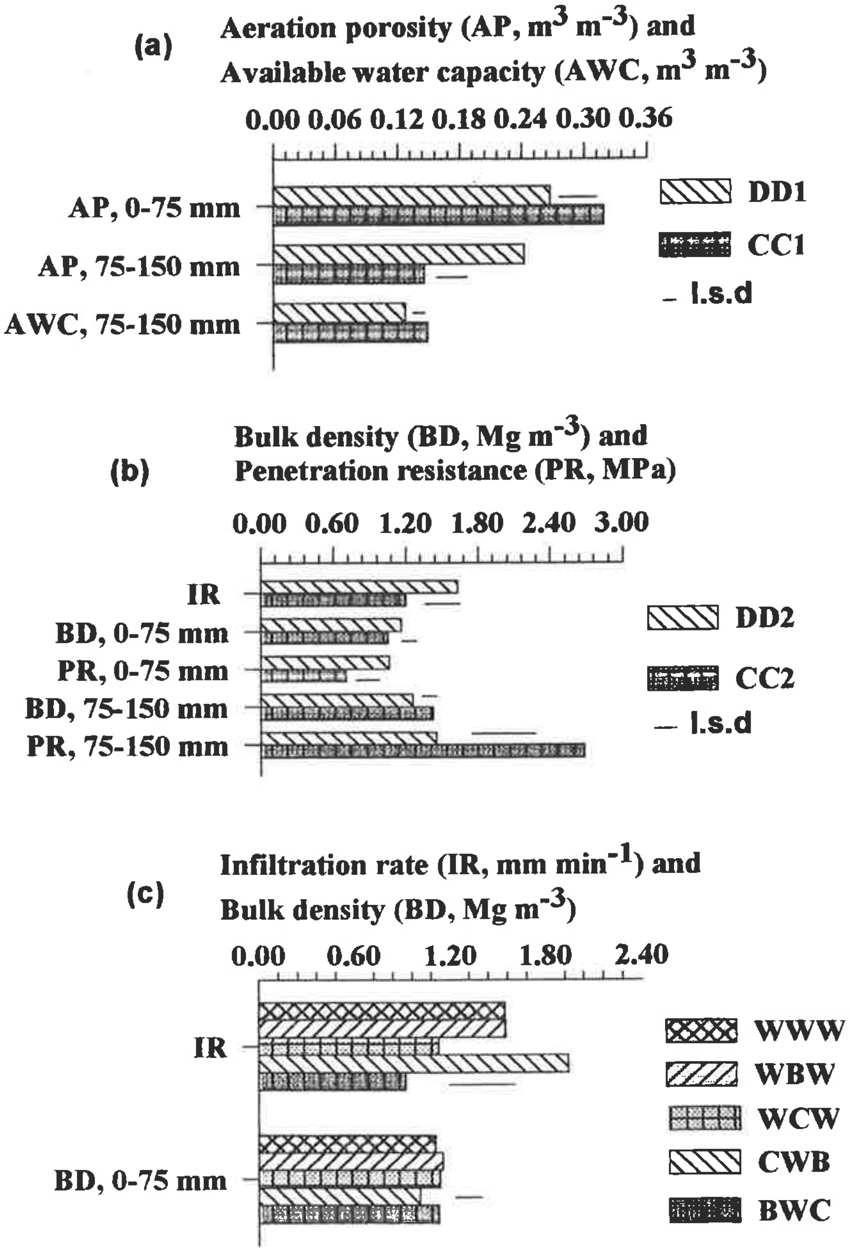


Figure 4.6 The effects of direct drilling (DD) and conventional cultivation (CC) on surface soil (0-75 mm) and subsurface soil (75-150 mm) properties, **(a)** aeration porosity (AP) and available water capacity (AWC), **(b)** bulk density (BD) and penetration resistance (PR), and **(c)** the effects of crop rotations of wheat (W), faba bean (B) and canola (C) as WWW, WBW, WCW, CWB and BWC, on infiltration rate (IR) and bulk density (BD) of the surface soil layer in 1994.

The crop rotation canola-wheat-faba bean (CWB) gave the lowest BD value (1.01 m^3/m^3) and highest values of IR (1.94 mm min^{-1}) of the surface soil compared with the other crop rotation treatments, WWW, WBW, WCW and BWC which gave BD equal to 1.11, 1.15, 1.14 and 1.13 Mg/m^3 and had IR values of 1.55, 1.55, 1.13, 1.94, and 0.92 mm min^{-1} respectively (Figures 4.6c).

The interactive effects did not show any significant levels among the treatments as shown in Table 4.7. The lack of significant interaction of tillage practices and crop rotation systems might be due to low rainfall and limited crop growth through the growing season.

4.3.5.2 Soil water characteristic

Results of the statistical analysis of soil water retention as a function of soil water content affected by tillage practices and crop rotation systems in 1994 are shown in Figure 4.7a and b for the surface (0-75 mm) and subsurface soil layers (75-150 mm) respectively. Figure 4.7a shows that tillage practices and crop rotation systems significantly affected soil water characteristics at suction of 0.0, 0.1 and 1 kPa of the surface soil layer and at every measured suction that was higher than 1 kPa (from 2 to 1500 kPa) for subsurface soil layer (Figure 4.7b). The data set of these soil water characteristics and the least significant of the mean values are presented in Appendix 4.

This suggested that conventional cultivation created a larger volume of macro porosity at soil water suctions of less than 2 kPa in the surface soil (Figure 4.7a)) but caused higher amount of capillary pores which have the air entry values at 2 kPa. in the subsoil layer compared with direct drilled treatments (Figures 4.7b).

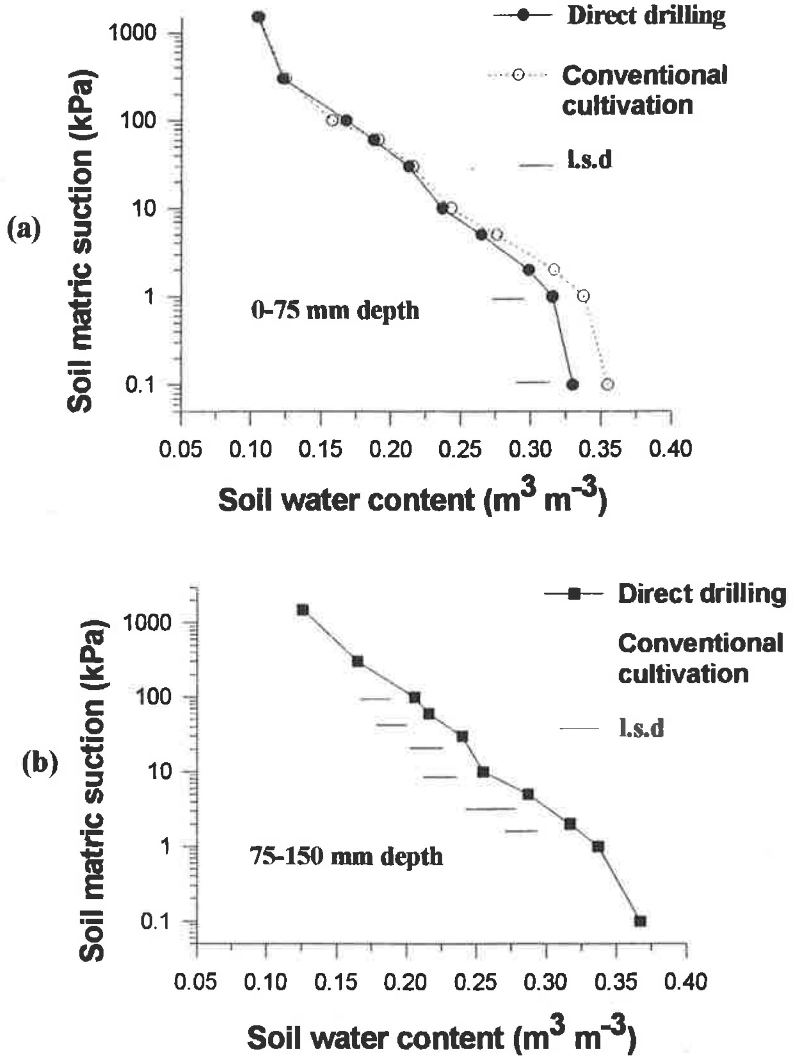


Figure 4.7 Soil water characteristic of the **(a)** surface soil layer (0-75 mm depth) and **(b)** subsurface soil layer (75-150 mm depth) as affected by direct drilling (DD) and conventional cultivation (CC) in 1994.

Most crop rotation systems did not influence pore size distribution within either surface or subsurface soil. Only CWB caused a larger volume of drainage porosity at soil water suction less than 1 kPa in the surface soil compared with the other crop rotations.

4.3.6 1995 experiment

Conventional cultivation (CC) caused higher values of bulk density (BD = 1.44 Mg m^{-3}), penetration resistance at the soil matric suction of 60 kPa. (PR = 2.30 MPa) and lower values of aeration porosity (AP = 0.10 m^3 m^{-3}) of the subsurface soil layer (75-150 mm depth) compared with direct drilled (DD) treatments (BD = 1.35 Mg m^{-3}, PR = 1.67 MPa and AP = 0.16 m^3 m^{-3}) as shown in Table 4.8 and Figure 4.8 respectively. In contrast, the surface soil had similar values for DD and CC. Conventional cultivation tended to cause the values of surface soil bulk density (BD = 1.17 Mg m^{-3}), available water capacity (AWC = 0.16 m^3 m^{-3}), stable aggregate (SAD = 38.51 %), mean weight diameter (MWD = 1.43 mm) and infiltration rate (IR = 0.81 mm min^{-1}) similar to direct drilled treatments (BD = 1.14 Mg m^{-3}, AWC = 0.15 m^3 m^{-3}, SAD = 35.8 %, MWD = 1.37 mm and IR = 0.84 mm min^{-1}) (Table 4.8).

The crop rotation of canola grown after wheat (WBWC) resulted in the lowest aeration porosity (AP = 0.22 m^3 m^{-3}) compared with other crop rotation systems. Continuous wheat (WWWW) gave almost equal values of AP to wheat following canola (BWCW). but caused higher AP values than canola following wheat (WBWC and WCWC).

Canola grown after wheat (WCWC) resulted in the highest values of stable aggregate (SAD = 0.432) and mean weight diameter (SAD = 1.66 mm) and the greatest values of infiltration rate (IR = 1.04 mm min^{-1}) compared with the other crop rotations. On the other hand, continuous wheat crop rotation (WWWW) caused the lowest stable aggregate (SAD = 0.32) and mean weight diameter (MWD = 1.03 mm) (Table 4.8).

Table 4.8 The 1995 main effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop rotations were wheat-wheat-wheat-wheat (WWWW), fababean-wheat-canola-wheat (BWCW), canola-wheat-fababean-wheat (CWBW), wheat-faba bean-wheat-canola (WBWC), and wheat-canola- wheat-canola (WCWC).

Soil properties	Depth	Tillage practices		l.s.d *	Crop rotation systems					l.s.d *
		DD	CC	T	WWWW	BWCW	CWBW	WBWC	WCWC	S
Bulk density	**0-75**	1.139	1.172	ns	1.114	1.117	1.147	1.214	1.154	ns
(BD, Mg m^{-3})	**75-150**	**1.354**	**1.439a**	0.045	1.373	1.381	1.400	1.395	1.434	ns
Available water capacity	**0-75**	**0.147b**	**0.162a**	0.016	0.152	0.136	0.155	0.165	0.165	ns
(AWC, $m^3 m^{-3}$)	**75-150**	0.178	0.191	si	0.160	0.176	0.183	0.188	0.192	si
Aeration porosity	**0-75**	0.272	0.251	ns	**0.280a**	**0.298a**	**0.260b**	**0.223c**	**0.246b**	0.020
(AP, $m^3 m^{-3}$)	**75-150**	**0.156a**	**0.102b**	0.017	0.152	0.155	0.132	0.119	0.099	ns
Stable aggregate (a) (SAT, % of total dry soil)	**0-50**	11.19	10.89	si	9.56	11.23	9.38	11.35	13.70	si
Stable aggregate (b) (SAD, % of dry aggregate)	**0-50**	35.78	38.51	ns	**32.10b**	**38.73a**	**33.47b**	**38.21a**	**43.22a**	6.51
Mean weight diameter (MWD, mm)	**0-50**	1.37	1.43	ns	**1.03b**	**1.62a**	**1.23b**	**1.45ab**	**1.66a**	0.33
Penetration resistance	**0-75**	0.911	1.021	ns	1.138	1.058	0.636	1.014	0.984	ns
(PR, MPa)	**75-150**	1.673	2.295	0.55	2.157	1.581	2.359	2.102	1.72	ns
Infiltration rate (IR, mm min^{-1})	**0**	0.84	0.81	ns	**0.88ab**	**0.68b**	**0.87ab**	**0.65b**	**1.04a**	0.27
Organic carbon	**0-100**	1.621	1.577	x	1.593	1.567	1.722	1.465	1.649	x
(OC, %)	**100-200**	0.816	0.837	x	0.83	0.864	0.825	0.854	0.762	x
Total nitrogen (N, %)	**0-100**	1.216	1.188	x	1.18	1.12	1.281	1.141	1.288	x

(a) and (b) are the percentage of stable aggregates in total dry soil (SAT) and in total dry aggregates (SAD) of the soil respectively.
l.s.d* T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)
a and b represent differences between the means, values followed by different letters, within any row are significantly different.
ns : is non-significant differences between different tillage practices, and among different cropping systems
si: is significant as interaction effect, x : no analysis of variences

Table 4.9 The 1995 interactive effects on the mean values and the least significant differences (l.s.d) obtained from comparison of soil properties after different tillage treatments (T) and different crop rotation systems (S). The tillage treatments were direct drill (DD) and conventional cultivation (CC), and the crop rotations were wheat-wheat-wheat-wheat (WWWW), fababean-wheat-canola-wheat (BWCW), canola-wheat-fababean-wheat (CWBW), wheat-faba bean-wheat-canola (WBWC), and wheat-canola- wheat-canola (WCWC).

Soil properties	**Depth**	**Interaction of Tillage practices and Crop rotation systems (TxS)^{ns}** **DD** **WWWW**	**BWCW**	**CWBW**	**WBWC**	**WCWC**	**CC** **WWWW**	**BWCW**	**CWBW**	**WBWC**	**WCWC**	**l.s.d* (1) TxS**	**l.s.d* (2) TxS**
Bulk density	**0-75**	1.097	1.099	1.128	1.197	1.172	1.130	1.136	1.166	1.231	1.137	ns	ns
(BD, Mg m^{-3})	**75-150**	1.377	1.308	1.337	1.323	1.452	1.370	1.455	1.462	1.467	1.442	ns	ns
Available water capacity	**0-75**	0.155	0.129	0.148	0.152	0.151	0.148	0.144	0.162	0.178	0.179	ns	ns
(AWC, $m^3 m^{-3}$)	**75-150**	**0.133b**	**0.179a**	**0.185a**	**0.180a**	**0.210a**	**0.187a**	**0.193a**	**0.181a**	**0.195a**	**0.196a**	0.033	0.035
Aeration porosity	**0-75**	0.295	0.305	0.274	0.233	0.252	0.265	0.292	0.245	0.213	0.240	ns	ns
(AP, $m^3 m^{-3}$)	**75-150**	0.175	0.188	0.168	0.151	0.104	0.129	0.121	0.096	0.087	0.094	ns	ns
Stable aggregate (a) (SAT, % of total dry soil)	**0-50**	**8.27bc**	**8.92bc**	**10.30bc**	**12.78ab**	**15.70a**	**10.85bc**	**13.54ab**	**8.46c**	**9.91bc**	**11.711bc**	4.974	4.256
Stable aggregate (b) (SAD, % of dry aggregate)	**0-50**	32.49	37.87	27.74	41.17	39.65	31.71	39.59	39.93	35.25	46.79	ns	ns
Mean weight diameter (MWD, mm)	**0-50**	1.08	1.46	0.97	1.82	1.51	0.98	1.78	1.54	1.08	1.82	ns	ns
Penetration resistance	**0-75**	1.285	0.618	0.695	0.907	1.049	0.990	1.497	0.577	1.120	0.919	ns	ns
(PR, MPa)	**75-150**	1.579	1.07	1.777	1.98	1.956	2.734	2.092	2.94	2.223	1.485	ns	ns
Infiltration rate (IR, mm min^{-1})		0.89	0.88	0.88	0.64	0.92	0.88	0.48	0.85	0.67	1.16745	ns	ns
Organic carbon	**0-100**	1.626	1.669	1.766	1.455	1.591	1.56	1.465	1.678	1.475	1.708	x	x
(OC, %)	**100-200**	0.859	0.844	0.699	0.873	0.805	0.8	0.883	0.951	0.835	0.718	x	x
Total nitrogen (N, %)	**0-100**	1.22	1.176	1.288	1.078	1.316	1.14	1.064	1.274	1.204	1.26	x	x

(a) and (b) are the percentage of stable aggregates in total dry soil (SAT) and in total dry aggregates (SAD) of the soil respectively.
l.s.d* T and S are the least significant differences of the means caused by interaction effects of tillage practices and crop rotation systems for comparison at $P < 0.05$ (*)
(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practies respectively
a and b represent differences between the means, values followed by different letters, within any row are significantly different.
ns : interaction effects are not significant, x : no analysis of variences

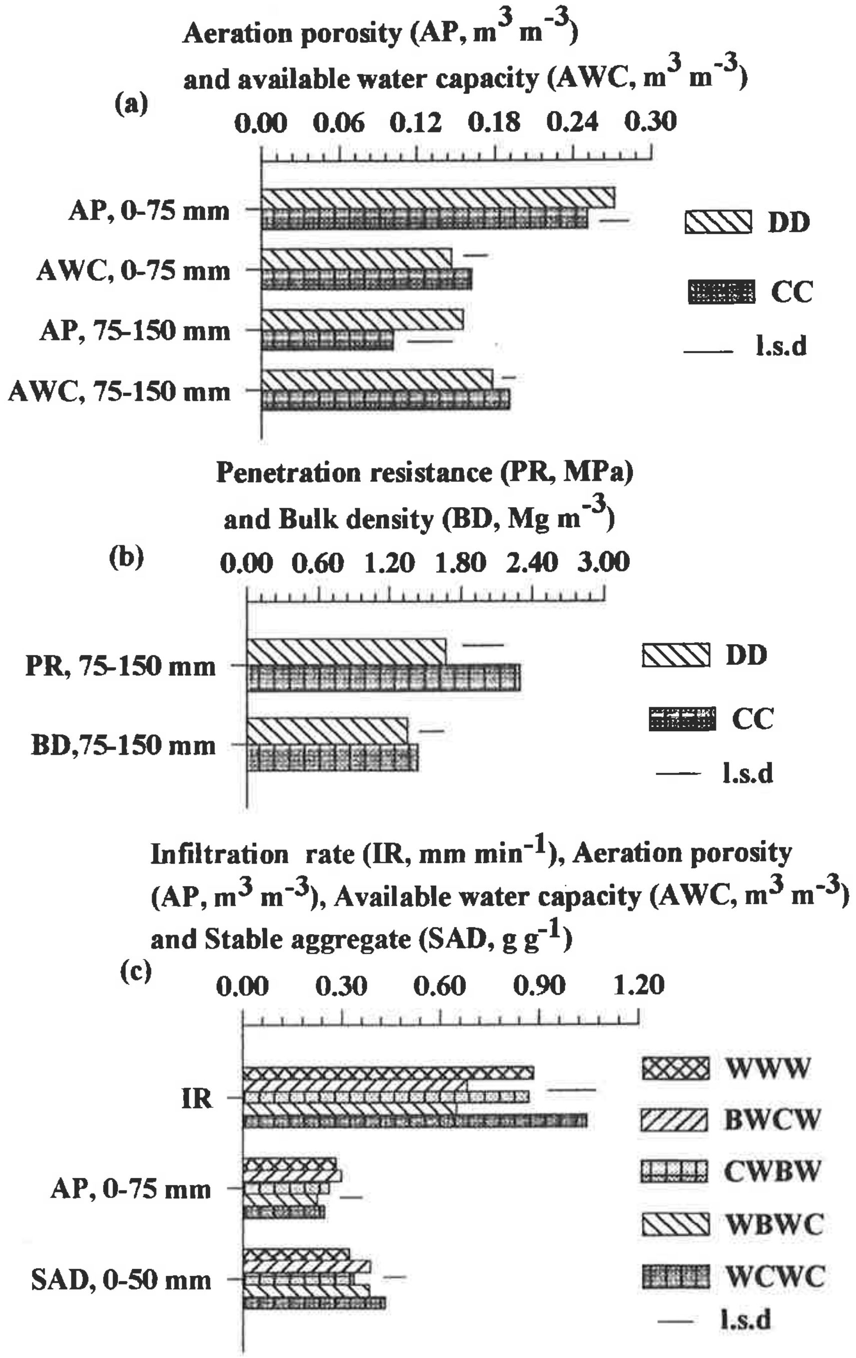


Figure 4.8 The effects of direct drilling (DD) and conventional cultivation (CC) on the surface (0-75 mm) and subsurface soil (75-150 mm) properties, **(a)** aeration porosity (AP), and available water capacity (AWC), **(b)** penetration resistance (PR) and bulk density (BD), and **(c)** infiltration rate (IR), aeration porosity (AP) and stable aggregate as a fraction of dry aggregate (SAD) in 1995.

Interactive effects (Table 4.9) showed that continuous wheat crop rotation sown by direct drilling (DD-WWWW) had caused the lowest value of available water capacity (AWC = 0.133 m^3 m^{-3}) in the subsurface soil layer (75-150 mm) compared with the other crop rotation systems. Canola sown after wheat by direct drilling (DD-WCWC) induced the highest values of available water capacity (AWC = 0.21 m^3 m^{-3}) in the subsurface (75-150 mm) soil layer and the greatest amount of stable aggregates (SAT = 15.70 %) in the surface soil layer (0-50 mm) compared to the other treatments.

4.3.7 Effects of rainfall and four years of tillage practices on soil physical properties.

The effects of tillage and crop rotation on soil properties were not consistent over the 4 years of field experimentation. The most plausible explanation for this variation probably lies in the difference in rainfall from one season to the next. This is particularly true for interaction of tillage and rotation.

In order to explain the effect of rainfall on the relationship between management and soil properties, I will focus only on the main effects of tillage practices (DD and CC) on soil properties in continuous wheat crop rotation (WWWW).

For two of the four-years of experimentation, direct drilling improved soil structure by generally reducing bulk density (Figure 4.9), increasing aeration porosity and decreasing available water capacity in both surface and subsurface soil layers compared with conventional cultivation (Figure 4.10 a and b respectively). In 1994, the surface of conventional cultivated plots was less compact than direct drilled plots. This was a reversal of the condition in 1992, 1993 and 1995. However, conventional cultivation did not degrade soil structure while structural stability in direct drilled plots tended to decrease from 1992 to 1995 (Figure 4.11).

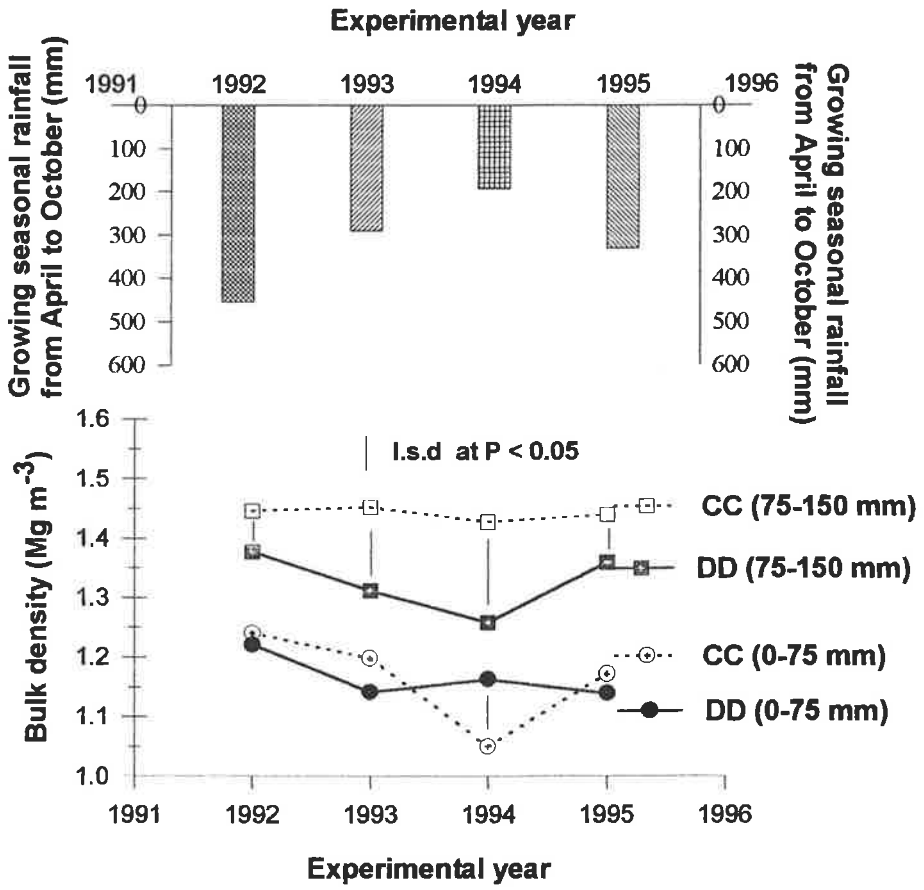


Figure 4.9 The effects of direct drilling (DD) and conventional cultivation (CC) on the surface soil (0-75 mm) and subsurface soil (75-150 mm) bulk density (BD) in continuous wheat crop rotations (WWWW), as influenced by the amount of rainfall during the growing season (April to October) from 1992 to 1995.

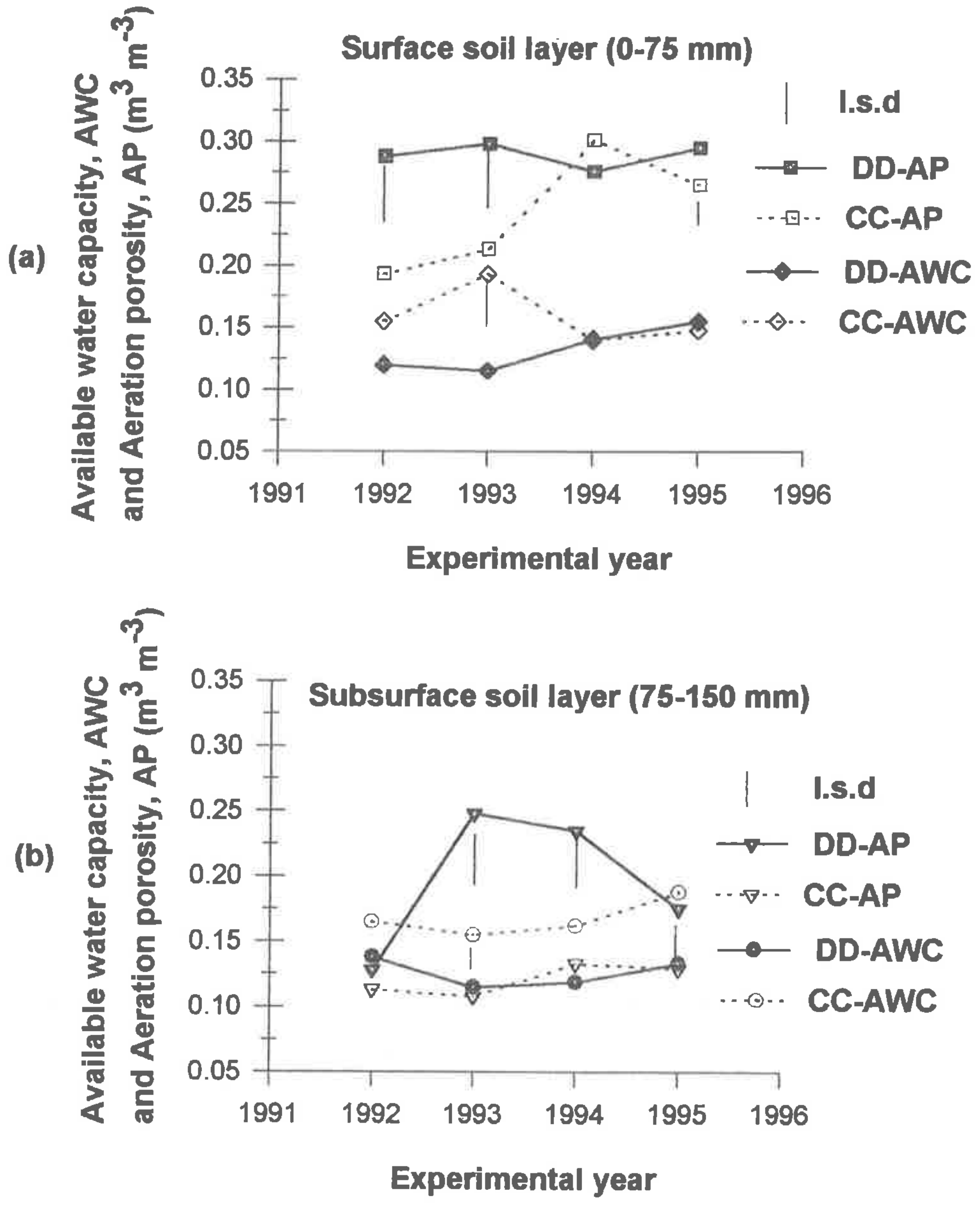


Figure 4.10 The effects of direct drilling (DD) and conventional cultivation (CC) on the available water capacity (AWC) and aeration porosity (AP) of **(a)** surface soil (0-75 mm) and **(b)** subsurface soil (75-150 mm) in continuous wheat crop rotations (WWWW) from 1992 to 1995.

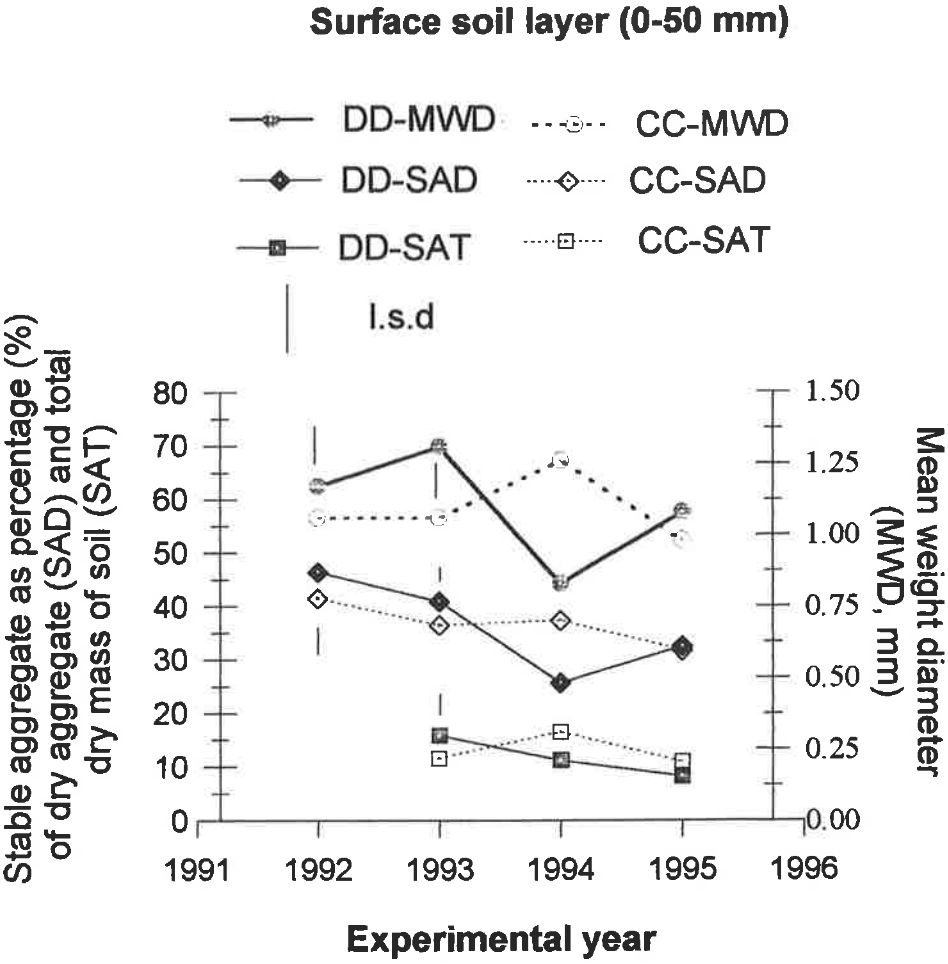
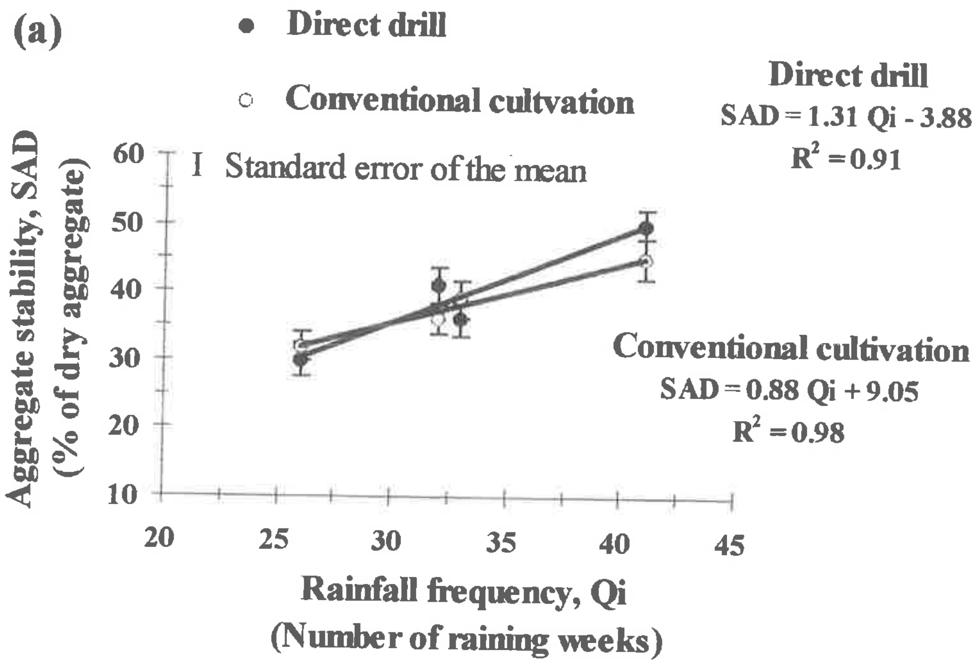


Figure 4.11 The effects of direct drilling (DD) and conventional cultivation (CC) on the stable aggregate as percentage of dry aggregate (SAD), total dry mass of soil (SAT) and mean weight diameter (MWD) of the surface soil (0-50 mm) in continuous wheat crop rotations (WWWW) from 1992 to 1995.

In general, the average aggregate stability (SAD) in both direct drilled and conventionally cultivated plots strongly correlated to the amount and the frequency of rainfall as presented in Figure 4.12. These results might be caused by the inter active effects between rainfall, crop growth, root density and tillage practices.



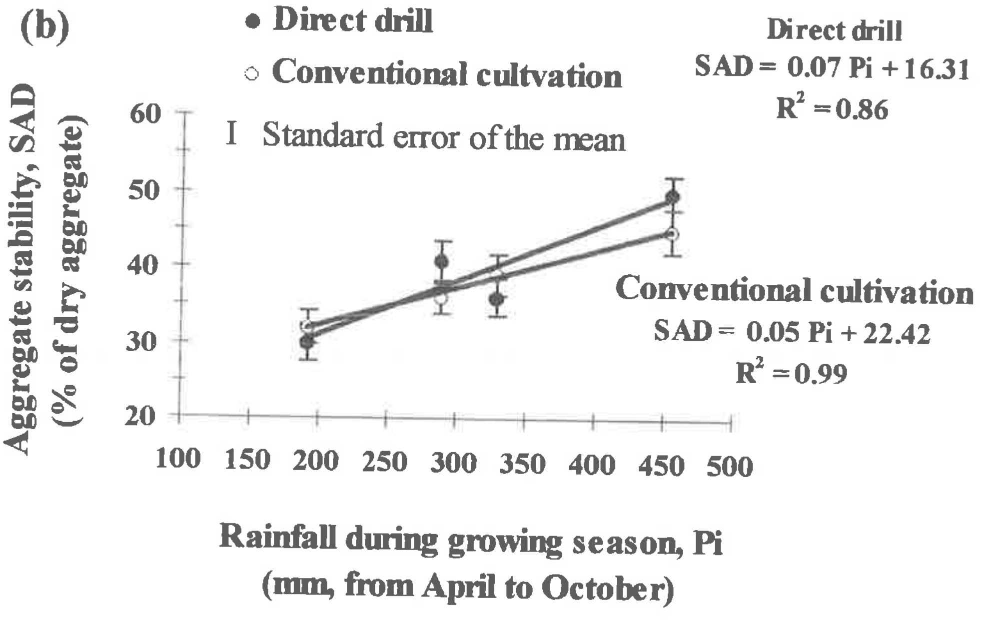


Figure 4.12 The influences of **(a)** rainfall frequency (Qi) and **(b)** the amount of rainfall (Pi) on aggregate stability as a percentage of dry aggregates (SAD) of the surface soil (0-50 mm) in average direct drilling (DD) and average conventional cultivation (CC) treatments from 1992 to 1995.

These results suggest that the effect of tillage practices on soil structure was strongly influenced by the amount of rainfall during the growing season. Interactive effects between tillage practices and rainfall caused different crop growt and different root densities in the surface soil layer. The better crop growth and the higher root density gave better surface soil structure improvement by adding organic matter and protecting the soil surface from rainfall impaction. Accumulation of organic matter in the surface soil layer (0-100 mm) may have caused a decrease in bulk density of the surface soil from 1992 to 1994 by incorporation of crop residues and roots.

Heavy rain in 1992 and 1993 caused more slaking leading to deterioration of surface soil structure. Crusting of the tilled layer in conventional cultivation treatments was more pronounced than in direct drilled treatments. Rain in 1994 was too low to cause slaking of the conventionally tilled layer during the growing season. Consequently it retained the low density level imposed by tillage.

The soil samples for soil structure analysis were obtained during the grain ripening stage 1 month before harvesting. Surface soil structure may change gradually from sowing to harvesting depending on the intensity and the distribution of growing seasonal rainfall. High intensity of rainfall and more frequent rain during early crop growth may give a denser surface soil structure with lower structural stability and smaller mean weight diameter in conventional cultivation than in direct drilled plots, as shown in Figure 4.12. On the other hand, lower rainfall frequency and low rainfall intensity can cause either indifferent or reversed results in surface soil properties.

4.4 Conclusions

(i) Direct drilling can improve soil structure by inducing better aeration, decreasing bulk density and penetration resistance, increasing total porosity, soil aggregate stability and mean weight diameter, causing greater amount of aeration and giving higher infiltration rate in both surface and sub-surface soil compared to the conventional cultivation treatment.

(ii) The effects of tillage practices and crop rotation systems on organic matter content and total nitrogen in the surface soil varied from year to year. There was no accumulation of organic matter in the surface soil layer from 1992 to 1995.

(iii) The changes of soil physical properties from 1992 to 1995 showed that conventional cultivation did not disrupt surface soil structure, but caused significant compaction of subsurface soil layers compared with direct drilling.

(iv) Intensity and frequency of rainfall during the growing season are the most important climatic factors that govern soil structural conditions. Direct drilling sustained better soil structure than conventional cultivation treatment in wet years. In drier years there was no clear effect of tillage.

(v) Direct drilling tended to cause higher soil evaporation loss from the soil surface compared with conventional cultivation. This result suggested that better soil structure induced by direct drilling may avoid or reduce surface crusting and promote greater capillary pore continuity between the surface soil and subsurface layers, consequently causing more soil evaporation compared with conventional cultivation treatments.

(vi) Rotation of wheat following canola gave the best protection to surface soil structure from rain impaction during early crop growth. However, canola was not able to be grown under low rainfall conditions with the conventionally cultivated treatments. Therefore, the other option was to grow wheat after faba bean to reduce the risk of an early drought period as in 1993. Wheat after wheat was the best crop system under dryland farming system in a very dry year as 1994. While this is contrary to general advice against monocropping, wheat is clearly most able to survive drought conditions which overrides disadvantages of disease development and fertility problems in very dry years.

(vii) Different crop sequences gave different values of subsoil properties and this varied according to the amount of rainfall and distribution of roots in the soil.

(viii) The interactive effects of tillage practices and crop rotation systems significantly affected soil properties when there was optimum rainfall during the growing season such as in 1993 and 1995. The interactive effects were not significant under high (1992) or lower (1994) rainfall conditions.

CHAPTER 5

EFFECTS OF TILLAGE PRACTICES AND CROP ROTATION SYSTEMS ON WATER USE, ROOT GROWTH AND WATER USE EFFICIENCY

5.1 Introduction

Crop water use or evapotranspiration is the amount of soil water lost to the atmosphere through the soil surface as vapour plus that lost through the stomata of plants growing in the soil. The amount of water used is the most important factor that limits production of wheat under rainfed conditions when biomass and grain yield are dominantly controlled by rainfall (Cornish, 1950). Considerable research effort has been expended in the search to increase rainfed wheat yield in South Australia since 1950. One of the most widely used indicators of success in this search is that of "water use efficiency" which is generally defined as the crop yield or biomass production per unit area of soil per unit equivalent depth of water used to produce the crop (water lost by evapotranspiration).

Many studies have been carried out on water use efficiency of dryland wheat in South Australia and are documented in Chapter 2, Section 2.2 (Fisher and Kohn, 1966a; French, 1978; French and Schultz, 1984; Greacen and Hignett, 1976; Schultz, 1971; Woodruff, 1983). Values of water use efficiency observed in these studies have ranged from 16 to 54 kg $ha^{-1}mm^{-1}$ for dry matter and from 4 to 19 kg ha^{-1} mm^{-1} for grain. These are very large ranges of water use efficiency and they possibly reflect variations of circumstances, rainfall amount and distribution and differences in soil types. The variations in water use efficiency are not only caused by rainfall variations but also by different environmental conditions such as general climatic variation.

The definition of water use efficiency is satisfactory when comparing crops with the same rainfall regime but may be somewhat misleading when comparing crops across years or locations with widely varying rainfall. For example, a crop grown under low rainfall and with a smaller water use and poorer grain yield may have a similar or higher water use efficiency compared with a high yielding crop grown in higher rainfall conditions. To compare efficiency of water use under different rainfall or climatic conditions, French and Schultz (1984) proposed two simple equations giving the optimum water use for producing the maximum yield (potential) under a given growing seasonal rainfall (Equations 2.2 and 2.3 in Chapter 2). These two equations were based largely on the best yields obtained across South Australia. The potential water use efficiency is calculated as the ratio of the estimated potential yield and the estimated optimum water use. Expressing the measured crop water use efficiency in a particular location under a given rainfall for a particular year as a fraction of this potential or estimated water use efficiency may provide a better assessment of efficient water use than the generally measured water use efficiency under dryland conditions. On the other hand "relative grain yield" which is the ratio of the actual measured grain yield to the estimated potential grain yield is also a good index to assess the success of crop production improvement.

An increase in water use efficiency is achieved by either reducing soil water lost by evaporation and/or increasing crop transpiration which will increase yield and growth. One way to increase crop transpiration is to improve root systems to the extent that the roots find new water resources. Another way is to improve the accession and storage of rainfall to the root zone by improving soil properties as reported in Chapter 4. The effects of agricultural practices using different tillage operations and different crop rotations on water use or crop evapotranspiration, soil water evaporation and grain yield are documented in Section 2.3.

In this project the effects of tillage practices and crop rotation systems were evaluated over four seasons in terms of their utility in improving soil structure (Chapter 4) and hence soil water relations. The aim of this chapter is to report the soil hydrological response to these tillage practices and cropping systems and to assess them in terms of crop water use efficiency.

5.2 Materials and methods

The effects of two tillage practices (direct drill, conventional cultivation) and several rotation systems using three crops (wheat, canola and faba bean) were evaluated in terms of total stored soil water, crop evapotranspiration, rooting depth, root length density, biomass production, grain yield and water use efficiency over four cropping seasons from 1992 to 1995. The experiment was commenced in 1992 as a split plot in randomised complete block design comprising 3 replications of 2 main plots of tillage practices and 3 subplots of crop rotation systems. The main plots were direct drill (DD) and conventional cultivation (CC), subplots consisted of 3 crop types in 1992 and 5 crop rotations of wheat (W), faba bean (B) and canola (C) in 1993, 1994 and 1995. The experimental design, the plot layout, the treatment combinations studied and soil preparation and management were described in Sections 3.3 and 3.4 respectively.

The soil water content in a 2 m depth soil profile was monitored with a neutron water meter every fortnight during each stage of crop growth from 1992 to 1995 as described in Section 3.5.2. The neutron water meter was calibrated in situ after the first cropping season (Section 3.4.1). Rainfall was measured by an automatic tipping raingauge at the center of the experimental site and was calibrated with the rainfall data from the weather station on the nearby (approximately 2 km) Roseworthy Campus as described in Section 3.5.3. Plant growth was measured as total biomass above the ground level at each stage of crop growth each year (Section 3.5.5). Root length density was measured in 200 mm increments down to maximum rooting depth during yield formation every year (Section 3.5.5).

Calculation of crop water use was based on the total stored soil water changes and the amount of rainfall that fell during each growing stage from 1992 to 1995. The water use efficiency of each crop was calculated from total dry matter and grain yield as described in Section 3.5.6.

5.3 Results and discussion

5.3.1 Overall effects of tillage practices and crop rotation systems

The F-values obtained from analysis of variance of total stored soil water (TSW) and cumulative water use (CWU), dry matter (DM) and water use efficiency (WUE), and root density distribution (RD) as affected by tillage practices (T) and crop rotation systems (S) are presented in Table 5.1, 5.2 and 5.12 respectively.

The average values of total stored water (TSW), cumulative water use (CWU), dry matter (DM), grain yields, water use efficiency (WUE) and root growth affected by different T and S from 1992 to 1995 are presented in Tables 5.3 to 5.10 and 5.13 to 5.15 respectively. Some relationships of the results for single years are shown as plotted graphs in Figures from 5.1 to 5.8. The results from 1992 to 1995 are compared in Figures from 5.9 to 5.12. respectively. The results of rainfall, measured and estimated (potential) values of water use, grain yield, and water use efficiency from 1992 to 1995 are presented in Table 5.11.

In general, Table 5.1 shows that tillage practices (T) had no significant effects on total stored soil water (TSW) measured at all growing stages in every year from 1992 to 1995. Significant effects of crop types or crop rotations (S) on TSW were found in 1992 and 1993 only. Interactive effect of tillage practices and crop rotations (TxS) on TSW was significant in the late growing season in 1993 only. Table 5.1 also shows that the main effects of tillage practices (T) were not significantly different in terms of cumulative water use (CWU) in 1992 and 1995, but were significantly different in 1993 and 1994. On the other hand, crop rotations (S) showed significantly different cumulative water use at all stages in 1993 and at early crop growth in 1994 and 1995.

Table 5.2 shows that dry matter (DM), water use efficiency (WUE) at all measured growing stages and yields each year were significantly affected by the main effects of tillage practices and crop rotation systems from 1992 to 1995. Interactive effects of tillage practices and crop rotation systems (TxS) on dry matter, water use efficiency and yield were significant in 1993 and 1995 only, insignificant effects were found in 1992 (only grain yield and WUE on grain yield were measured) and 1994 which were the exceptionally wet and very dry years respectively.

Table 5.1 The statistical significance of F values obtained from analysis of variance of the effects of tillage practices (T) and crop rotation systems (S) on total stored soil water (TSW) and cumulative water use (CWU) within 2000 mm soil depth in 1992, 1993, 1994 and 1995.

Total stored soil water and cumulative water use at different stages of crop growth	Tillage practices and crop rotation systems															
	1992				1993				1994				1995			
	Days after sowing	T	S	T x S	Days after sowing	T	S	T x S	Days after sowing	T	S	T x S	Days after sowing	T	S	T x S
Total stored soil water (mm)																
Sowing or seeding	-	-	-	-	-	-	-	-	0	3.91	2.51	0.38	-	-	-	-
Seedling	-	-	-	-	38	2.85	0.66	0.47	36	0.53	2.97	0.37	36	0.06	0.96	1.37
Tillering	75	1.54	1.89	2.16	68	7.31	2.02	0.14	75	0.02	2.04	0.65	58	0.12	1.97	1.95
Heading	95	0.41	2.43	1.73	-	-	-	-	87	0.36	1.39	0.82	78	0.75	1.16	1.31
Flowering	115	1.01	0.52	0.45	110	0.02	2.12	6.64*	100	0.06	1.82	0.71	97	0.63	0.96	1.59
Yield formation	145	0.90	4.44*	0.71	-	-	-	-	-	-	-	-	107	0.33	1.07	1.71
Grain or seed filling	160	0.13	8.67**	2.08	122	0.14	7.42**	8.15**	114	0.16	1.75	0.69	118	0.62	0.76	1.52
Ripening	185	0.11	5.5*	2.61	138	0.17	4.20**	5.98**	138	0.88	1.60	0.82	140	0.44	0.56	1.13
Harvesting	195	0.00	10.13**	1.81	163	0.14	5.02**	6.54**	155	0.27	1.20	0.56	198	0.69	0.43	1.18
Cumulative water use (mm)																
Seedling	-	-	-	-	-	-	-	-	36	14.64*	4.00*	2.42	-	-	-	-
Tillering	75	1.27	3.08	0.25	68	13.52**	4.54**	1.68	75	17.91*	1.60	1.29	58	0.03	3.89*	0.44
Heading	-	-	-	-	-	-	-	-	87	41.77*	1.25	1.50	78	16.6	1.04	2.44
Flowering	115	0.03	3.17	4.98*	110	9.38*	5.60**	10.60**	100	25.64*	0.90	1.08	97	4.02	1.5	4.07*
Yield formation	145	0.54	13.93**	2.66	-	-	-	-	114	25.52*	1.07	0.77	118	3.12	0.53	2.8
Grain or seed filling	160	0.13	27.92**	2.06	122	7.02	5.63**	3.26*	120	-	-	-	125	-	-	-
Ripening	185	1.30	15.52**	12.42**	138	14.04*	7.48**	8.45**	138	16.39*	0.76	0.78	140	2.5	0.73	3.31
Harvesting	195	0.42	10.75**	1.93	163	-	-	-	155	4.68	1.74	0.78	146	-	-	-

* represent the significant F- values at probability (P) of 0.05 ;

** represent the significant F- values at probability (P) of 0.01 ;

- , Total stored soil water were not measured.

Table 5.2 The statistical significance of F values obtained from analysis of variance of the effects of tillage practices (T) and crop rotation systems (S) on dry matter (DM), crop yield (grain or seed) and water use efficiency (WUE) of crops at differrent stages of crop growth during growing season from 1992 to 1995.

Dry matter, yield and water use efficiency at different stages of crop growth	Tillage practices and crop rotation systems															
	1992				1993				1994				1995			
	Days after sowing	T	S	T x S	Days after sowing	T	S	T x S	Days after sowing	T	S	T x S	Days after sowing	T	S	T x S
Dry matter and yield (t ha^{-1})																
Tillering	75	-	-	-	75	20.63*	7.42**	0.71	68	6.21*	9.09**	0.98	58	88.91**	51.15**	8.90**
Heading	95	-	-	-	85	186.76**	2.42	4.93**	87	88.24**	16.34*	1.68	78	11.81*	32.32**	34.09**
Flowering	115	-	-	-	110	-	-	-	100	16.57*	16.17**	0.83	97	58.35**	60.79**	7.15**
Yield formation - grain filling	145	-	-	-	122	76.60**	4.91**	3.15*	114	9.98*	19.82**	2.01	118	338.64**	38.07**	5.77**
Ripening	185	-	-	-	138	0.04	11.03**	0.94	138	18.47*	15.63**	0.37	140	57.39**	38.23**	6.80**
Relative yield	195	9.89*	0.67	2.34	163	0.49	4.19**	0.91	155	5.07	5.09*	0.58	146	66.40**	4.447**	5.58**
Water use efficiency (kg ha^{-1} mm^{-1})																
Tillering	75	-	-	-	76	7.65*	3.68*	3.80*	87	81.86**	6.99**	1.64	58	61.87**	10.94**	7.44**
Flowering	115	-	-	-	110	22.10*	5.60**		100	8.82*	9.77**	0.43	97	30.83**	11.05**	16.58**
Yield formation -grain filling	145	-	-	-	122	24.95*	4.96**	4.24**	114	3.55	13.97**	1.34	118	18.87*	21.09*	30.92**
Ripening	185	-	-	-	138	3.07	3.44*	1.38	138	10.06*	12.23*	0.35	140	23.20**	38.82**	31.10**
Harvesting	195	-	-	-	163	-	-	-	155	7.80*	11.13**	0.19	146	34.47**	44.77**	12.68**
Relative yields	195	8.73*	4.70*	0.92	163	14.36*	90.78**	2.96*	155	16.28*	3.44*	0.74	146	37.25**	3.32*	5.16**

* represent the significant F- values at probability (P) of 0.05 :

* * represent the significant F- values at probability (P) of 0.01 :

- , Dry matter and water use efficiency were not measured.

5.3.2 Water use and crop production in 1992

Few of the measured parameters showed significant differences between tillage practices or crops in 1992. The reason for this was probably that the exceptionally high rainfall during the growing season that year (Figure 5.1) did not induce sufficient moisture stresses to cause the plants to exploit any differences between treatments. The one exception to this condition was the possibility of aeration limitations. There were, however, trends in the data which emerged more clearly in later years when rainfall conditions were less favourable. These trends are discussed in this section with acknowledgment that not all are statistically significant.

Table 5.3 shows that total stored soil water (TSW) and cumulative water use (CWU) caused by direct drilling (DD) were not different from those caused by conventional cultivation (CC) for every growing stage. However, the average yields of the three crops (wheat, faba bean and canola) from direct drilling (1.92 t ha^{-1}) was higher than that obtained from conventional cultivation (1.65 t ha^{-1}). Direct drilling (DD) also caused higher water use efficiency on average yield of the three crop types (5.20 kg ha^{-1} mm^{-1}) compared to conventional cultivation treatment (4.42 kg ha^{-1} mm^{-1}). Table 5.3 also showed that wheat tended to have the highest TSW values while faba bean had the lowest values of TSW from yield formation to ripening. The average cumulative water use by faba bean from seedling to yield formation and harvesting were higher than water used by either wheat or canola.

Table 5.4 indicates that the cumulative water use during flowering by canola (C) sown by direct drilling was the lowest (64 mm), while faba bean sown using conventional cultivation was the highest (126 mm).

Table 5.3 The main effects of tillage practices (T, direct drill, DD and conventional cultivation, CC) and crop types (S, wheat, W, faba bean, B and canola, C) on the average values and the least significant differences of the mean of total stored soil water (TSW), cumulative water use (CWU), water use efficiency (WUE) and crop yields within 2000 mm soil depth during growing season in 1992.

Total stored soil water, cumulative water use, crop yield and water use efficiency at different growing stages	**Days after sowing**	**Tillage practice**		**l.s.d.***	**Crop rotation system**			**l.s.d.***
		DD	**CC**	**T**	**W**	**B**	**C**	**S**
Total stored soil water, TSW (mm)								
Tillering	**75**	655	682	ns	699	667	640	-
Flowering	**115**	737	768	ns	798	729	731	-
Yield formation	**145**	744	770	ns	**808a**	**714c**	**748b**	29
Ripening	**185**	659	685	ns	**723a**	**643b**	**650b**	36
Cumulative water use, CWU (mm) from	**68**							
Tillering	**75**	30	36	ns	38	27	32	ns
Flowering	**115**	89	91	si	81	108	83	si
Yield formation	**145**	181	187	ns	**168b**	**220a**	**164b**	24
Ripening	**185**	351	358	si	340	377	348	si
Yield (t ha^{-1})	**195**	**1.919a**	**1.653b**	*	2.918	1.625	0.815	ns
Water use efficiency on yield (kg ha^{-1} mm^{-1})		**5.200a**	**4.420b**	*	**8.180a**	**4.260b**	**2.000c**	*

l.s.d* T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$, * : comparison is based on relative l.s.d values.

a, b, c and d represent differences between the means, values followed by different letters, within any row are significantly different.

ns : is non-significant differences between different tillage practices, and among different cropping systems

si: is significant as interactive effect

Table 5.4 The interactive effects (TxS) of tillage practices (direct drill, DD and conventional cultivation, CC) and crop types (wheat, W, faba bean, B and canola, C) on the average values and the least significant differences of the mean of total stored soil water (TSW), cumulative water use (CWU), water use efficiency (WUE) and crop yields within 2000 mm soil depth during growing season in 1992.

Total stored soil water, cumulative water use, crop yield and water use efficiency at different growing stages	**Days after sowing**	**Interaction of Tillage practices and Crop rotation systems**						**l.s.d* (1) TxS**	**l.s.d* (2) TxS**
		DD			**CC**				
		W	**B**	**C**	**W**	**B**	**C**		
Total stored soil water, TSW (mm)									
Tillering	75	691	652	622	706	682	657	ns	ns
Flowering	**115**	789	730	693	807	728	769	ns	ns
Yield formation	**145**	805	710	717	813	719	780	ns	ns
Ripening	**185**	728	610	641	719	677	659	ns	ns
Cumulative water use , WUE (mm) from	**68**								
Tillering	75	34	25	31	43	30	34	ns	ns
Flowering	**115**	**78bc**	**89bc**	**102ab**	**84bc**	**126a**	**64c**	**34**	**33**
Yield formation	**145**	160	207	176	176	233	151	ns	ns
Ripening	**185**	**323c**	**393a**	**338bc**	**356bc**	**361b**	**358b**	**21**	**19**
Yield (t ha^{-1})	**195**	3.006	1.925	0.825	2.830	1.326	0.805	ns	ns
Water use efficiency on yield (kg ha^{-1} mm^{-1})		8.560	4.950	2.090	7.800	3.560	1.900	ns	ns

l.s.d* T x S are the least significant differences of the means caused by interactive effects of tillage practices and crop rotation systems for comparison at $P < 0.05$, * : comparison is based on relative l.s.d values.
(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practices respectively
a, b and c represent differences between the means, values followed by different letters, within any row are significantly different.
ns : interaction effects are not significant

When the crops were mature, the lowest consumption of water to ripening was found in wheat with direct drill (323 mm), and the highest cumulative water use was obtained by faba bean with direct drill (393 mm). At other growth stages, differences were not significantly different. The relationships between total stored soil water and cumulative water use of different crop types as influenced by direct drilling and conventional cultivation treatments are presented in Figure 5.1.

Figure 5.1a shows rainfall during each growing stage in 1992 and the crop water consumption (cumulative water use, CWU) as a function of total stored water at different growth stages. Figure 5.1 differentiates periods when water consumption was by depletion of soil water in the absence of rain (sloping lines in b) and when negligible depletion of soil water occurred and plant water consumption was supplied by regular rainfall (lines horizontal in b).

Figure 5.1 shows that TSW increased from tillering (75 days) to flowering (115 days) as excess rain was stored in the soil. There was no further change in soil water until yield formation (145 days) because rainfall was sufficient to maintain the maximum soil water holding capacity and supply the crop water requirement. From 145 days to 160 days after sowing, the total stored soil water decreased because of low rainfall and high crop water requirement.

Conventional cultivation had a greater amount of TSW under all crops compared to crops sown by direct drilling. Faba beans used more water during the period of crop growth before maturity and reached the ripening stage earlier than wheat or canola. After maturity, faba beans used less water while wheat and canola maintained and decreased TSW values during ripening to harvesting respectively.

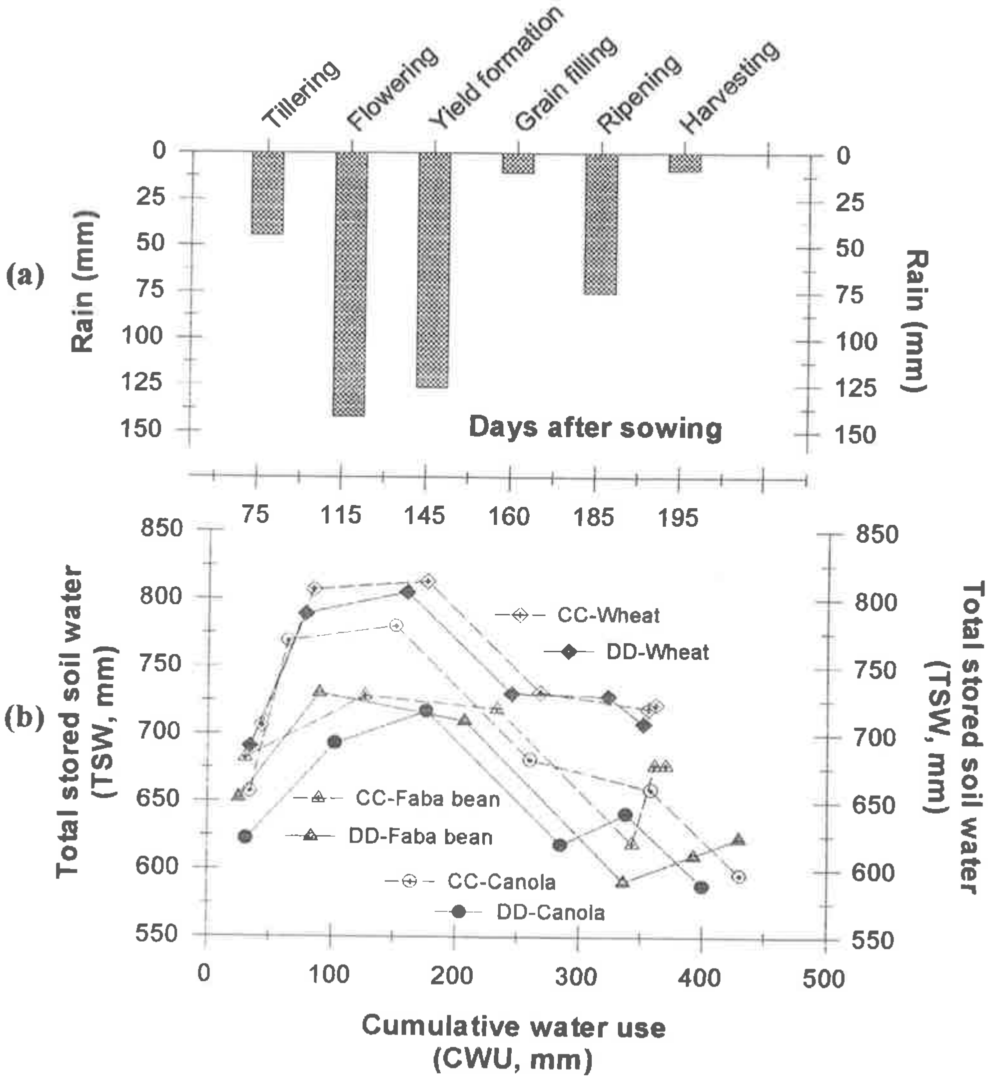


Figure 5.1 **(a)** The 1992 rainfall during each growing stage and the days after sowing on which biomass was sampled for graphs (b) and (c), **(b)** the 1992 crop water consumption (cumulative water use, CWU) as a function of total stored soil water for different crops, sown by either direct drilling (DD) or conventional cultivation (CC). The x axis of (a) corresponds to the x axis of (b).

Table 5.4 also shows that direct drilling tended to give higher yields for each crop type, (wheat, 3.01, faba bean 1.93 and canola 0.83 t ha^{-1} respectively) than conventional cultivation (2.83, 1.33 and 0.81 t ha^{-1} respectively). Crop yields and water use efficiency are also presented graphically in Figure 5.2.

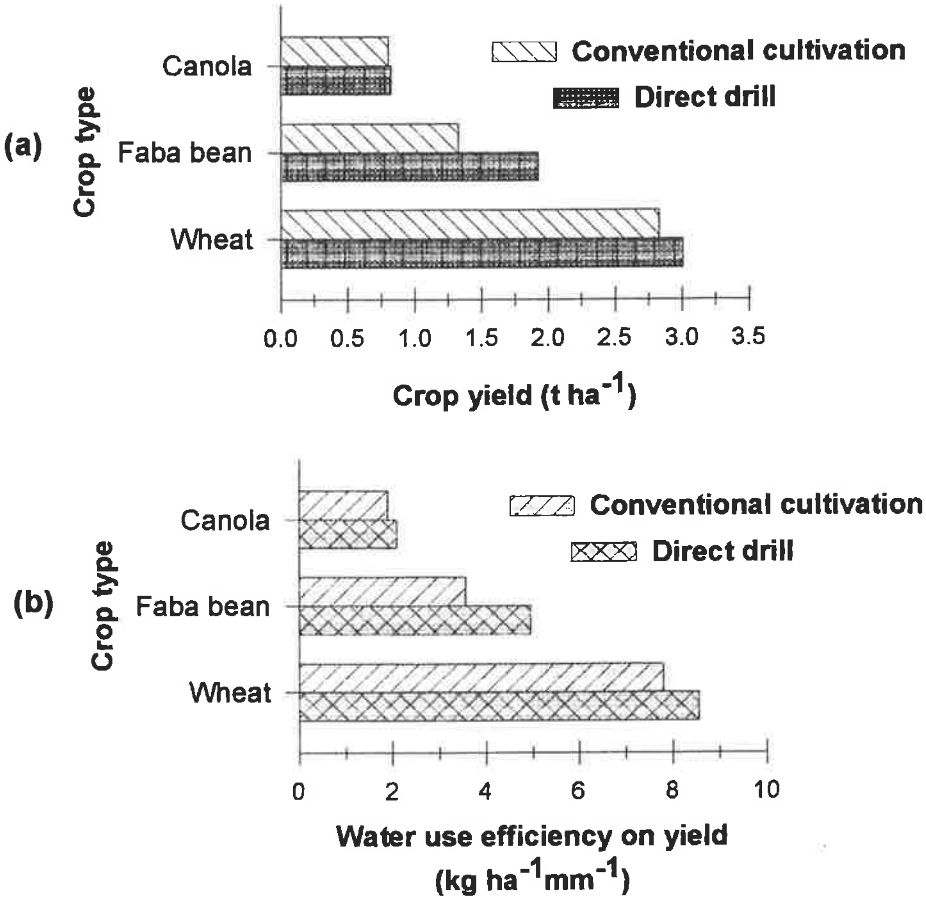


Figure 5.2 The trends associated with direct drilling and conventional cultivation on **(a)** crop yields and **(b)** grain water use efficiency in 1992.

Figure 5.2 showed that faba bean and wheat grown using direct drilling resulted in higher yield and higher water use efficiency than using conventional cultivation. Canola yields for either tillage system were not different. However, the average yields and water use efficiency of the three crop types sown by direct drilling were higher than by conventional cultivation (Figure 5.2).

5.3.3 Water use and crop production in 1993

Interactive effects of tillage practices (T) and crop rotation systems (S) on TSW, CWU, DM, and WUE were found to be significant at almost every growing stage in 1993 (Tables 5.1 and 5.2). Only at the tillering stage did the main effects show that direct drilling (DD) caused higher values of CWU (126 mm) and greater average dry matter (3.04 t ha^{-1}) than conventional cultivation (CC) which caused CWU and DM of 107 mm and 2.24 t ha^{-1} respectively as shown in Table 5.5.

Crop rotations had significant differences of CWU at tillering, DM at tillering and ripening, and WUE at ripening only (Table 5.5). Canola after wheat (WC) had the highest amount of CWU (130 mm) while wheat after canola had the lowest amount of CWU (100 mm) compared with the other treatments.

By tillering, BW had produced more dry matter (2.83 t ha^{-1}) than CW (2.22 t ha^{-1}) which had more DM than WW (2.04 t ha^{-1}) while WB and WC had accumulated similar amounts of DM (3.05 t ha^{-1}). By ripening, BW had produced the largest amount of cumulative dry matter and yield compared with the other crop rotations.

The interactive effects (TxS) of tillage practices and crop rotation systems on TSW, CWU, DM, Yield and WUE presented in Table 5.6 indicates that wheat grown after faba bean in direct drilled plots (DD-BW) was associated with the lowest TSW during flowering to ripening (110 to 138 days after sowing) compared with the other treatments. Canola and faba bean grown after wheat in conventional cultivation plot (CC-WC and CC- WB) tended to have lower TSW at all growing stages compared with those grown in direct drilled plots (DD-WC and CC-WB). The relationships between CWU and

Table 5.5 The main effects of tillage practices (T, direct drill, DD and conventional cultivation, CC) and crop rotations S, wheat-wheat, WW, faba bean-wheat, BW, canola-wheat, CW, wheat-faba bean, WB and wheat-canola, WC) affected on the average values and the least significant difference of the means of total stored soil water within 2000 mm depth, cumulative water use , dry matter, water use efficiency and crop yields in 1993

Total stored soil water, cumulative water use, crop yield and water use efficiency at different growing stages	**Days after sowing**	**Tillage practice**		**l.s.d.***	**Crop rotation system**					**l.s.d.***
		DD	**CC**	**T**	**WW**	**BW**	**CW**	**WB**	**WC**	**S**
Total stored soil water, TSW (mm)										
Tillering	**68**	522	519	ns	549	515	532	525	483	ns
Flowering	**110**	478	481	si	506	457	481	482	472	si
Ripening	**138**	466	487	si	506	447	482	488	462	si
Cumulative water use, CWU (mm) from	**38**									
Tillering	**68**	**126a**	**107b**	16	**118b**	**120b**	**100d**	**114c**	**130a**	10
Flowering	**110**	253	229	si	245	261	235	241	225	si
Ripening	**138**	340	298	si	320	346	310	310	310	si
Dry matter, DM (t-ha^{-1})										
Tillering	**76**	**3.042a**	**2.238b**	0.573	**2.040d**	**2.832b**	**2.220c**	**3.054a**	**3.045a**	0.050
Yield formation	**122**	9.762	7.164	si	7.452	8.664	8.226	10.218	7.752	si
Ripening	**138**	6.280	6.400	ns	**5.720bc**	**8.740a**	**6.800b**	**5.380c**	**5.080c**	1.321
Yields (t ha^{-1})	**163**	2.654	2.558	ns	**2.276b**	**2.836a**	**2.706a**	1.027	0.212	*
Water use efficiency, WUE (kg ha^{-1} mm^{-1})										
Tillering	**76**	20.25	17.18	si	14.35	19.28	17.69	22.13	20.56	si
Yield formation	**122**	35.89	27.98	si	28.23	30.08	31.16	40.39	30.76	si
Ripening	**138**	18.47	21.48	ns	**17.88b**	**25.30a**	**21.94ab**	**17.47b**	**16.33b**	7.43
Water use efficiency on yield (kg ha^{-1} mm^{-1})		**7.81**	**8.58**	si	**7.11**	**8.15**	**8.73**	**3.34**	**0.69**	si

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$, * : comparison is based on relative l.s.d values.

a, b, c represent differences between the means, values followed by different letters, within any row, are significantly different.

ns : is non-significant differences between different tillage practices, and among different cropping systems

si : is significant as interactive effect

Table 5.6 The Interactive effects (TxS) of tillage practices (DD and CC) and crop rotation systems (WW, BW, CW, WB and WC) affected on the average values and the least significant difference of the means of total stored soil water within 2000 mm depth, cumulative water use , dry matter, water use efficiency and crop yields in 1993.

Total stored soil water, cumulative water use, crop yield and water use efficiency at different growing stages	**Days after sowing**	**Interaction of Tillage practice and Crop rotation system (TxS)**										**l.s.d* (1) TxS**	**l.s.d* (2) TxS**
		DD					**CC**						
		WW	**BW**	**CW**	**WB**	**WC**	**WW**	**BW**	**CW**	**WB**	**WC**		
Total stored soil water, TSW (mm)													
Tillering	**68**	541	497	534	545	491	556	532	529	505	474	ns	ns
Flowering	**110**	**490a**	**410b**	**480a**	**511a**	**499a**	**522a**	**504a**	**481a**	**453ab**	**445ab**	73	70
Ripening	**138**	**478b**	**384c**	**483b**	**519a**	**467b**	**533a**	**509a**	**480b**	**457b**	**457b**	74	71
Cumulative water use, CWU (mm) from	**38**												
Tillering	**68**	120	128	119	118	143	116	111	82	109	117	ns	ns
Flowering	**110**	**255b**	**299a**	**255b**	**236bc**	**219c**	**234cd**	**223cd**	**214d**	**245c**	**230cd**	31	28
Ripening	**138**	**342b**	**400a**	**329bc**	**303c**	**326cbc**	**298c**	**293c**	**290c**	**316c**	**293c**	30	31
Dry matter, DM (t-ha^{-1})													
Tillering	**76**	2.316	3.372	2.454	3.462	3.612	1.758	2.298	1.992	2.640	2.490	ns	ns
Yield formation	**122**	**8.556c**	**8.850c**	**9.354b**	**12.822a**	**9.222b**	**6.348f**	**8.478c**	**7.098d**	**7.620a**	**6.282f**	0.340	0.360
Ripening	**138**	6.040	9.200	6.240	5.000	4.940	5.420	8.300	7.360	5.760	5.200	ns	ns
Yields (t ha^{-1})	**163**	2.200	2.989	2.600	0.917	0.206	2.172	2.683	2.817	1.133	0.217	ns	ns
Water use efficiency, WUE (kg ha^{-1} mm^{-1})													
Tillering	**76**	**15.89e**	**21.00e**	**16.94e**	**24.64ab**	**22.94b**	**12.70f**	**17.37e**	**18.59d**	**19.57d**	**17.98de**	1.66	1.77
Yield formation	**122**	**32.66de**	**28.46e**	**33.77c**	**51.08a**	**35.74b**	**23.86f**	**32.11d**	**28.39e**	**29.88e**	**25.43f**	1.594	1.626
Ripening	**138**	17.70	23.00	19.00	16.50	15.20	18.20	28.90	25.40	18.20	17.70	ns	ns
Water use efficiency on yield (kg ha^{-1} mm^{-1})		**6.43b**	**7.47b**	**7.90b**	3.03c	0.632d	**7.29b**	**9.10a**	**9.71a**	3.59c	0.74d	*	*

l.s.d* T x S are the least significant differences of the means caused by interactive effects of tillage practices and crop rotation systems for comparison at $P < 0.05$, * : comparison is based on relative l.s.d values.

(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practices respectively

a, b and c represent differences between the means, values followed by different letters, within any row are significantly different.

ns : interactive effects are not significant

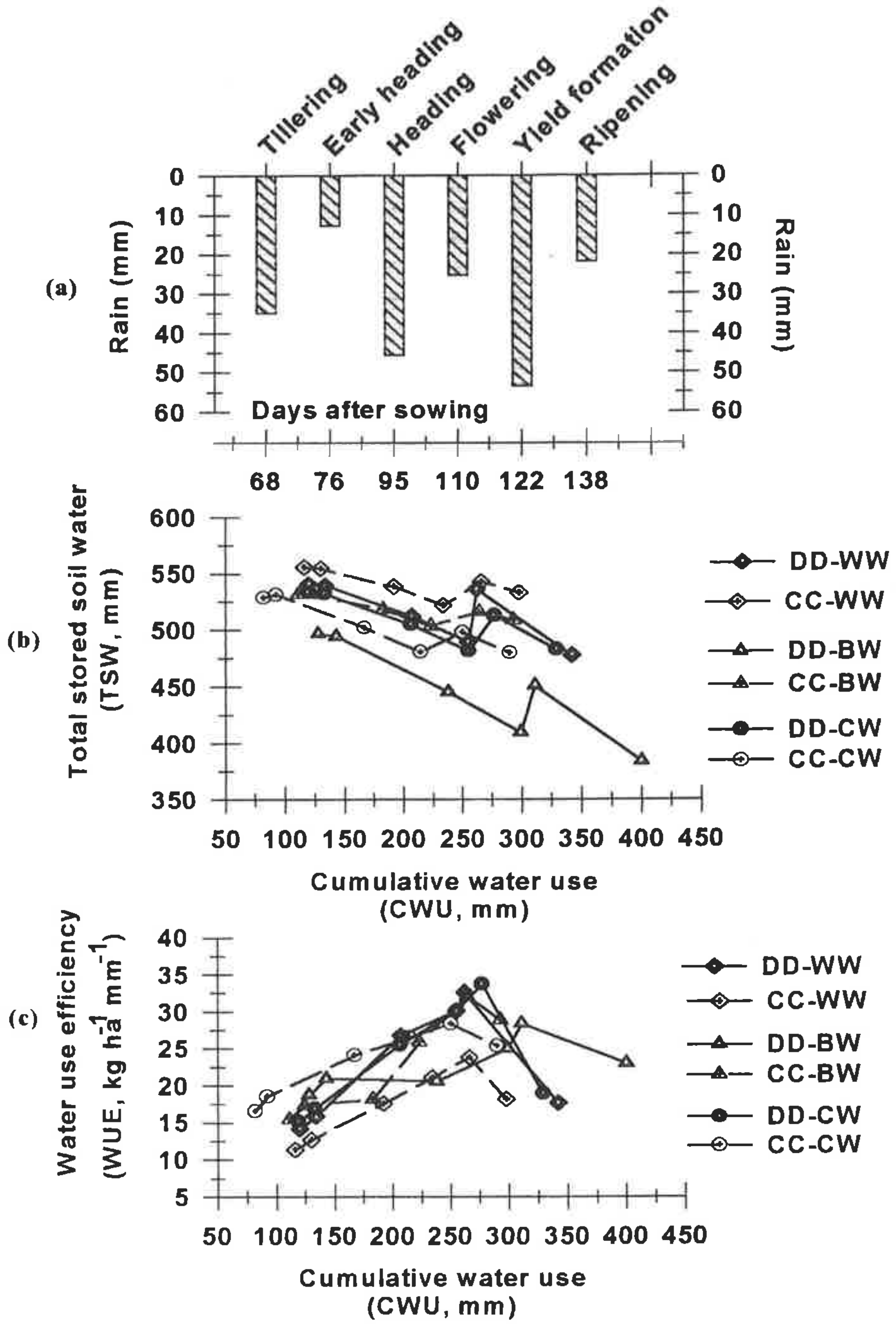


Figure 5.3 **(a)** Rainfall distribution during the main growth stages and the days after sowing on which biomass was sampled for graph (b) and (c), **(b)** total stored soil water (TSW) and **(c)** water use efficiency (WUE) as functions of cumulative water use (CWU) by wheat in different crop rotations with wheat (WW), faba bean (BW) and canola (CW) sown using either direct drilling (DD) or conventional cultivation (CC) in 1993. The x axes of each of the graphs correspond to each other.

The relationships between CWU and TSW, CWU and WUE, and CWU and DM of wheat as influenced by tillage practices and crop rotation systems are presented in Figure 5.3 and 5.4 respectively.

In general, Figure 5.3 shows that total stored soil water decreased with increasing cumulative water use of the crop from tillering (68 days) to flowering (110 days) (b) because of the low rainfall (a). This caused relatively inefficient use of soil water (c) because the crop was stressed as total stored soil water was close to or below the wilting point of 427 mm (b). However, favourable rainfall occurred during flowering to yield formation (53 mm rainfall during 12 days), and total stored soil water increased. Water use efficiency responded before again declining as this water was used by the crop.

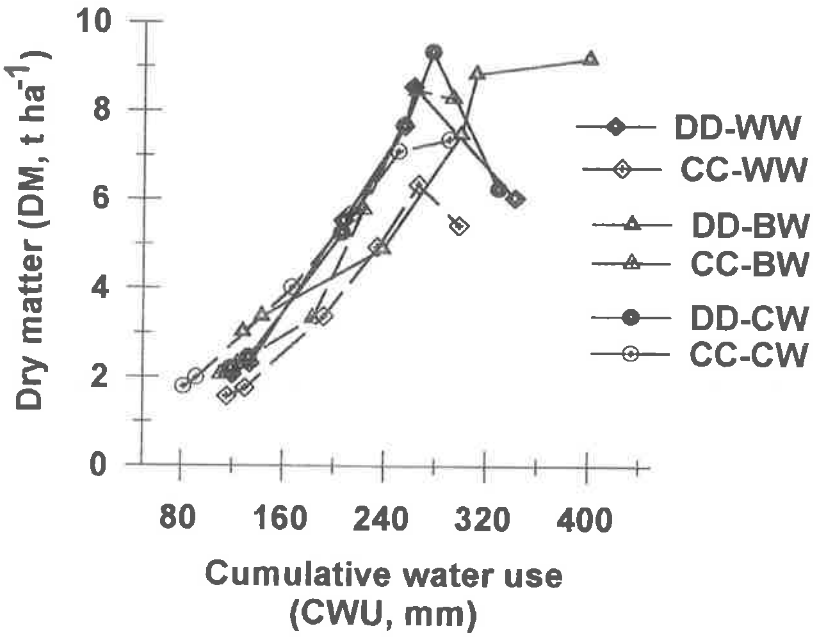


Figure 5.4 The relationship between cumulative dry matter production (DM) and cumulative water use (CWU) of wheat sown after wheat (WW), after faba bean (BW), and after canola (CW) by direct drilling (DD) or conventional cultivation (CC) in 1993.

Figure 5.4 shows water use efficiency (slope of the graph) was the highest during flowering to yield formation. Cumulative water use varied from 250 mm in CC-CW to 311 mm in DD-BW during the highest dry matter production of wheat which varied from 6.36 t ha^{-1} in CC-WW to 9.35 t ha^{-1} in DD-CW. Dry matter decreased during ripening (the last coordinate or the largest CWU) because leaf senescence had set in except for DD-BW. This resulted in DD-BW having the highest dry matter production at ripening compared with the other wheat rotations.

Furthermore, the lowest total stored soil water was under DD-BW due to this treatment having the highest cumulative water use (CWU) from flowering to ripening (110 to 138 days after sowing) as shown in Figure 5.3 (b). This tended to favour higher dry matter production (Figure 5.4) and higher grain yield (Figure 5.5 a). However, DD-BW did not give the highest water use efficiency during heading to yield formation (95 to 122 days) compared to DD-WW and DD-CW, and had lower WUE than CC-BW (Figure 5.3 c). This might have been caused by a rapid depletion of soil water during flowering, the most sensitive growth period of wheat. However, DD-BW produced the highest yield (2.99 t ha^{-1}) compared with the other rotations and conventional cultivation (Figure 5.5 a). On the other hand, every crop rotation sown by conventional cultivation (CC-WW, CC-BW, CC-CW, CC-WB and CC-WC) tended to give higher grain yield water use efficiency (WUE) compared with that sown by direct drilling (DD-WW, DD-BW, DD-CW, DD-WB and DD-WC) (Figure 5.5 b).

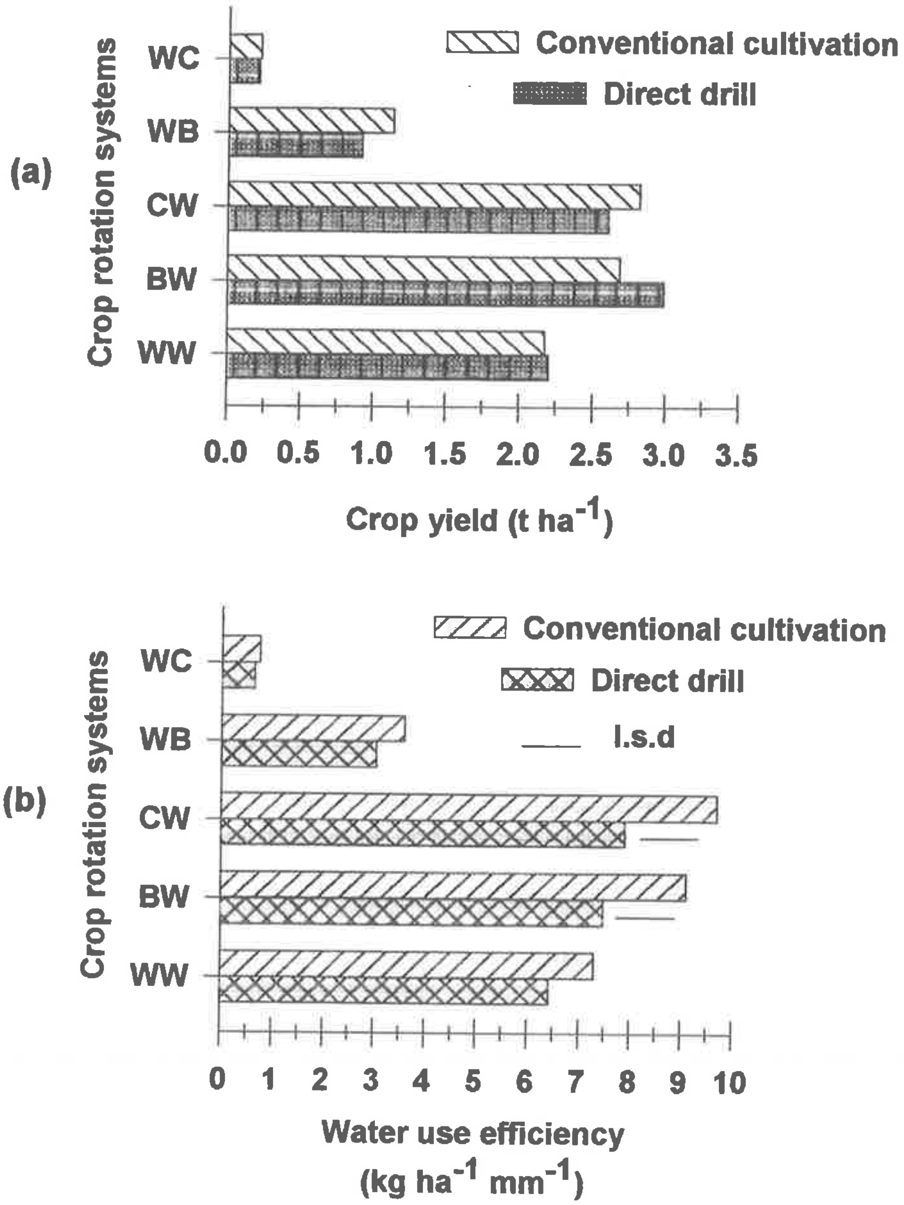


Figure 5.5 The effects of direct drilling and conventional cultivation on **(a)** crop grain yields and **(b)** grain yield water use efficiency of wheat (W), faba bean (B) and canola (C) grown as rotations of WW, BW, CW, WB and WC in 1993. Significance levels are shown in Table 5.5.

5.3.4 Water use and crop production in 1994

In 1994, tillage treatments (T) created significant differences in cumulative water use (CWU) at all growing stages (Table 5.1). Both tillage practices (T) and crop rotations (S) significantly affected cumulative dry matter (DM), crop yields and water use efficiency (WUE) at every stage of crop growth in 1994 (Table 5.2).

Table 5.7 shows that crops sown by direct drilling (DD) although they used more water (larger cumulative water use), they also produced more dry matter and had higher average yields. This resulted in higher efficiency of water use than conventional cultivation (CC) treatments at every stage of crop growth from seedling to harvesting. Different crop rotation systems did not show differences in total stored soil water (TSW) or cumulative water use (CWU). Crop rotations did show differences in dry matter, yields and water use efficiency at every stage of crop growth. However, the differences tended to be caused by differences in crop phenology. Canola appeared to be very sensitive to water stress and establishment was poor due to exceptionally low rainfall after seeding (Figure 5.6). As a result, BWC gave the lowest dry matter and water use efficiency in all growing stages compared with other crop rotations. Faba bean produced the largest mass of dry matter at tillering and gave lower dry matter than wheat after tillering to maturity. This resulted in lower dry matter water use efficiency at ripening in the CWB treatment than in any other wheat rotations (Table 5.7). WWW, WBW and WCW showed no significant differences in either dry matter or water use efficiency at any growing stage in 1994 (Table 5.7).

Table 5.7 The main effects of tillage practices (T, direct drill, DD and conventional cultivation, CC) and crop rotation systems (S, wheat-wheat-wheat, WWW, wheat-faba bean-wheat, WBW, wheat-canola- wheat, WCW,canola-wheat-faba bean, CWB and faba bean- wheat-canola, BWC) on the average values and least significant differences (l.s.d) of the means of total stored soil water within 2000 mm depth and cumulative water use, dry matter and crop yields in 1994.

Total stored soil water and cumulative water use at different stages of crop growth	**Days after sowing**	**Tillage practice**		**l.s.d.***	**Crop rotation system**					**l.s.d ***
		DD	**CC**	**T**	**WWW**	**WBW**	**WCW**	**CWB**	**BWC**	**S**
Total stored soil water, TSW (mm)										
Tillering	**75**	570	566	ns	615	565	563	584	514	ns
Flowering	**100**	533	528	ns	573	531	529	544	475	ns
Ripening	**138**	520	508	ns	557	516	513	522	462	ns
Cumulative water use, CWU from sowing (mm)										
Tillering	**75**	**117a**	**96b**	16	109	116	107	102	100	ns
Flowering	**100**	**186a**	**166b**	13	183	181	173	173	170	ns
Ripening	**138**	**230a**	**217b**	10	229	227	220	227	215	ns
Dry matter , DM (t-ha^{-1})										
Tillering	**63**	1.48	1.24	ns	**1.10a**	**1.38a**	**1.30a**	**1.97b**	**1.03ac**	0.360
Flowering	**100**	**3.61a**	**2.62b**	0.077	**3.57a**	**3.84a**	**3.44a**	**3.28a**	**1.46b**	0.69
Ripening	**138**	**3.07a**	**2.35b**	0.053	**3.82a**	**3.12a**	**3.37a**	**1.95b**	**1.31b**	0.710
Yields (t ha^{-1})	**155**	**0.675a**	**0.583b**	*	**0.974a**	**0.558b**	**0.854ab**	0.458c	0.277d	*
Water use efficiency, WUE (kg ha^{-1} mm^{-1})										
Tillering	**87**	**22.65a**	**18.82b**	1.34	**21.64a**	**24.50a**	**23.55a**	**20.65a**	**13.33b**	6.60
Flowering	**100**	**19.71a**	**15.74b**	3.26	**19.85a**	**21.30a**	**19.91a**	**18.91a**	**8.65b**	6.52
Ripening	**138**	**13.46a**	**10.83b**	2.64	**16.96a**	**13.76a**	**15.26a**	**8.67b**	**6.08b**	5.20
Water use efficiency on yield (kg ha^{-1} mm^{-1})		**2.93a**	**2.59b**	*	**4.18a**	**2.43a**	**3.88a**	2.019c	1.291d	*

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$, * : comparison is based on relative l.s.d values.

a, b, c represent differences between the means, values followed by different letters, within any row, are significantly different.

ns : non-significant differences between different tillage practices, and among different cropping systems

Table 5.8 The Interactive effects (TxS) of tillage practices (DD and CC) and crop rotation systems (WWW,WBW, WCW, CWB and BWC) on the average values and the least significant difference of the means of total stored soil water within 2000 mm depth, cumulative water use, dry matter and crop yields during growing season in 1994.

Total stored soil water and cumulative water use at different stages of crop growth	Days after sowing	Interaction of Tillage practices and Crop rotation systems, $(TxS)^{ns}$ DD WWW	WBW	WCW	CWB	BWC	CC WWW	WBW	WCW	CWB	BWC
Total stored soil water, TSW (mm)											
Tillering	75	606	585	586	578	497	623	544	540	591	531
Flowering	100	574	548	551	539	452	570	513	506	551	498
Ripening	138	561	538	536	527	437	552	493	489	517	486
Cumulative water use, CWU (mm) from sowing											
Tillering	75	124	121	112	120	109	95	111	102	84	90
Flowering	100	186	189	178	190	185	179	172	167	156	154
Ripening	138	231	230	225	233	232	228	224	216	220	197
Dry matter, DM ($t\ ha^{-1}$)											
Tillering	63	1.38	1.43	1.30	2.20	1.09	0.83	1.32	1.30	1.74	0.98
Flowering	100	4.20	4.20	3.95	4.05	1.67	2.95	3.48	2.93	2.52	1.24
Yield formation and grain filling	114	4.81	4.19	3.70	4.32	1.65	3.62	3.44	3.61	2.44	1.21
Ripening	138	4.12	3.36	3.98	2.35	1.53	3.51	2.88	2.75	1.54	1.09
Yields ($t\ ha^{-1}$)	155	0.913	0.689	0.879	0.562	0.332	1.035	0.426	0.876	0.354	0.222
Water use efficiency, WUE ($kg\ ha^{-1}\ mm^{-1}$)											
Tillering	87	26.94	25.79	26.14	20.56	13.85	16.35	23.20	20.96	20.75	12.81
Flowering	100	23.07	22.41	22.35	21.43	9.27	16.63	20.19	17.47	16.39	8.02
Yield formation and grain filling	114	24.84	21.24	19.79	21.18	8.69	19.05	18.87	21.15	14.03	7.43
Ripening	138	18.82	14.53	17.82	10.09	6.65	15.69	12.98	12.70	7.26	5.50
Water use efficiency on yield ($kg\ ha^{-1}\ mm^{-1}$)		4.032	2.965	3.786	2.412	1.431	4.360	1.899	3.970	1.609	1.130

$(TxS)^{ns}$: all interaction effects are not significant at $P < 0.05$

The 1994 rainfall during the crop growth stages is presented as a function of time after sowing in Figure 5.6. These data are related in this figure to total stored water and dry matter water use efficiency as functions of cumulative water use as influenced by tillage practices (DD and CC) and crop rotations (WWW, WBW and WCW) from seeding to harvesting. Figure 5.7 shows a similar relationship for dry matter production.

Figure 5.6 (a) shows that rainfall and consequently soil water reserves were adequate at seeding, but a decline in rainfall for most of the pre-heading period resulting in a decline in total stored soil water (TSW) (Figure 5.6 b) due to the increasing cumulative water use associated with the high crop water requirement during the vegetative period. This caused an increase in dry matter water use efficiency during the seeding to heading stage (Figure 5.6 c). During early heading (75 days after sowing) to heading (87 days) the crop was severely stressed due to the high evaporative demand resulting in a drop of in the rate of dry matter production (Figure 5.7) and consequently decreased dry mater water use efficiency (Figure 5.6 c).

Rain fell (35 mm) over a period of 13 days between heading and flowering (Figure 5.6a). Total stored soil water was not increased by detectable amounts (Figure 5.6b), but crop growth recovered (figure 5.7) and water use efficiency rose slightly at this time (Figure 5.6c). Thereafter, as the crop proceeded into grain production and ripening, dry matter water use efficiency declined as expected.

Crops sown by direct drilling tended to have higher dry matter water use efficiency during heading to ripening compared to crops sown by conventional cultivation (Figure 5.6 c), because of higher dry matter production in DD than in CC plots (Figure 5.7).

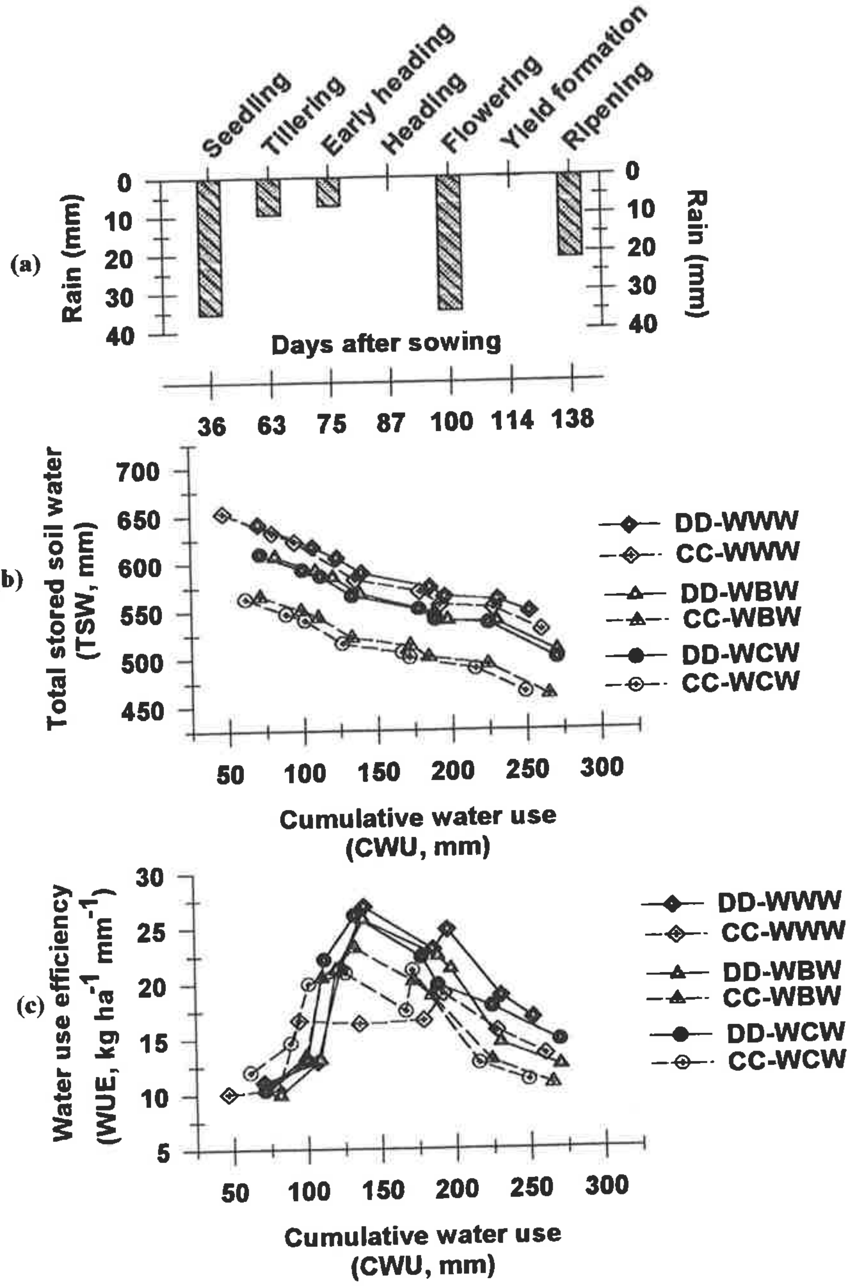


Figure 5.6 The influence of **(a)** rainfall distribution during growth stages on the relationships between **(b)** total stored soil water (TSW) and cumulative water use (CWU) and **(c)** water use efficiency (WUE) and cumulative water use (CWU) of wheat sown as wheat after wheat,(WWW), wheat after faba bean (WBW) and wheat after canola (WCW) using either direct drilling (DD) or conventional cultivation (CC) in 1994. The x axes of all graphs correspond to each other. Days after sowing correspond to the sequent coordinate along the cumulative water use.

Generally, in 1994 total stored soil water decreased rapidly from sowing to ripening due to the very low rainfall (110 mm) and high crop water requirement under high evaporative demand (data is presented in Chapter 7), resulting in low biomass production (≤ 5.0 t ha^{-1}).

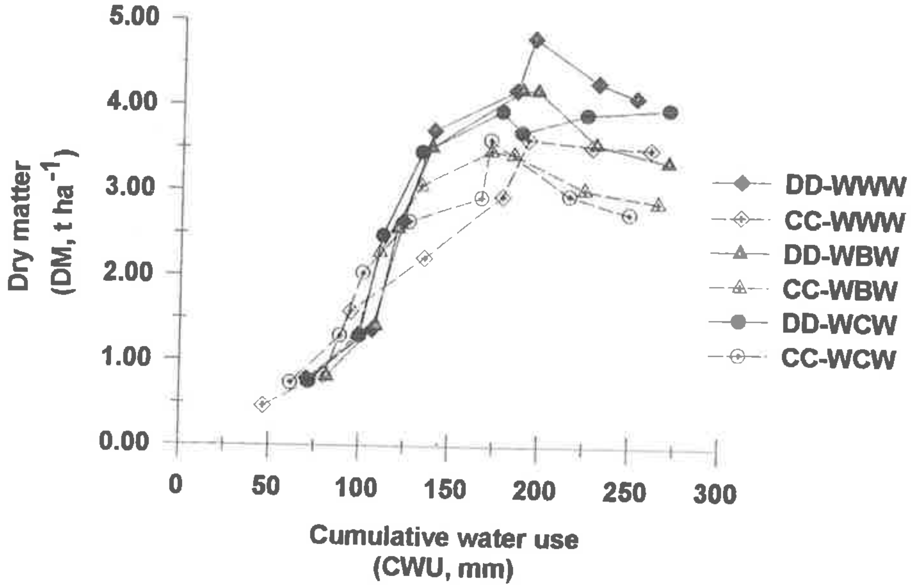


Figure 5.7 The relationships between cumulative dry matter production and cumulative water use (CWU) of wheat sown as wheat after wheat,(WWW), wheat after faba bean (WBW) and wheat after canola (WCW) sown by direct drilling (DD) or conventional cultivation (CC) in 1994.

The higher dry matter production and the higher dry matter water use efficiency (slopes of the graph shown in Figure 5.7) in the direct drilled crops compared to the conventionally cultivated crops, did not translate into superior grain yields. Presumably this was because of the limitations of the reduced 1994 rainfall (Table 5.8 and Figure 5.8).

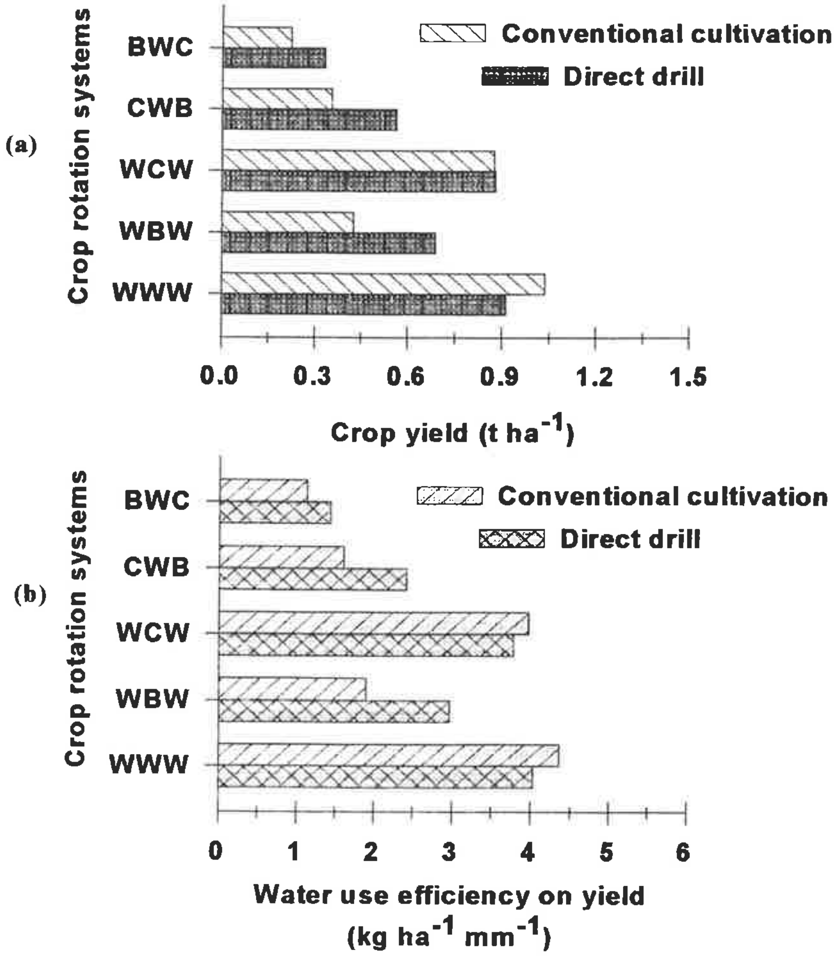


Figure 5.8 The 1994 effects of direct drilling and conventional cultivation on **(a)** crop yields and **(b)** water use efficiency on yield, of wheat (W), faba bean (B) and canola (C) grown in rotations of WWW, WBW, WCW, CWB and BWC from 1992 to 1994.

The effects of crop rotations on water use efficiency in grain production presented in Figure 5.8 shows that WBW, although not significant, gave lower water use efficiency and lower wheat yield than WWW or WCW. This was probably caused by greater cumulative water use with a smaller dry matter production which resulted in a lower dry matter water use efficiency during flowering to yield formation (Figure 5.6). This caused greater stress at flowering and less water was left for grain filling than in WWW or WCW rotations. However, although not significant, direct drilling, as in 1993, again tended to give higher grain yields and higher grain water use efficiency compared to the conventional cultivation.

5.3.5 Water use and crop production in 1995

Climatic conditions in 1995 were less extreme. Total stored soil water (TSW) and cumulative water use (CWU) were hardly influenced by the tillage or rotation treatments (Table 5.1). However, dry matter (DM), grain yields and water use efficiency (WUE) at all stages of crop growth were significantly influenced by both tillage and rotations and these treatments showed strong interactions in 1995 as shown in Table 5.2.

Table 5.9 shows that wheat following canola, BWCW used more water (CWU of 99 mm) only at tillering than the other crop rotations. No differences in CWU were observed in the later growing stage. This result was possibly caused by better crop development at tillering (DM 1.364 t ha^{-1}) due to higher amounts of nutrients left from the 1994 season compared with the other crop rotations, because canola did not grow well and failed to fully exploit fertiliser applied in 1994. This is evidenced by nitrogen in BWCW which was higher than in the other treatments at seeding in 1995 (Chapter 4).

The interactive effects of tillage practices and crop rotation systems show that crop rotations WWWW, CWBW and WCWC sown by conventional cultivation used more water (higher CWU) while CWBW sown by direct drilling used less water (lowest CWU) at flowering compared with the other treatments (Table 5.10).

Table 5.9 The main effects of tillage practices (T, direct drill,DD and conventional cultivation,CC) and crop rotation systems (S, wheat-wheat- wheat-wheat, W WWW, faba bean-wheat-canola-wheat, BWCW, canola-wheat-faba bean-wheat, CWBW, wheat-faba bean-wheat-canola, WBWC and wheat-canola- wheat-canola, WCWC on the average values and least significant differences (l.s.d) of the means of total stored soil water (2000 mm depth), cumulative water use, dry matter and crop yields in 1995.

Total stored soil water and cumulative water use at different stages of crop growth (mm)	Days after sowing	Tillage practices		l.s.d *	crop rotation systems					l.s.d *
		DD	CC	T	WWWW	BWCW	CWBW	WBWC	WCWC	S
Total stored soil water, TSW (mm)										
Tillering	58	590	593	ns	631	544	574	603	605	ns
Flowering	97	541	521	ns	563	498	525	531	537	ns
Ripening	140	516	501	ns	545	489	500	507	501	ns
Cumulative water use, CWU (mm)										
Tillering	58	82	82	ns	**80bc**	**99a**	**82b**	**74c**	**74c**	7
Flowering	97	200	222	si	216	214	200	214	211	si
Ripening	140	243	264	ns	256	247	246	254	263	ns
Dry matter, DM (t ha^{-1})										
Tillering	66	1.046	1.079	si	0.918	1.364	0.912	1.036	0.664	si
Flowering	97	3.992	3.833	si	4.503	4.402	4.157	3.049	2.095	si
Ripening	140	6.802	6.335	si	8.030	7.420	6.540	4.380	3.390	si
Yields (grain or seed , t ha^{-1})	146	2.544	2.226	si	3.566	3.121	2.939	0.945	0.775	si
Water use efficiency, WUE (kg ha^{-1} mm^{-1})					20.85	20.57	20.79	14.25	9.93	
Tillering	58	11.16	9.74	si	10.10	12.13	9.73	12.37	7.91	si
Flowering	97	20.30	14.84	si	20.99	20.51	21.74	14.22	10.39	si
Ripening	140	28.35	19.56	si	31.65	30.05	27.63	17.19	13.26	si
Water use efficiency on yield (kg ha^{-1} mm^{-1})		10.71	7.61		14.04	12.63	12.36	3.71	3.04	si

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at $P < 0.05$, * : comparison is based on relative l.s.d values.

a, b, c represent differences between the means, values followed by different letters, with any row, are significantly different.

ns : non-significant differences between different tillage practices, and among different cropping systems , si : significant as interactive effect

Table 5.10 **The Interactive effects (TxS) of tillage practices (DD and CC) and crop rotation systems (WWWW, BWCW, CWBW, WBWC and CWCW) affected on the average values and the least significant difference of the means of total stored soil water (2000 mm depth) , cumulative water use, dry matter and crop yields during growing season in 1995.**

Total stored soil water and cumulative water use at different stages of crop growth	**Days after sowing**	**Interaction of Tillage practices and Crop rotation systems**										**l.s.d* (1) TxS**	**l.s.d* (2) TxS**
		DD					CC						
		WWWW	BWCW	CWBW	WBWC	WCWC	WWWW	BWCW	CWBW	WBWC	WCWC		
Total stored soil water, TSW (mm)													
Tillering	58	625	513	542	620	649	637	576	606	587	560	ns	ns
Flowering	97	569	474	520	545	595	557	521	530	518	479	ns	ns
Ripening	140	551	460	500	511	557	538	518	499	504	446	ns	ns
Cumulative water use, CWU (mm)													
Tillering	58	77	105	84	72	73	83	93	81	75	76	ns	ns
Flowering	97	201bc	212ab	174c	216ab	195b	231a	217ab	225a	212ab	226a	33	24
Ripening	140	239	250	217	260	249	273	244	276	247	277	ns	ns
Dry matter, DM (t ha^{-1})													
Tillering	66	0.911bcd	1.392a	1.100b	0.990bc	0.834d	0.924c	1.336a	0.725d	1.083b	0.494e	0.138	0.150
Flowering	97	4.219a	2.886c	4.470a	3.121bc	3.407bc	3.941b	4.778a	3.015b	2.674b	0.973d	0.702	0.660
Ripening	140	8.670a	7.000b	7.900b	5.250c	5.190c	7.390ab	7.840ab	5.180c	3.510d	1.580c	1.369	1.424
Yields (t ha^{-1})	146	3.815a	3.104a	3.441a	1.143a	1.216a	3.317ab	3.137ab	2.437b	0.748c	0.333d	*	*
Water use efficiency, WUE (kg ha^{-1} mm^{-1})													
Tillering	58	10.40b	11.68ab	11.57a	12.03b	10.11bc	9.81c	12.57b	7.89cd	12.71b	5.70d	7.45	7.88
Flowering	97	23.00b	17.69c	28.96a	15.48c	16.38c	18.98b	23.32b	14.53d	12.96d	4.39e	6.52	5.36
Ripening	140	36.26a	28.00b	36.49b	20.18c	20.82c	27.03b	32.10a	18.77c	14.20d	5.70e	7.07	7.40
Water use efficiency on yield (kg ha^{-1} mm^{-1})		15.95a	12.42ab	15.89a	4.39d	4.88c	12.13b	12.85a	8.83b	3.03cd	1.20d	*	*

l.s.d* T x S are the least significant differences of the means caused by interactive effects of tillage practices and crop rotation systems for comparison at $P < 0.05$. * : comparison is based on relative l.s.d values.

(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practices

a, b, c represent differences between the means, values followed by different letters, with any row, are significantly different. ns ; interactive effects are not significant

The 1995 rainfall during the crop growth stages is presented as a function of time after sowing in Figure 5.9. These data are related to total stored water and dry matter water use efficiency as functions of cumulative water use as influenced by tillage practices (DD and CC) and crop rotations (WWWW, WBWW and CWBW) from seeding to harvesting. Figure 5.10 shows a similar relationship for dry matter production.

Figure 5.9 shows that total stored soil water decreased steadily with cumulative water use by wheat from sowing to ripening (Figure 5.9 b). However, distribution of rainfall over the sensitive crop growth period from early heading (78 days) to flowering (110 days) was uniform (Figure 5.9 a), resulting in the development of significant differences in water use efficiency between treatments as shown in Figure 5.9 c. Although TSW depletions were similar among all treatments (Figure 5.9 b), continuous wheat (WWWW) and wheat after faba bean (CWBW) sown by direct drilling gave better biomass water use efficiency (Figure 5.9 c) because of higher dry matter production compared to these crops sown by conventional cultivation. (Figure 5.10). However, wheat following canola (BWCW) sown by direct drilling had lower WUE and lower dry matter production compared to BWCW sown by conventional cultivation (Figures 5.9 and 5.10).

Generally, the crops suffered little moisture stress through the 1995 growing season because there was better distribution of rainfall compared to the 1993 and 1994 seasons and therfore sufficient soil water. Total stored water (TSW) did not approach wilting point levels until late in the growing season. This resulted in significant interactive effects between tillage practices and crop rotations on yield and grain water use efficiency (Figure 5.11).

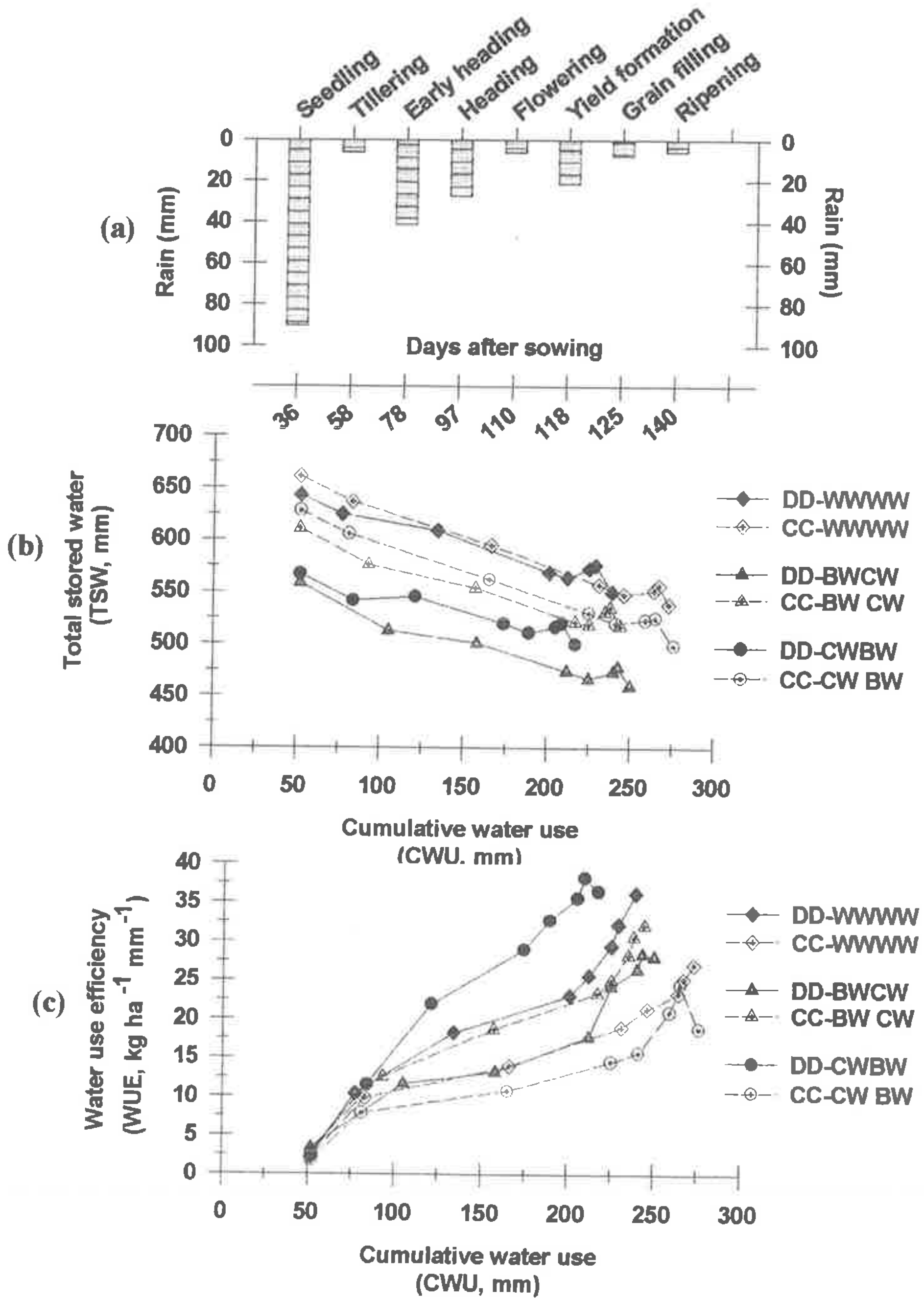


Figure 5.9 The influences of **(a)** rainfall distribution during crop growth stages on the relationships between **(b)** total stored soil water (TSW) and cumulative water use (CWU) and **(c)** water use efficiency (WUE) and cumulative water use (CWU) of wheat sown as wheat after, wheat (WWWW), faba bean (CWBW), and canola (BWCW) using direct drilling (DD) or conventional cultivation (CC) 1995. The x axes of all graphs correspond to each other. Days after sowing correspond to the sequent coordinate along the cumulative water use.

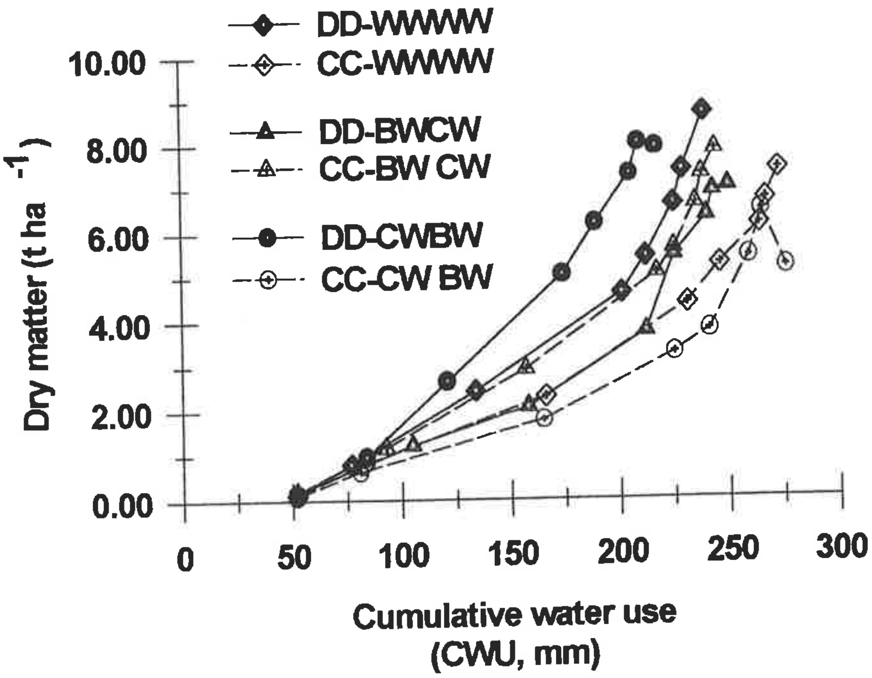


Figure 5.10 The relationships between cumulative water use (CWU) and cumulative dry matter production of wheat grown in the continuous wheat rotation (WWWW), wheat in canola - faba bean rotations (CWBW) and (BWCW) sown by direct drilling (DD) and conventional cultivation (CC) in 1995.

Figure 5.11 indicates that direct drilling of crops tended to give higher grain yields (Figure 5.11 a) and higher grain water use efficiency (Figure 5.11 b) than conventionally cultivated wheat, faba bean and canola in the rotations WWWW, CWBW, WBWC and WCWC. Wheat sown by direct drilling after canola gave a similar yield to that sown by conventional cultivation.

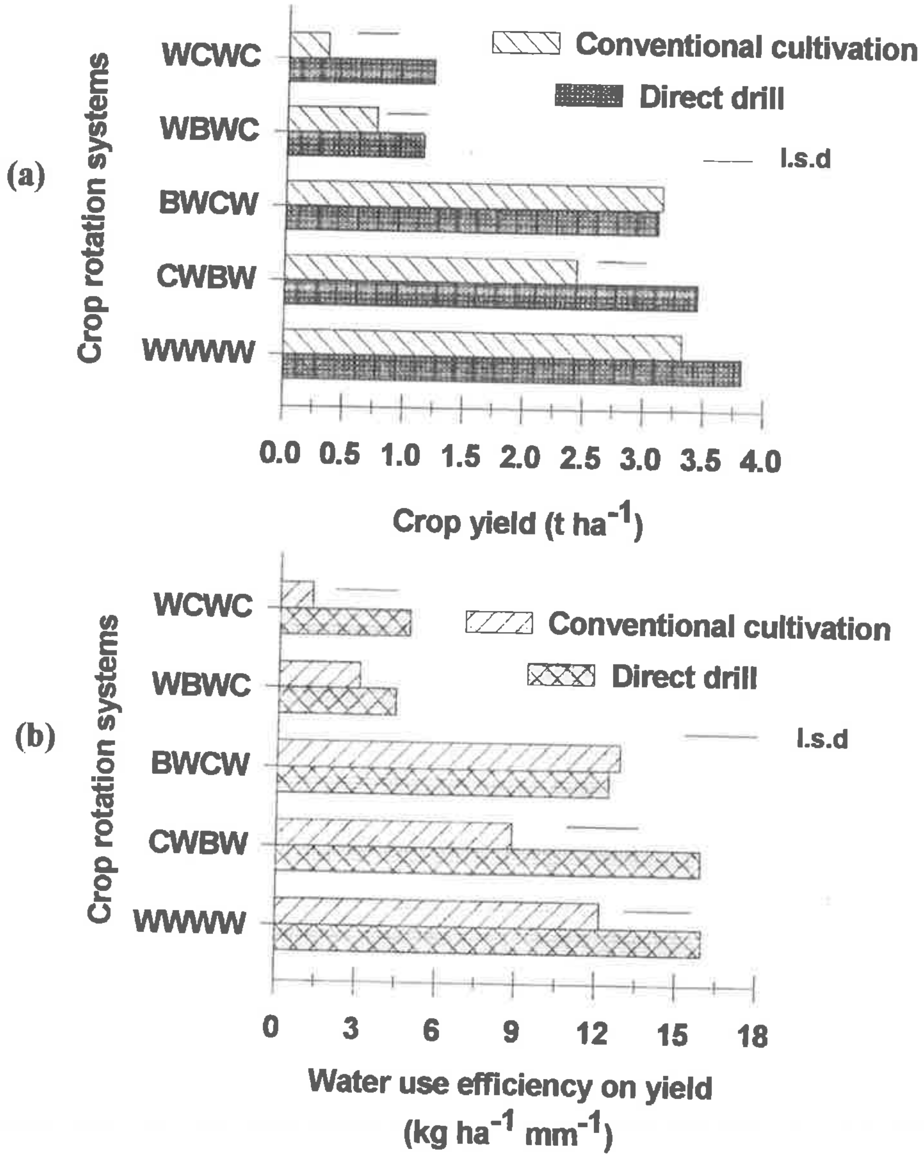


Figure 5.11 The 1995 effects of direct drilling or conventional cultivation on **(a)** crop yields and **(b)** grain water use efficiency of wheat (W), faba bean (B) and canola (C) grown in rotations of WWWW, CWBW, BWCW, WBWC and WCWC. from 1992 to 1995.

5.3.6 Crop water use from 1992 to 1995

Direct drilling and conventional cultivation of wheat, faba bean and canola grown in various rotations influenced total stored water, cumulative water use, dry matter, crop yield and water use efficiency differently from year to year over the period from 1992 to 1995. Interaction between tillage and crop rotations on TSW, CWU, WUE, DM and grain yield was significant in climatically moderate years (1993 and 1995) but not significant in exceptionally wet or dry years (1992 and 1994 respectively). These significant interactions were caused by the responses of different soil structural conditions to variations of climatic conditions, particularly differences in rainfall distribution over the 4 years of experimentation.

This section will focus on the effects of direct drilling and conventional cultivation on water use and grain yield of wheat in continuous rotations (W, WW, WWW and WWWW) for 1992 to 1995 respectively. The emphasis in this thesis is on wheat production and these rotations provide unambiguous insights into the effects of tillage on wheat growth and yield. In addition the effects of crop rotations involving wheat only in 1995 were compared using only direct drilling results. The factors used in these comparisons are cumulative water use (CWU) and total stored soil water (TSW), cumulative rain (CR) and cumulative dry matter (CDM), cumulative dry matter (CDM) and water use efficiency (WUE), and dry matter and yield (Figures 5.12, to 5.18 respectively).

5.3.6.1 The effects of direct drilling and conventional cultivation on the relationships between stored soil water, rainfall and water use efficiency

Figure 5.12a shows that in a wet year like 1992, the change in total stored soil water with crop water use was small except for example, in a dry period after flowering to grain filling (Figure 5.1a). Water use by the wheat crops significantly reduced the amount of total stored soil water at some stages of crop growth in 1993 to 1995 when rainfall was limited.

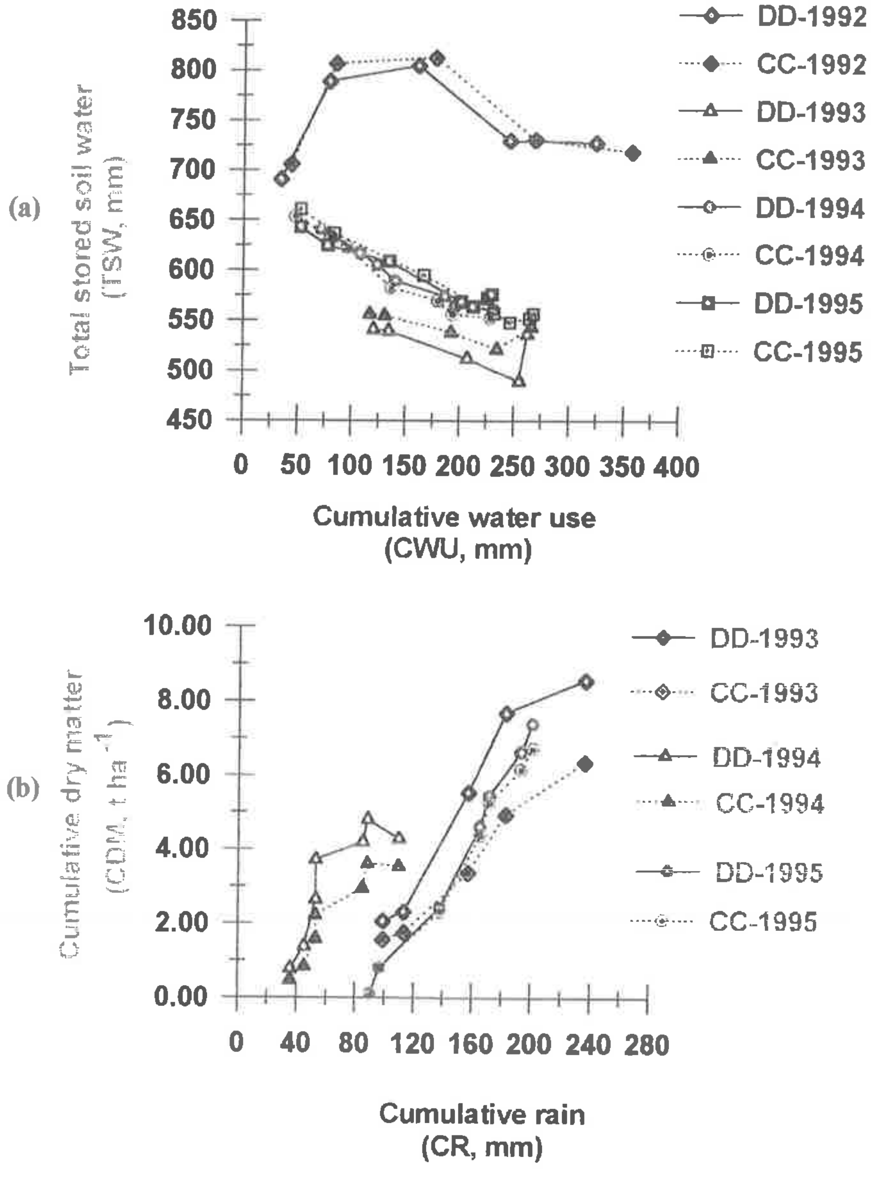


Figure 5.12 The relationship between **(a)** cumulative water use and total stored soil water and **(b)** cumulative rainfall and cumulative dry matter production of wheat sown by direct drilling (DD) or conventional cultivation (CC) in continuous rotations of W, WW, WWW and WWWW between 1992 and 1995 respectively.

In 1993 total stored soil water was the lowest compared with other years (Figure 5.12 a). This was caused by the high evaporative demand and reduced rainfall during the early growing stage (from post tillering to early heading) in 1993. Biomass production was dependent on rainfall as shown by Figure 5.12b. This figure shows that changes in stored water were very similar in 1993 and 1995, whereas dry matter production was very different in these years.

Figure 5.13 shows that direct drilling of wheat resulted in higher cumulative dry matter production compared to conventional cultivation during every year from 1993 to 1995. Results from the particularly dry years, 1993 and 1994, showed significantly greater biomass production in DD compared to CC treatments. The cumulative dry matter produced by the same amount of cumulative water use from seeding to ripening was the highest in 1995 and the lowest in 1994.

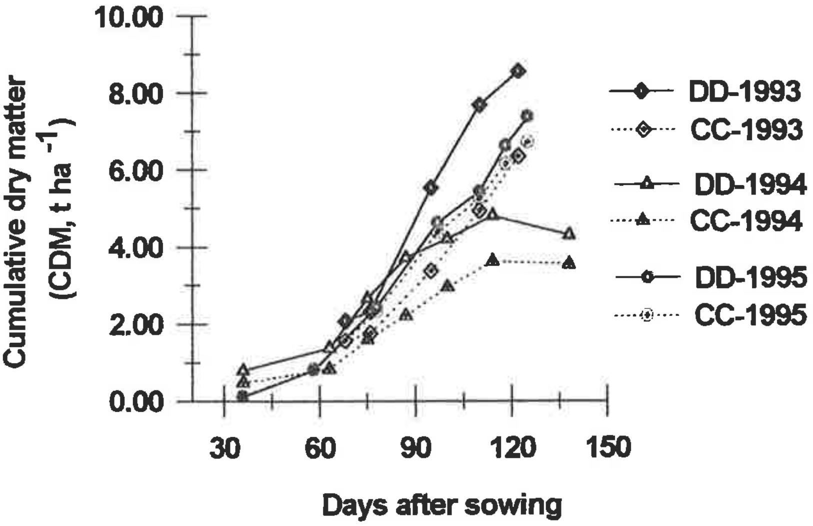


Figure 5.13 Cumulative dry matter production of wheat, from tillering to maturity, sown by direct drilling (DD) or conventional cultivation (CC) in continuous rotations of WW, WWW, WWWW in 1993, 1994 and 1995 respectively.

In direct drilled wheat, dry matter produced per unit of water used was higher than in conventional cultivated wheat plots during every experimental year. This means that direct drilling caused higher water use efficiency for dry matter production during tillering to maturity than conventional cultivation (Figures 5.14 and 5.15).

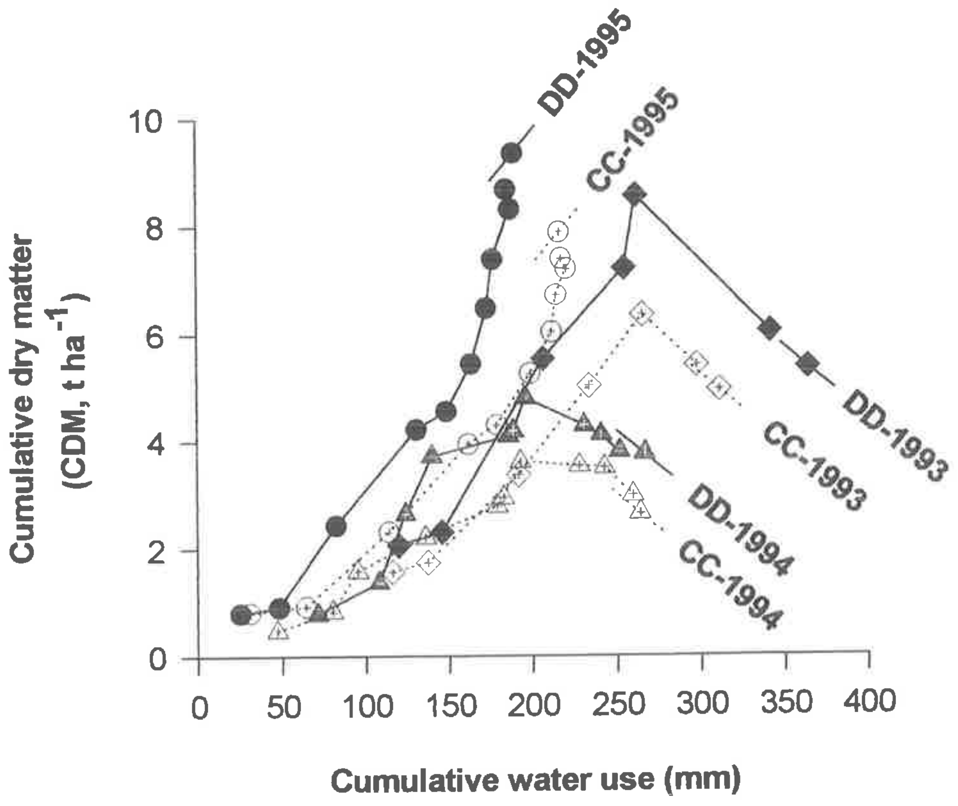


Figure 5.14 The relationship between cumulative dry matter production and cumulative water use of wheat, from seeding to ripening, sown by direct drilling (DD) or conventional cultivation (CC) in continuous rotations of WW, WWW, WWWW in 1993, 1994 and 1995 respectively.

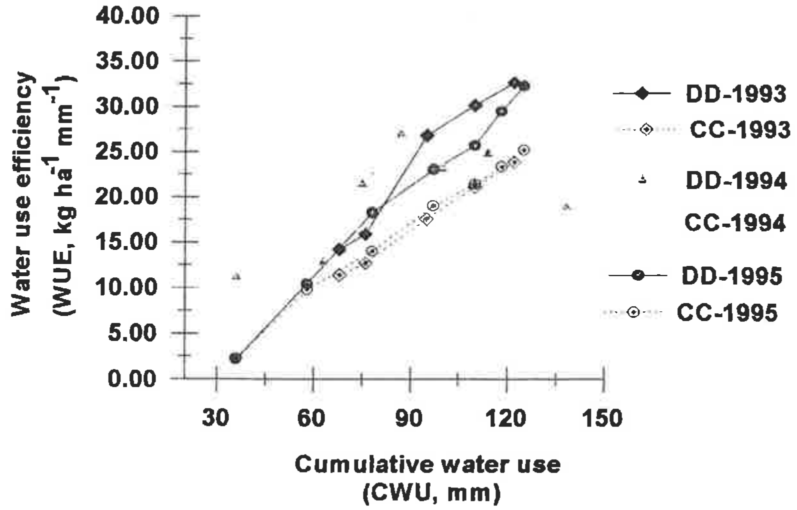


Figure 5.15 The relationships between dry matter water use efficiency and cumulative water use of wheat sown by direct drilling (DD) or conventional cultivation (CC) in continuous rotations of WW, WWW, WWWW in 1993, 1994 and 1995 respectively.

5.3.6.2 The effects of crop rotations on the relationships between stored soil water, rainfall and water use efficiency

Different crops and rotations gave different amounts of total stored soil water as shown in Figure 5.16 a. In 1992, wheat tended to use the least stored water during flowering to ripening. Faba bean used more of the stored soil water, leaving the least water within the soil profile compared with other crops.

In 1993 the depletion of stored soil water by wheat after wheat was similar to that of either wheat after faba bean or wheat after canola. The rate of stored soil water reduction in 1993 was approximately similar to that obtained in 1994 and in 1995 as shown by Figure 5.16 a. However, the differences in total stored water became significant during flowering to maturity or ripening because this is the critical period of crop growth.

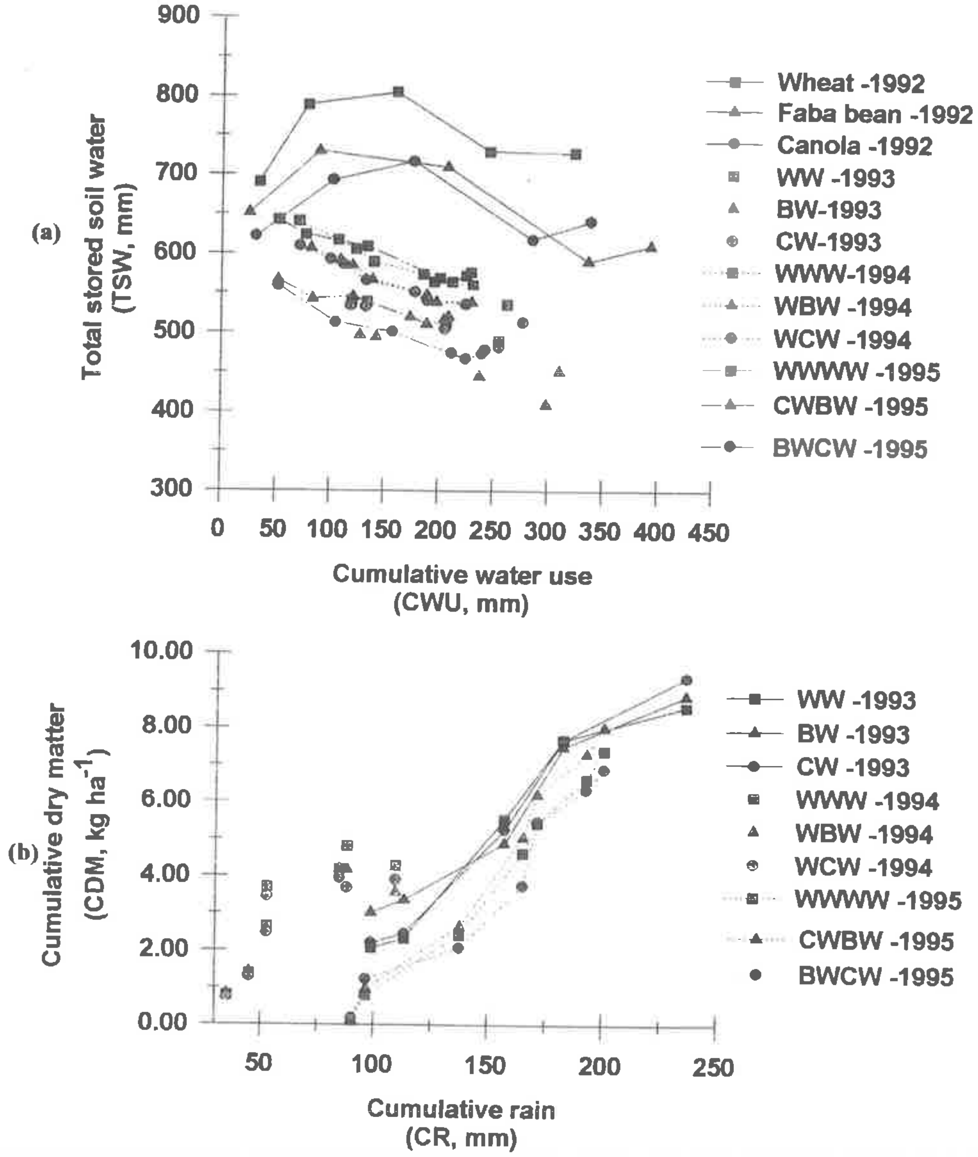


Figure 5.16 The relationship between **(a)** cumulative water use and total stored soil water, and **(b)** cumulative rain and cumulative dry matter of wheat sown by direct drilling in rotations with wheat (-WW), with faba bean (-BW) and with canola (-CW) from 1992 to 1995 respectively.

The biomass production of wheat grown in different rotations in 1993, 1994 and 1995 were dependent on rainfall rather than total stored water as shown by Figure 5.16 (b). The lowest seasonal rainfall in 1994 gave the lowest biomass production while higher rainfall from seeding to ripening (258 mm) in 1993 gave higher biomass production compared to that of 1995. Wheat after faba bean tended to give greater biomass than wheat after wheat or wheat after canola in 1993 and 1995. However cumulative production of dry matter from sowing to grain filling in 1993 was higher than that observed in 1994 or 1995 for the same cumulative rainfall. These differences were significant from heading to grain filling (85 to 125 days after sowing) as presented in Figure 5.17 (a).

Greater dry matter production did not always translate to higher dry matter water use efficiency. The highest dry matter production, obtained in 1993, had a lower water use efficiency than observed in 1994 and 1995. Dry matter water use efficiency in 1995 for wheat was the highest compared with that obtained in 1993 and in 1994 as shown in Figure 5.18 whereas dry matter production was lower than in 1993. These results suggest that water use efficiency of dryland crops is dependent on rainfall and climatic conditions rather than stored soil water. The relative water use efficiency obtained by relating measured water use efficiency to the potential water use efficiency of French and Schultz's model (1986) should be computed before comparing the WUE of different years with different climatic conditions. The definition of water use efficiency is unsatisfactory when comparing crops with the different rainfall regimes. Crops grown under low rainfall with poorer grain yields in 1994 should have the lower water use efficiency compared with the higher grain yield obtained under higher rainfall in 1993 or in 1995.

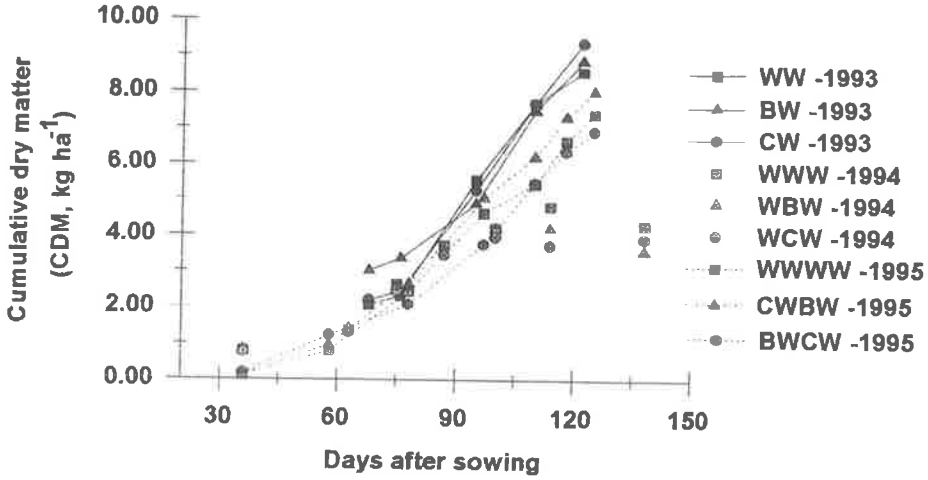


Figure 5.17 The cumulative dry matter production of wheat sown by direct drilling in continuous wheat rotations (-WW), or after faba bean (-BW) and canola (-CW) from 1993 to 1995.

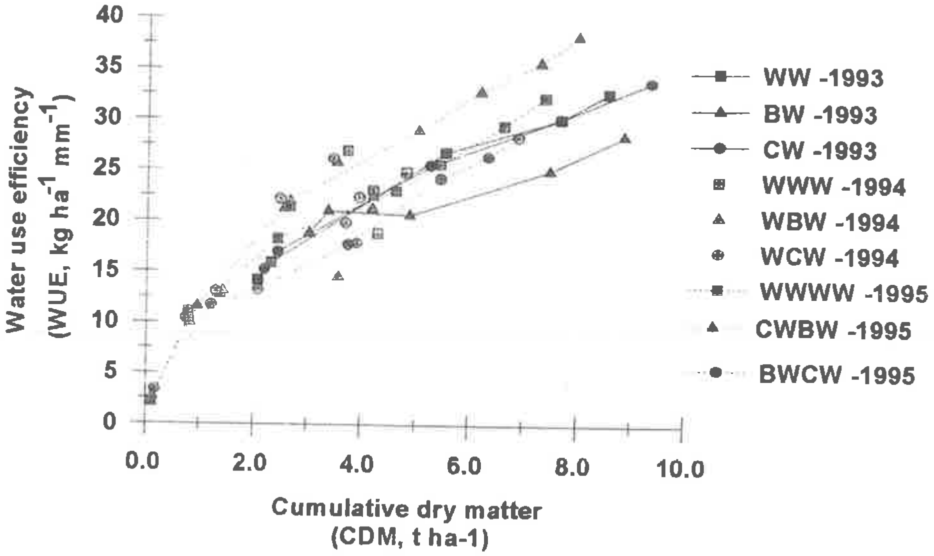


Figure 5.18 The relationships between cumulative dry matter production and dry matter water use efficiency of wheat sown by direct drilling in continuous wheat rotations (-WW), or after faba bean (-BW) and canola (-CW) from 1992 to 1995.

In any year, the measured total stored water depended not only on that seasons rainfall, but also on the water left in the soil from the previous year. The lowest total stored water at ripening in 1992, 1993, 1994 and 1995 was found in B, BW and BWC and BWCW treatment respectively (Figure 5.19). From this a reasonable deduction might be that the highest amount of water used by faba bean (B) and wheat grown after faba bean (BW) which occured in 1992 and 1993 (Figure 5.16 a) left the lowest total stored soil water in 1994, which lead to the lowest total water use by canola (BWC) in that year. (Table 5.7). This then gave the lowest growth rate and cumulative dry matter production by wheat following canola (BWCW) in 1995 compared with other cropping systems (Figure 5.17).

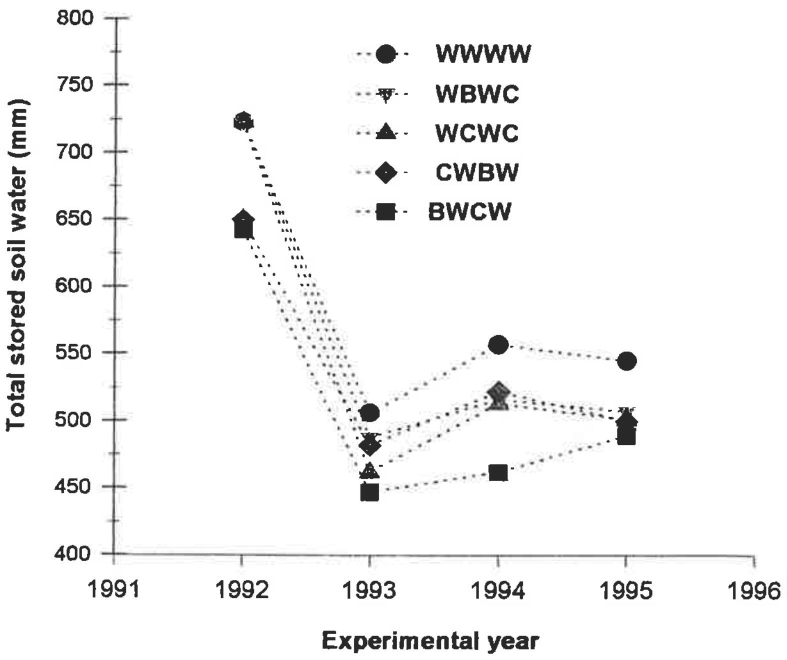


Figure 5.19 Total stored soil water to 2 m depth at the ripening stage of wheat, faba bean and canola in rotations of WWWW, WBWC, WCWC, CWBW and BWCW from 1992 to 1995.

5.3.6.3 The effects of tillage practices and crop rotations on wheat yield and relative water use efficiency

The potential water use based on growing season rainfall from April to October and the potential yield of wheat were calculated using the French and Schultz (1986) equations (Equations 2.4 and 2.5 in Chapter 2). These values were used to calculate the potential grain water use efficiency of wheat from 1992 to 1995. The ratio of measured to potential water use efficiency, the relative water use efficiency (RWUE), was used to interpret the effects of tillage practices and crop rotations on wheat yield and water use efficiency. The results were presented in Table 5.11.

The maximum wheat yield (3.82 t ha^{-1}), obtained in 1995, corresponds to the maximum yield water use efficiency (15.96 t ha^{-1} mm^{-1}) of the best treatment (Table 5.11). In 1993, the highest amount of water used (400 mm) did not give the best water use efficiency on grain production compared with the other years. Most available soil water was used to produce biomass during tillering to grain filling. The crop became short of water during the dry period at grain filling, causing inefficient use of water for grain production or poor grain yield water use efficiency. The high rainfall in 1992 did not produce maximum wheat yields probably because of the poor soil aeration associated with soil waterlogging. In 1994, wheat gave the lowest yield and the lowest water use efficiency of the best treatment in 4 years of the experiment due to the low amount and poor distribution of rainfall.

The measured total water use of wheat from sowing to ripening as a function of tillage practices and crop rotations is compared to the potential water use (estimated from Equation 2.4) in Figure 5.20. Wheat yield and relative water use efficiency (RWUE) for yield production are presented with growing season rainfall in Figure 5.21.

Table 5.11 The rainfall during growing season (April - October), during crop growth (Sowing - Ripening), the estimated potential and the measured values of water use, yield and water use efficiency (WUE), and the relative water use efficiency of wheat during 1992 to 1995. Measured WUE of wheat as a function of direct drilling or conventional cultivation was calculated from the average of the three wheat crop rotations (-WW, -BW and -CW)

Rainfall, Yield and Water use	**1992**	**1993**	**1994**	**1995**
Rainfall from April to October (Pt, mm)	**454**	**290**	**194**	**329**
Rainfall from seeding to ripening (Pi, mm)	457	251	115	218
Estimated water use at potential yield (WUp, mm): WUp = 1.04 Pi - 18.4	**453**	**283**	**183**	**324**
Estimated potential yield (Yp, t ha^{-1}): Yp = 0.018 WUp - 1.98: or Yp = 0.019 Pt - 2.31	**6.17**	**3.11**	**1.31**	**3.85**
Estimated potential water use efficiency (WUEp, kg ha^{-1} mm^{-1}): WUEp = Yp/WUp	**13.62**	**10.99**	**7.18**	**11.88**
Measured maximum actual yield (Yam, t ha^{-1})	**3.01**	**3.00**	**1.04**	**3.82**
Measured water use at Yam (WUam, mm)	**323**	**400**	**228**	**239**
Measured WUE at maximum yield (WUEa, kg ha^{-1} mm^{-1}): WUEam = Yam/WUa	**9.32**	**7.50**	**4.56**	**15.98**
Relative water use efficiency (RWUE): RWUE = WUEai/WUEp				
Direct drill (DD)	**0.63**	**0.66**	**0.49**	**1.27**
Conventional cultivation (CC)	**0.57**	**0.79**	**0.48**	**0.95**
wheat after wheat (-WW) in DD	**0.63**	**0.59**	**0.56**	**1.38**
Wheat faba bean (-BW) in DD	-	**0.68**	**0.42**	**1.04**
Wheat after canola (-CW) in DD	-	**0.72**	**0.53**	**1.34**

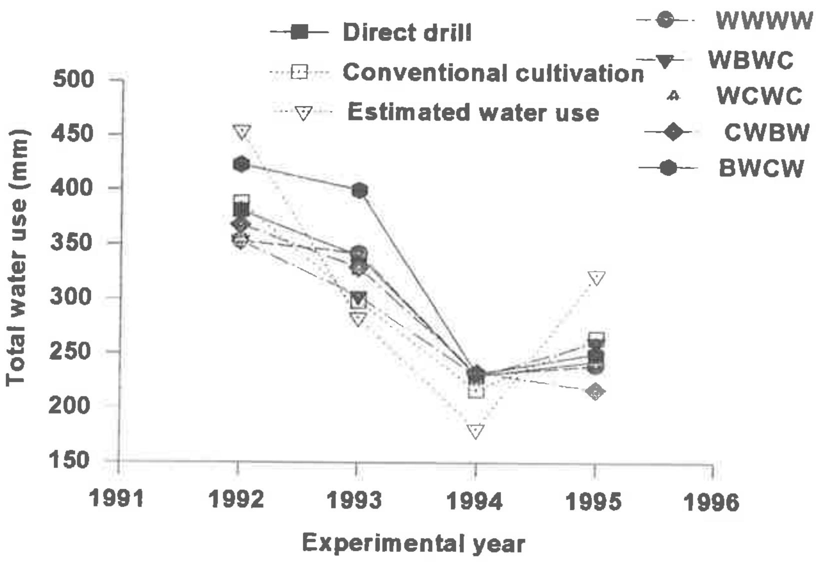


Figure 5.20 Total water use from sowing to ripening in 1992 to 1995 for wheat sown by direct drilling or conventional cultivation and for a selection of rotations of wheat (W), faba bean (B) and canola (C) sown by direct drilling (DD-WWWW, DD-WBWC, DD-WCWC, DD-CWBW and DD-BWCW). Water use calculated from Equation 2.4 is also shown for 1992 to 1995.

Figure 5.20 shows that crop rotations sown as faba bean (B) in 1992 and wheat sown after faba bean (BW) in 1993 used more water than other crop rotations. This effect corresponded to the observation that the lowest total stored soil water left at ripening occurred in B and BW treatments causing the lowest biomass production due to the limited stored soil water during the exceptionally dry year, 1994 (see Section 5.3.6.2). The water used by canola sown after wheat (BWC) in 1994 and wheat sown after canola (BWCW) in 1995 was not different from the other crop rotations.

Figure 5.21 shows that the grain yield of wheat in 1992, 1993 and 1994 was influenced by tillage practices. Direct drilling of wheat tended to give a higher grain yield than conventional cultivation in each year as shown by Figure 5.21 (b).

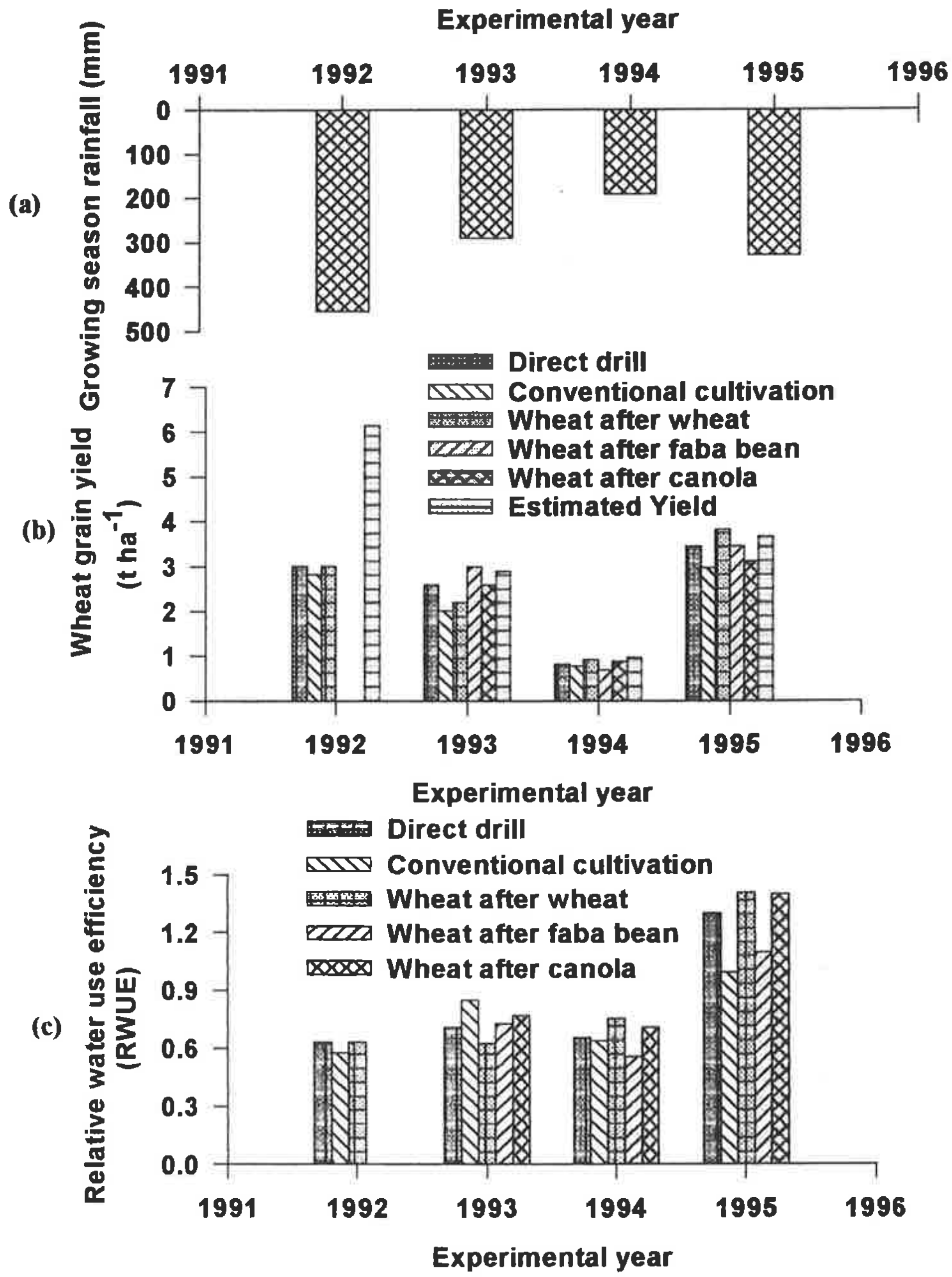


Figure 5.21 The influence of **(a)** rainfall during growing season (April to October) from 1992 to 1995 on **(b)** grain yield and **(c)** relative water use efficiency for wheat sown by direct drilling or by conventional cultivation in different rotations of continuous wheat or with faba bean and canola. Potential yields calculated from Equation 2.5 are shown for 1992 to 1995.

Wheat after faba bean gave the highest yield in 1993 and the lowest yield in 1994 while wheat after wheat had the highest yield in 1995 compared to the other crop rotations sown by direct drilling. The highest yields of wheat in 1993, 1994 and 1995 were 3.00, 1.04 and 3.82 t ha^{-1} respectively. These yields correspond approximately to the estimated potential yields in 1993, 1994 and 1995 of 3.11, 1.31 and 3.85 t ha^{-1} respectively. Figure 5.21 (c) indicates that the effects of direct drilling and conventional cultivation on relative water use efficiency were similar in 1992 and 1994. Conventional cultivation resulted in higher RWUE than direct drilling in 1993 while the reverse result was obtained in 1995.

The rotations wheat after wheat and wheat after canola gave higher values of RWUE than wheat after faba beans in 1994 and 1995. The RWUE of wheat in 1992, 1993 and in 1994 were approximately equal. However, the RWUE obtained in 1995 were higher than in all the previous years. This difference suggests that the water use efficiency of the crops was not only limited by the amount of rainfall but also depends on rainfall distribution. For example, RWUE in 1993 was lower than in 1995 (Figure 5.21 c) due to lack of rainfall during a critical period of crop growth (tillering to flowering), despite rainfall during 1993 (258 mm) being higher than in 1995 (206 mm) (Table 5.10). The favourable RWUE in 1995 possibly resulted from the better distribution of rainfall in 1995 than in 1993. This avoided moisture stress during a critical growth period (tillering to flowering) in 1995.

In 1992, average grain yield and water use efficiency for grain production of wheat were approximately 40% lower than the estimated potential yield and estimated water use efficiency. This suggests that the French and Schultz (1986) equation is not accurate in exceptionally wet years such as 1992. The high rainfall in 1992 caused poor soil aeration almost throughout the entire crop growth period, resulting in poor yield production and poor water use efficiency. This assertion is confirmed by results presented by French and Schultz (1984). In 1995, when actual yield equaled potential yield WUE was higher than predicted by French and Shultz, indicating that the rainfall was exceptionally well distributed.

5.3.7 The effects of tillage practice and crop rotation system on root density and root distribution from 1992 to 1995.

F-values and the average values of root length density at different soil depths for different tillage practices (T) and crop rotation systems (S) during 1992 to 1994 are presented in Tables 5.12 to 5.15. In 1995, samples were taken from only two replications of DD-WWWW, CC-CWBW, DD-WCWC and WBWC treatments and these root length density data were not included in the statistical analysis. The total root length density for each soil depth interval and the distribution of root length density down the soil profile as functions of the main and interactive effects of tillage and crop rotations from 1992 to 1994 are presented in Figures 5.22 to 5.27 respectively.

Table 5.12 shows that the interaction between tillage practices and crop rotation systems (TxS) resulted in significant differences in the root length density in both the 0 to100 and 200 to 1000 mm soil depth intervals for all years in which the necessary root sampling was carried out. The main effects of tillage practices (T) and crop rotation systems (S) all gave significantly differences of root length density in the 100 to 200 and 0 to 1000 mm soil depth intervals. In 1994 root length density were not significantly different for different tillage practices but were significantly different in the crop rotation systems studied

Table 5.12 The statistcal significance of F values obtained from analysis of variance of the effects of tillage practices (T) and crop rotation systems (S) on the variation of root length density within different soil depths from 1992 to 1995.

	Tillage practices and crop rotation systems											
	1992			**1993**			**1994**			**1995**		
Soil depth (mm)	**T**	**S**	**T x S**	**T**	**S**	**T x S**	**T**	**S**	**T x S**	**T**	**S**	**T x S**
0-100	**21.54***	**27.18****	**10.64****	1.15	**23.87****	0.07	3.22	2.59	0.37	x	x	x
100-200	7.23	**14.16****	0.89	0.69	**4.67****	2.03	3.94	**3.13***	0.85	x	x	x
200-1000	**13.06***	**9.15****	**8.30****	3.25	**6.23****	1.17	0.04	1.52	0.71	x	x	x
0-1000	**53.38****	**48.67****	0.72	0.17	0.68	1.61	0.17	1.61	0.75	x	x	x

* : represent the significant F- values at probability (p) of 0.05 ;
* *: represent the significant F- values at probability (p) of 0.01 ;
x : no analysis of variance

Table 5.13 The 1992 main effects and interactive effects of tillage practices (T, direct drill DD and conventional cultivation CC) and crop types (S, wheat W, faba bean B and canola C) on the average values and the least significant differences of the means (l.s.d) of root length density (mm-cm^{-2}) within different soil depths.

Soil depth (mm)	**Tillage practice**		**l.s.d.***	**Crop rotation system**			**l.s.d.***
	DD	**CC**	**T**	**W**	**B**	**C**	**S**
0-100	1254	1129	si	1557	1093	926	si
100-200	710	580	ns	**910a**	**540b**	**490b**	190
200-1000	1920	1360	si	2000	1400	1540	si
0-1000	**3884a**	**3069b**	318	**3557a**	**2493b**	**2466b**	411

Soil depth (mm)	**Interaction of Tillage practices and Crop rotation systems**							
	DD			**CC**			**l.s.d***	**l.s.d***
	W	**B**	**C**	**W**	**B**	**C**	**TxS**	**TxS**
							(1)	**(2)**
0-100	**1390b**	**1210b**	**1160c**	**1720a**	**980c**	**690d**	235	278
100-200	978	656	494	841	415	483	ns	ns
200-1000	**2600a**	**1400bc**	**1780b**	**1400bc**	**1400c**	**1280c**	574	518
0-1000	4968	3266	3434	3961	2795	2453	ns	ns

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop types
l.s.d * T x S are the least significant differences of the means caused by interaction of tillage practices and crop types for comparison at $P < 0.05$ (*) si is significant as interaction effect
(1) and (2) : l.s.d. for comparing mean with the same level and with different levels of tillage practices
a, b, c represent differences between the means, values followed by different letters are significantly different
ns : no significant differences between different tillage practices, and among different crop types.

Table 5.14 Average root length density values and least significant differences (l.s.d) (mm cm^{-2}) in 1993 as functions of soil depths, tillage practices (T: direct drill DD and conventional cultivation CC) and crop rotations for 1993 (S: wheat-wheat WW, faba bean-wheat BW, canola-wheat CW, wheat-faba bean WB and wheat-canola WC)

Soil depth (mm)	Tillage practice		l.s.d.*	Crop rotation system					l.s.d.*
	DD	CC	T	WW	BW	CW	WB	WC	S
0-100	1101.0	1205.0	ns	**1510a**	**1220b**	**1200b**	**700c**	**1130b**	170
100-200	702.0	794.0	ns	**810a**	**720a**	**860a**	**530c**	**810a**	190
200-1000	1834.0	1924.0	ns	**1980b**	**1600c**	**2300a**	**1540c**	**1980b**	360
0-1000	3637.0	3923.0	ns	4300	3540	4360	2770	3920	ns

Soil depth (mm)	Interaction of Tillage practice and Crop rotation system $(TxS)^{ns}$										l.s.d.* (1)	l.s.d.* (2)
	DD					CC						
	WW	BW	CW	WB	WC	WW	BW	CW	WB	WC	TxS	TxS
0-100	1446	1156	1153	669	1080	1581	1289	1246	725	1182	14.48	12.03
100-200	860	587	908	455	702	762	849	819	613	924	15.4	12.09
200-1000	1922	1794	2160	1418	1870	2024	1414	2442	1646	2090	11.5	12.56
0-1000	4228	3537	4221	2542	3652	4367	3552	4506	2984	4196	ns	ns

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop rotations for comparison at $P < 0.05$: a, b, c represent differences between the means, values followed by different letters are significantly different

ns : there is no significant differences between different tillage practices, and among different crop types.

$(T \times S)^{ns}$: all interaction effects of tillage practices and crop rotation systems are not significant at $P < 0.05$

Table 5.15 Average root length density values and least significant differences (l.s.d) (mm cm^{-2}) in 1994 as functions of soil depths, tillage practices (T: direct drill DD and conventional cultivation CC) and crop rotations systems (S: wheat-wheat-wheat WWW, wheat-faba bean-wheat WBW, wheat-canola- wheat WCW, canola-wheat-faba bean CWB and faba bean-wheat-canola BWC)

Soil depth (mm)	Tillage practice		l.s.d.*	Crop rotation system					l.s.d *
	DD	CC	T	WWW	WBW	WCW	CWB	BWC	S
0-100	1362	1293	ns	1416.0	1312.0	1474.0	1088.0	1356.0	ns
100-200	666	769	ns	**900a**	**650bc**	**740ab**	**520c**	**770b**	230
200-1000	2000	2040	ns	1168	980	1162	978	786	ns
0-1000	4028	4102	ns	2210.0	1761.6	2049.8	1606.4	1692.0	ns

Soil depth (mm)	Interaction of Tillage practice and Crop rotation system $(TxS)^{ns}$										l.s.d.*	l.s.d.*
	DD					CC					(1)	(2)
	WWW	WBW	WCW	CWB	BWC	WWW	WBW	WCW	CWB	BWC	TxS	TxS
0-100	1456	1438	1446	1122	1366	1375	1187	1501	1053	1347	17.0	18.4
100-200	826	657	726	517	603	974	651	751	523	945	15.2	16.0
200-400	1796	2124	1996	2342	1740	2366	1704	2172	2458	1556	23.4	22.3
0-1000	4078	4219	4168	3981	3709	4715	3543	4424	4034	3848	ns	ns

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop rotations at $P < 0.05$ (*)

a, b, c represent differences between the means, values followed by different letters are significantly different

ns : there is no significant differences between different tillage practices, and among different crop types.

Table 5.13 shows that in 1992, root length density of wheat was significantly greater than faba bean and canola in any soil depth interval. Direct drilling of wheat resulted in a greater average root length density (293 mm cm^{-2}) in the 0 to 1000 mm soil depth interval compared to conventional cultivation (Figure 5.22 a).

The interactive effect showed that direct drilling of wheat resulted in a lower root length density in the 0 to 100 mm interval compared to conventional cultivation (Figure 5.22 b). However, from 200 to 1000 mm this was substantially reversed with direct drilled wheat having a greater root length density. Root length density of faba bean and canola was less than that of wheat in the top soil layer (0-100 mm) and both were greater in DD than in CC (Figure 5.22 a) and (b)).

In 1993 wheat after wheat had a greater root length density in the 0 to 100 mm depth interval than other crop rotations (Figure 5.23 (a)).. Wheat after canola had the highest root length density in the deeper soil layers (100-200 mm and 200-1000 mm depth) while faba bean had the lowest root length density in every soil depth range compared with the other crops.

In 1994, wheat following wheat had the largest root length density in the 100-200 mm soil depth interval and faba bean gave the smallest values compared with the other cropping systems. There were no sigificant differences in root length density within any soil depth interval for all treatments (Figure 5.23 b). This might been due to poor root development caused by the low soil water content and low rainfall in 1994. Lack of rainfall in this year resulted in the poorest crop development and the lowest dry matter production compared with the other years of experimentation.

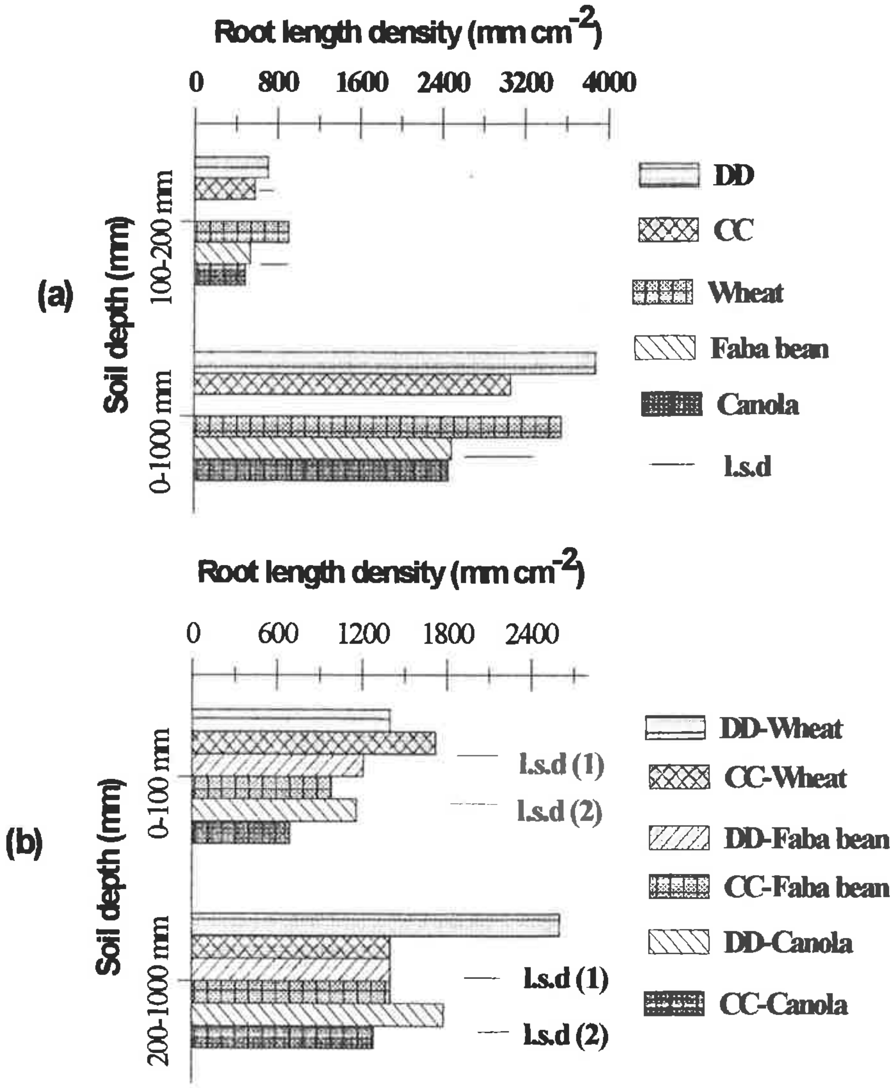


Figure 5.22 Root length density in 1992 as a function of two soil depth intervals for **(a)** the main effects and **(b)** the interactive effects of tillage practices (direct drilling DD and conventional cultivation CC) and crop types (wheat W, faba bean B and canola C). Least significant differences for comparing the same level, lsd (1) and different levels, lsd (2) of tillage practices are shown.

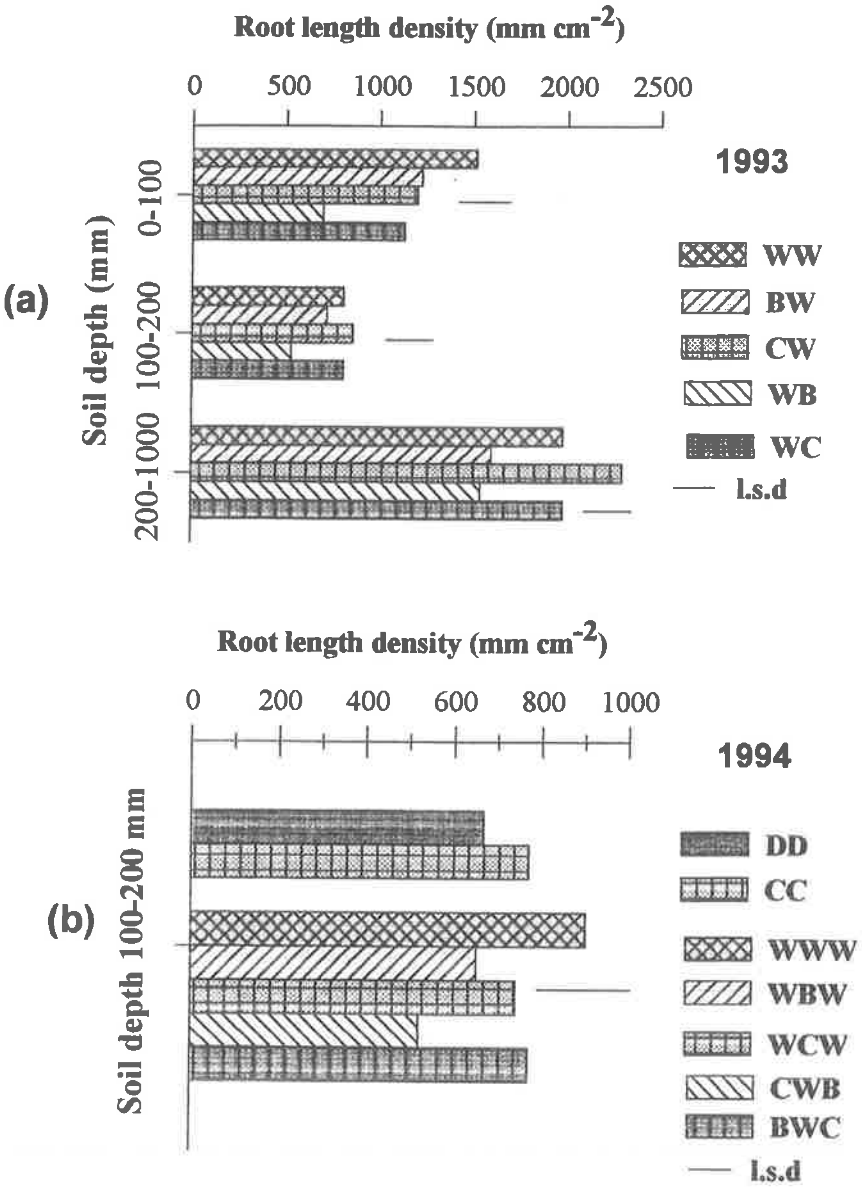


Figure 5.23 Root length density of wheat (W), faba bean (B) and canola (C) rotations for **(a)** soil depth intervals 0-100 mm, 100-200 mm and 200-1000 mm in 1993 and **(b)** soil depth interval 100 to 200 mm and tillage practices (direct drill DD and conventional cultivation CC) in 1994. Least significant differences (lsd) are shown.

Figures 5.24 to 5.27 show root length density (mm cm^{-3}) as a function of soil depth for tillage and/or rotations from 1992 to 1995. These data are presented to give an overall view of root distribution in soil at the ripening stage during the experimental period. Significant effects are shown elsewhere (Tables 5.12 to 5.15 and Figures 5.22 and 5.23)

Generally wheat root length density at depths between 100 and 500 mm tended to be greater than that for either faba bean or canola, particularly in 1992 and 1995 in direct drilled wheat. These data suggest that root penetration through the tillage pan (75 - 150 mm depth) is superior in direct drilled treatments compared to conventional cultivation. In 1994, this pattern is not evident (Figure 5.25) possibly because generally low and poorly distributed rainfall tended to confine roots to shallow layers. Canola showed no difference between DD and CC as shown in Figure 5.26.

Figure 5.27 shows that the average root length density of wheat tended to be lower in direct-drilled top soil (0-100 mm) and higher in subsoil (200-400 mm) compared to the conventional cultivated soil in both 1992 and 1995 when there was sufficient rainfall during the crop growth period. Direct drilling gave higher root length density in the deeper layers because soil bulk density was lower and aeration was better compared to the tillage pan that developed in conventionally cultivated rotations as discussed in Chapter 4. The results in 1993 and 1994 were also supported by the soil matric suction at 200 mm soil depth as shown in Appendix 5. In 1993, direct drilling induced a lower matric suction during tillering due to better accession of rainfall and caused the higher matric suction during flowering due to greater water use compared to the conventional cultivation. In 1994, soil matric suction was almost equally high in both DD and CC throughout the whole growing season because of low and poorly distributed rainfall.

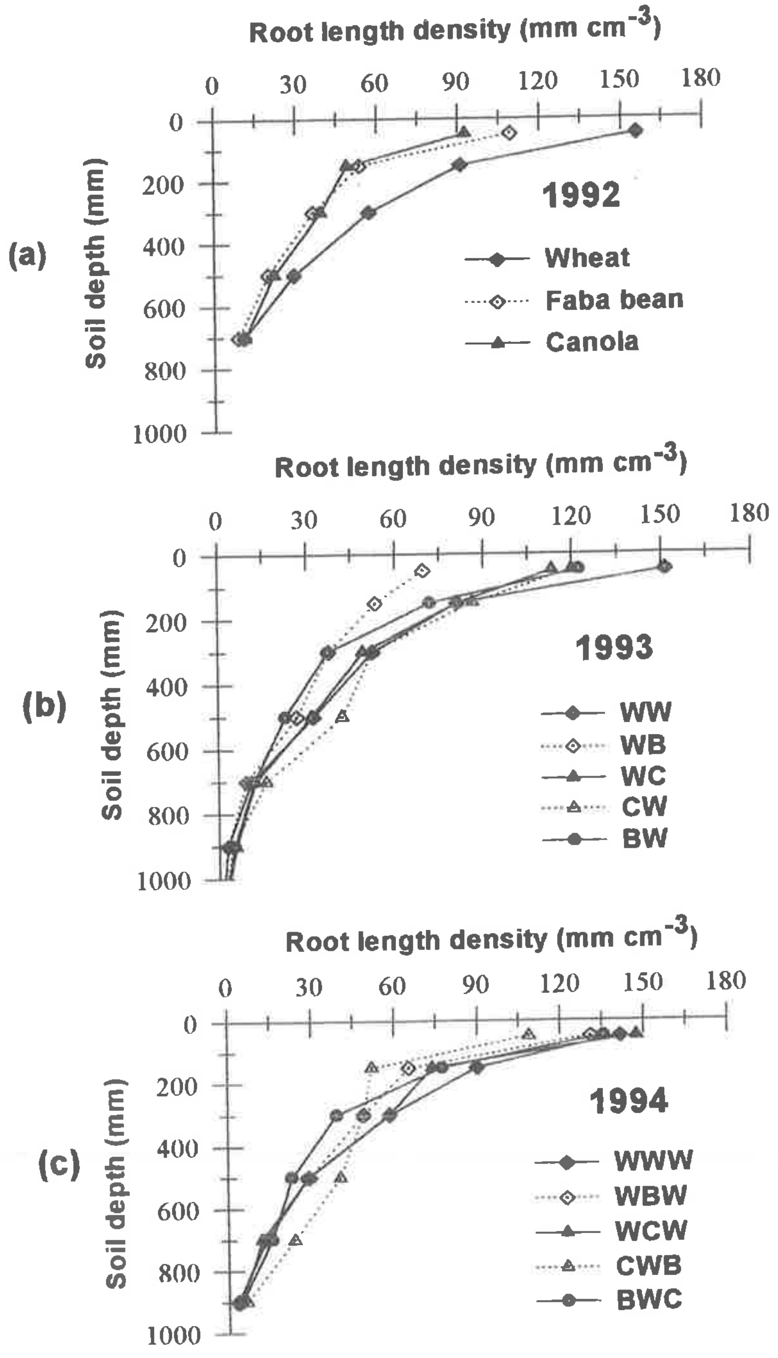


Figure 5.24 The effects of crop types and crop rotations on root length density of rotations of wheat (W), faba bean (B) and canola (C) along the soil profile in **(a)** 1992, **(b)** 1993 and **(c)** 1994.

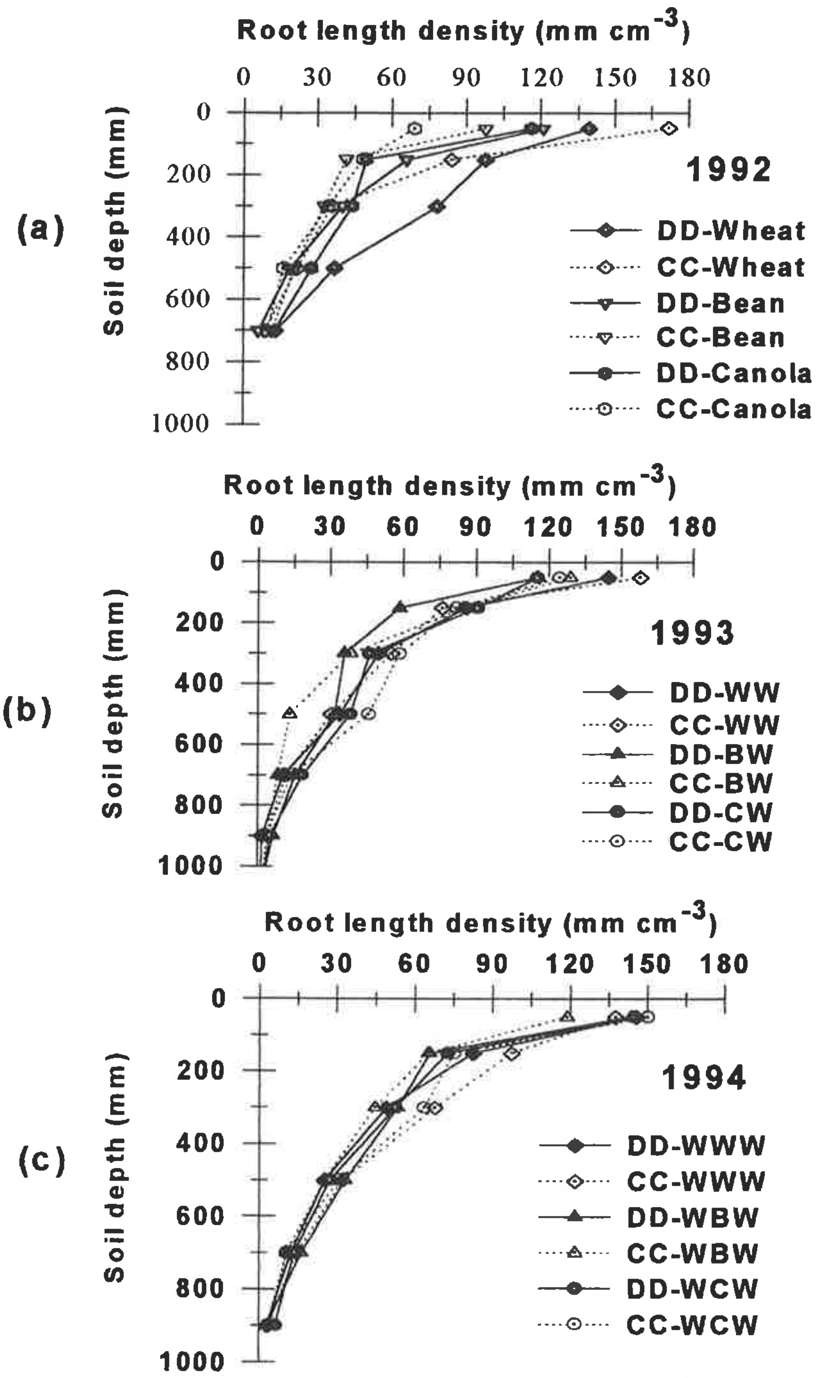


Figure 5.25 Root length density as functions of soil depth and the interactive effects of tillage practices (direct drill DD and conventional cultivation CC) and crop rotations of wheat (W), faba bean (B) and canola (C) **(a)** 1992, **(b)** 1993 and **(c)** 1994.

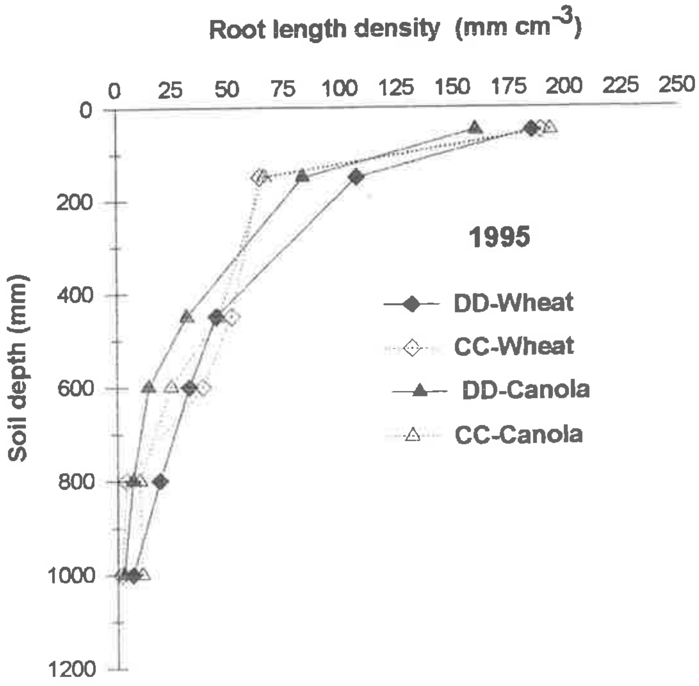


Figure 5.26 The effects of direct drilling (DD) and conventional cultivation (CC) on the average of root length density distributions of wheat and canola in 1995.

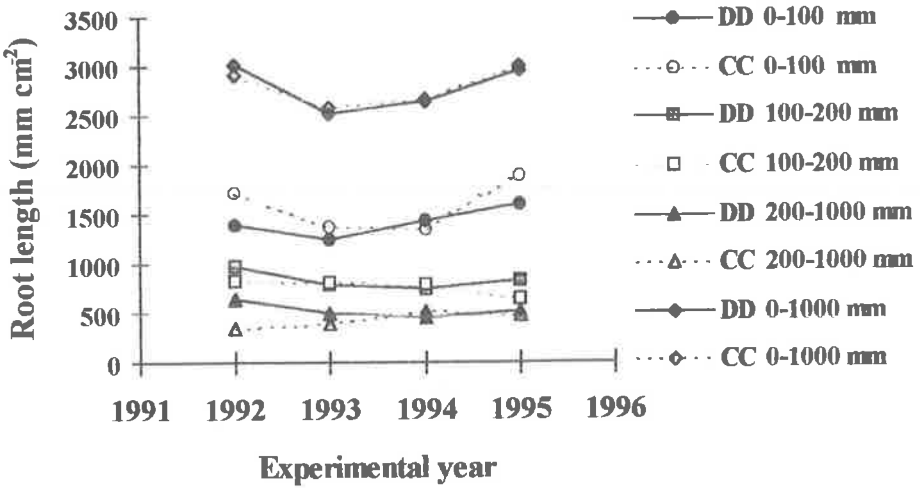


Figure 5.27 The effects of direct drilling (DD) and conventional cultivation (CC) on the average of root length density of wheat in different soil depth intervals from 1992 to 1995.

5.4 Conclusions

(i) Water use in dryland crop production from 1992 to 1995 was mainly controlled by climatic conditions. Stored soil water was generally used by the crop only when rainfall was limited during a critical stage of crop growth such as from tillering to early yield formation.

(ii) The variations of total stored soil water within a soil depth of 2 m during tillering to maturity mainly depended on the amount and distribution of rainfall during the growing season. Total stored water in direct drilled plots was not significantly different from conventionally cultivated plots during the four years of experimentation. However, direct drilled plots tended to have lower total stored soil water because these crops tended to use more water and produce greater biomass compared to conventionally cultivated plots.

(iii) Total stored soil water in any year was influenced by the stored water left from the previous year. Crop rotations of faba beans (B), wheat after faba beans (BW) and canola after wheat (BWC) then wheat after the latter (BWCW) tended to have the lowest total stored water at ripening due to the largest water consumption and the greatest biomass production in 1992 and 1993. This caused total stored soil water and biomass production of canola sown after wheat (BWC) in 1994 and wheat after canola (BWCW) in 1995 to be low.

(iv) Crop biomass production was dependent on the amount and distribution of rainfall more than on stored soil water during pre-tillering because of the shallow root systems at this stage of growth. The higher rainfall in the early stages of crop growth, the greater the biomass production.

(v) Direct drilling tended to have higher dry matter and grain water use efficiency because of greater biomass production and grain yields compared to conventional cultivation. Results from the four years of experimentation suggest that the improvement of soil structure by direct drilling (Chapter 4) may provide better accession of rainfall to the soil profile and enable plants to use water more efficiently compared with conventional cultivation.

(vi) Wheat sown after faba bean (-BW) tended to use water for dry matter production more efficiently than wheat following wheat (-WW) or wheat following canola (CW) particularly in 1995. In 1993 and 1994, wheat sown after faba bean produced dry matter faster during tillering to heading, but this caused depletion of soil water reserves before flowering was reached due to the limited rainfall in 1994, and resulted in very poor grain water use efficiency among all the studied treatments. Wheat sown after faba bean in 1993 produced the highest grain yield but not in 1994 nor 1995.

(vii) In all years of study, direct drilling of all crops resulted in higher water use efficiency compared with conventional cultivation because of greater biomass production for the same water consumption.

(viii) Wheat sown by direct drilling in 1993 produced higher grain yield but had lower grain water use efficiency than wheat sown by conventional cultivation. This suggests that water use efficiency is not a good measure for dryland crop yield productivity. When rainfall is limiting, yields may be low while water use efficiency may be high as in 1994.

(ix) Higher water use efficiency did not always translate to higher yields. In 1993, dry matter production was high but water use efficiency was low compared with 1995. This suggested that crop yield does not depend only on total rainfall but also on rainfall distribution during the growing season. Low rainfall at critical periods from tillering to yield formation can lead to low water use efficiency and poor yield.

(x) Relative grain water use efficiency of wheat in 1995 was higher than other years and almost equal to the potential water use efficiency because there was better distribution and a sufficient amount of rain to supply water to the crop during all periods of crop growth.

(xi) The higher root length density in the 100 to 200 mm depth interval developed by wheat sown by direct drilling did not result in greater water use either under high (1992) or low rainfall (1994) conditions compared to water use by wheat sown by conventional cultivation. Under medium rainfall conditions (1993), the higher root length density and deeper penetration of wheat roots in direct drilled plots induced more efficient water use and consequently gave greater dry matter production at all growing stages from tillering to maturity. This lead to higher yields compared with the conventionally cultivated plots. This results agreed with Goss et al. (1984) and (Dexter (1985).

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CHAPTER 6

MODELLING SOIL WATER EVAPORATION

6.1 Introduction

Soil water evaporation (Es) is an important component of the water balance equation influencing water use efficiency. A model is generally necessary to predict soil water lost from the soil surface by evaporation to the atmosphere. A review of soil water evaporation processes, mechanisms, dependent factors and some of the available soil water evaporation models is presented in Chapter 2, Section 2.4.

There is general agreement (Idso et al., 1974, Ritchie, 1972, Kutilek and Nielsen, 1994) that while the soil surface is wet, evaporation will be dominantly controlled by the atmospheric evaporative demand ('Stage I' soil water evaporation). When the soil is drying (wilting point < θ < field capacity) (Stage II) soil water evaporation is governed by the soil hydraulic properties. The final stage of soil water evaporation (Stage III) is limited by the very dry soil conditions (θ < wilting point) and is dominated by upward vapour flow under high evaporative demand. Little research work has been done on the mechanism of Stage III soil water evaporation, but there is general agreement that in the context of the water balance of an annual crop, it accounts for a very small proportion of the total water flux unless very long periods under high evaporative demand are involved.

The transition of the evaporation rate from Stage I to Stage II varies with matric suction and evaporative demand. Under dryland conditions, Stage I occurs for short periods immediately after rainfall or may not occur at all under high evaporative demand (Kutilek and Nielsen, 1994). Stage II soil water evaporation is the most important stage and occurs for a longer period, which significantly affects water use efficiency under dryland conditions. It is the most crucial stage in crop water use and the subject of much experimental work.

Two of the most widely used evaporation models, Ritchie (1972) and Stroosnijder (1987), have been developed for circumstances where an initially wet profile dries continuously until rewetted. This type of model proved unsuitable for predicting evaporation under the experimental conditions reported here, where rainfall was often insufficient to fully refill the soil profile. Subsequent evaporation occurred after only partial rewetting of the surface soil layers. Neither the Ritchie (1972) model which relies on time (Equation 2.43) nor the Stroosnijder (1987) model which relies on evaporative demand (Equation 2.46), will deal with these circumstances, which frequently occur in dryland conditions.

Neither of these two models directly accounted for the actual soil hydraulic properties which control Stage II soil water evaporation. The soil parameters may vary with the soil surface management and rainfall during growing season. Furthermore, the Ritchie (1972) model cannot be used when the soil water evaporation in Stage I and Stage II occur alternately several times within a day depending on variation of surface soil matric suction (which controls the upward flow of soil water) and evaporative demand. In modelling soil water evaporation, the soil water characteristic and evaporative demand need to be considered in all the three stages of soil water evaporation.

The aim of this Chapter is to develop a model that can be used to predict soil water evaporation from the soil surface in any structural condition, or at any soil water content or matric suction, under any evaporative demand and at any stage of soil water evaporation. This model needs to be based on an equation that combines the three stages soil water evaporation (Es) as a single function dependent on evaporative demand (Em) and soil water suction (S).

6.2 Materials and methods

Experimental methods used to measure soil water evaporation (Es) were described in Chapter 3, Section 3.6. Evaporative demand (Em) was measured by using a small evaporimeter (diameter 80, height 60 mm) buried to soil surface level under the crop canopy. The microevaporimeter was filled with water (20 mm) above a (50 mm) layer of soil. The mass loss of water over a 4 to 6 h period was used as a measure of potential evaporation or evaporative demand (Em) under a range of sensible and latent heat fluxes across the soil surface (see Sections 3.6.1 and 3.6.2). The microevaporimeter was used in conjunction with a microlysimeter, buried nearby.

Measured Es, Em and Es/Em ratio values obtained under field conditions in 1994 were related to the soil water content (θ) or soil water matric suction (S). These data were used to develop a function relating soil water evaporation (Es) to matric suction (S) and the evaporative demand (Em). The measured Es, Em and S obtained in 1995 were used to test the model performance. The model was also used to predict the soil water evaporation in the water use model described in Chapter 7.

6.3 Model development

Soil water evaporation was measured under continuous wheat sown by both direct drilling and conventional cultivation. Measurements were done in the field in 1993, 1994 and 1995 as described in Chapter 3. The results in 1993 showed that the direct drilled treatments had a higher soil water evaporation rate (Es) due to the higher soil water content of the surface layer. This higher water content in direct drilled treatments was brought about by increased capillary rise of water from deeper soil layers compared to the conventional cultivated soil cores (Chapter 4). The results from three years of experimentation showed that soil water evaporation (Es) was dominantly dependent on evaporative demand (Em) and soil water content (θ) of the surface soil (0 to 75 mm depth).

6.3.1 The soil water retention function

To generalise the model, soil water evaporation (Es) was related to soil water suction instead of soil water content. The soil water retention function obtained from continuous wheat plots sown by direct drilling and conventional cultivation in 1994 (Section 4.3.5.2) was used to transform soil water content to soil water suction. The soil water retention functions for the direct drilled and conventionally cultivated treatments are presented in Equations 6.1 and 6.2 respectively.

$$\log_{10}(S) = 4.18 - 13.09\,\theta \qquad (6.1)$$

$$\log_{10}(S) = 3.90 - 11.53\,\theta \qquad (6.2)$$

where S is the soil water suction with units of kPa, θ is volumetric soil water content (m^3 m^{-3}). These equations were fitted over the matric suction range of 1 to 1,500 kPa. R^2 values obtained were 0.99 for both Equations 6.1 and 6.2.

6.3.2 Two dimensional soil water evaporation function

Soil water matric suction (S, kPa) and soil water evaporation (Es, mm) measured in DD-WWW treatments at different levels of evaporative demand (Em) in 1994 was used as a data base to generate the soil water evaporation function. The data are listed in Appendix 6. Relationships between Es and S at different Em values were grouped in four ranges of Em and the logistic function was fitted to each group (SigmaPlot, 1994) as presented in Figure 6.1. Soil water evaporation was described as a function of soil water suction at each average value (Table 6.1) of the ranges (Figure 6.1) of evaporative demand as follows

$$\mathbf{Es} \quad = \quad \mathbf{(a\text{-}d) / (1+(log_{10}\ S/c)^{\ b}) + d} \qquad \mathbf{(6.3)}$$

where **a** is the maximum Es value occurring at field capacity, **b** is the slope coefficient at the point of maximum change of Es per unit change of soil water suction, **c** is the logarithm of soil water suction ($\log_{10}$ S) at a maximum slope coefficient "**b**", and **d** is the minimum Es. The regression coefficients **a, b, c** and **d** were constant for a given average evaporative demand (Em).

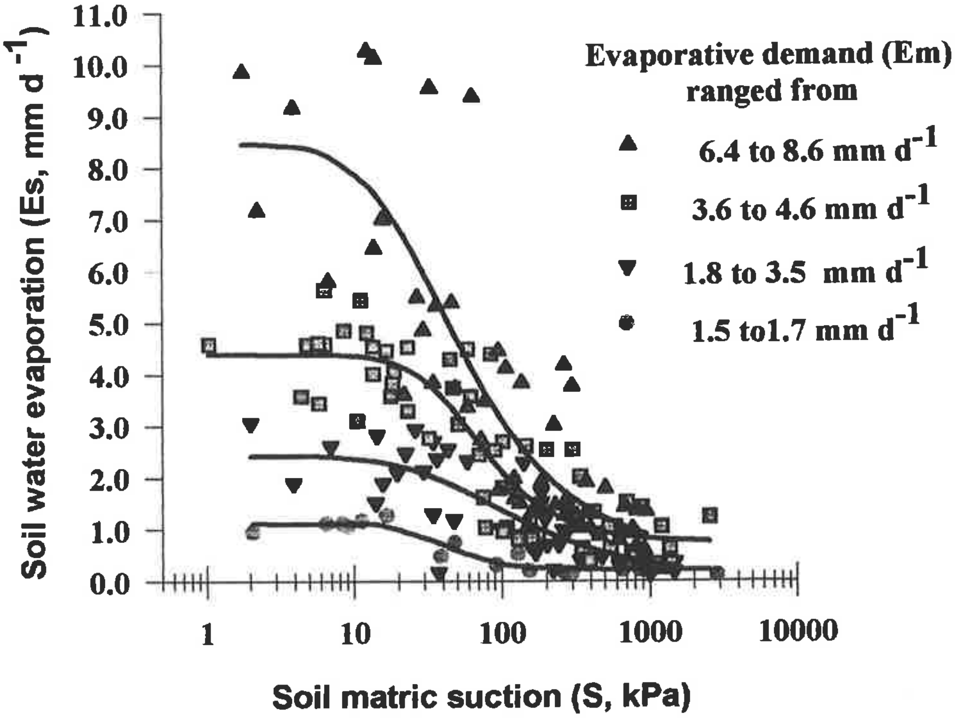


Figure 6.1 The fitted relationship between soil water matric suction (S) and soil water evaporation (Es) at different values of evaporative demand (Em) measured under field conditions in 1994.

The goodness of fit of the four fitted functions (R^2) and the F ratio of the models including standard error and the F-ratio of all regression coefficients are shown in Table 6.1. The fitted function had a coefficient of determination (R^2) at least 0.67 and a highly significant F ratio ($p = 0.01$).

Table 6.1 The statistical analysis of variance for the regression and model fitting results of soil water evaporation (Es, dependent variable) and soil water suction (S, independent variable) at each level of evaporative demand (Em).

Regression	**Regression Coefficients**				**Model**
Analysis of variance	**a**	**b**	**c**	**d**	
For average Em 1.66 mm d^{-1}					
Estimated values of Coefficients	1.11	9.07	1.64	0.20	
Standard errors	0.17	4.48	0.09	0.07	
The F ratios	4.23	1.93	17.99	2.91	112**
Coefficient of Determination, R^2					0.91
For average Em 2.50 mm d^{-1}					
Estimated values of Coefficients	2.42	8.02	2.11	0.00	
Standard errors	1.23	2.33	0.42	1.33	
The F ratios	1.39	1.77	5.32	0.30	80.3**
Coefficient of Determination, R^2					0.67
For average Em 4.05 mm d^{-1}					
Estimated values of Coefficients	4.39	7.65	1.90	0.72	
Standard errors	0.61	2.77	0.07	0.26	
The F ratios	4.65	2.95	26.97	2.88	208.7**
Coefficient of Determination, R^2					0.78
For average Em 7.52 mm d^{-1}					
Estimated values of Coefficients	8.46	4.74	1.800	0.29	
Standard errors	2.61	1.76	0.14	1.11	
The F ratios	3.02	2.70	12.48	0.266	106.7**
Coefficient of Determination, R^2					0.74

** the model is significant at $p < 0.01$

Figure 6.1 and Table 6.1 show that soil water evaporation rate (Es) was dependent on both soil matric suction (S) and evaporative demand (Em). At a fixed level of evaporative demand (Em), soil water evaporation (Es) may be limited by either hydraulic diffusivity (D_θ) and/or soil water content (θ_i) as described in Equation 2.13, Chapter 2 (Gardner, 1959; Black et al., 1969; Kutilek and Nielsen, 1994). However, when matric suction was high ($S > 1000$ kPa), Es was very low ($Es < 1$ mm d^{-1}) and hardly varied with Em. At this low soil water content, Es may be limited by either unsaturated upward flow rate under low soil water diffusivity (Equation 2.13) or water vapour flow in soil under high Em (Equation 2.14) (Hanks, 1992).

6.3.3 Three dimensional soil water evaporation function

The transient nature of Es under field conditions, controlled by Em and S, implies that it cannot be conveniently estimated using Equations 2.43 and 2.46 (Chapter 2). Figure 6.1 shows that Es depends on two of the regression coefficients, **a** and **b,** but these coefficients are not explicitly identified in these equations. Furthermore Equation 6.3 contains parameters that are not sensitive to Em which suggests that the equation may be simplified without loss of precision. Therefore, a single logistic function was considered to be preferable for estimation of daily soil water evaporation (Es). Equation 6.3 was modified by substituting constant values for **c** and **d** and developing relationships between **a** and **b** and Em (Figure 6.2) then substituting them into Equation 6.3.

The relationships between regression coefficients **a** and **b** and the Em values are witten as

$$\mathbf{a} = \mathbf{1.20\ Em - 0.57} \qquad (\mathbf{R^2 = 0.99, p > 0.01}) \qquad (6.4)$$

$$\mathbf{b} = \mathbf{10.14 - 0.71\ Em} \qquad (\mathbf{R^2 = 0.97, p > 0.01}). \qquad (6.5)$$

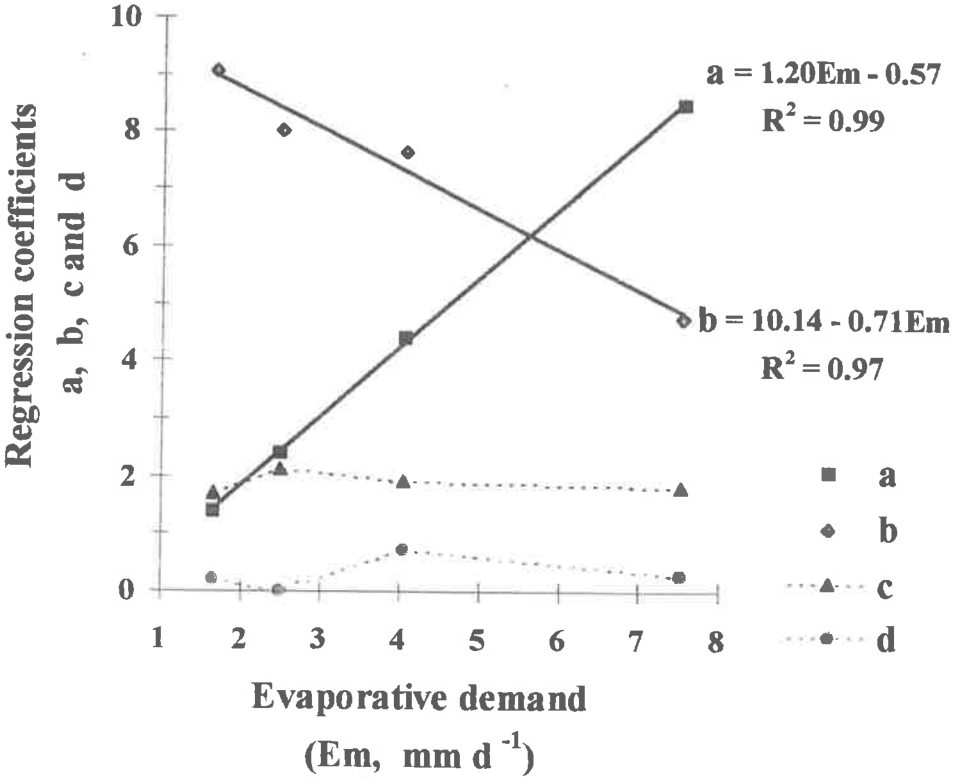


Figure 6.2 The relationships between the coefficients of Equation 6.3 (**a, b, c** and **d**) and evaporative demand (Em) with fitted linear regression functions for **a** and **b**.

Equations 6.4 and 6.5 show that both **a** and **b** are dependent on evaporative demand (Em) and the correlation coefficients of both with Em are significant ($p > 0.01$). However, **c** and **d** were not correlated with Em. The regression coefficient c varied from 1.64 to 2.11 with an average value of 1.90 which showed that the largest soil water evaporation changes per unit change of soil matric suction (ΔEs / ΔS) for any Em occurred at a matric suction of approximately 80 kPa. The coefficient **d** was less than 1 mm d^{-1} and was considered negligible.

Substitution of Equation 6.4 and 6.5 into Equation 6.3 provided the relationship between Es and Em as

$$Es \quad = \quad (1.20\ Em - 0.57) / (1 + (\log_{10} S/1.90)^{(10.14 - 0.71\ Em)}. \qquad (6.6)$$

Generalisation of Equation 6.6 gives

$$Es \quad = \quad (k_1\ Em - k_2) / (1 + (\log_{10} S/ k_3)^{(k_4 - k_5\ Em)} \qquad (6.7)$$

where k_1, k_2 k_3 k_4 and k_5 are constant for a given soil and can be varied according to soil water characteristic and evaporative demand.

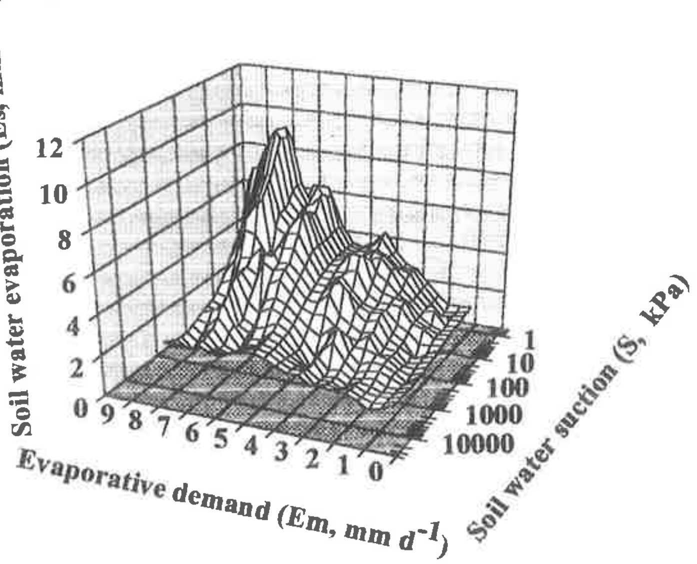
Equation 6.7 was used to fit a data set of Es values obtained on plots of continuous wheat growth sown by direct drilling and conventional cultivation in 1994 (data are presented in Appendixes 6 and 7 respectively). The fitted function for each set of data is presented in Equation 6.8 and 6.9 respectively.

$$Es \ = \ (1.179\ Em - 0.295) / (1 + (\log_{10} S/1.765)^{(1.470 + 0.375\ Em)}),\ R^2 \ = \ 0.782 \quad (6.8)$$

$$Es \ = \ (1.253\ Em + 0.909) / (1 + (\log_{10} S/2.175)^{(4.010 + 0.578\ Em)}),\ R^2 = \ 0.910. \quad (6.9)$$

The graphs of the measured and the estimated soil water evaporation rate (Es) from direct drilled and conventional cultivated plots as influenced by evaporative demand (Em) and soil water suction (S) are presented in Figures 6.3 and 6.4 respectively.

(a) Measured Es in DD-WWW, 1994



(b) Estimated Es in DD-WWW, 1994

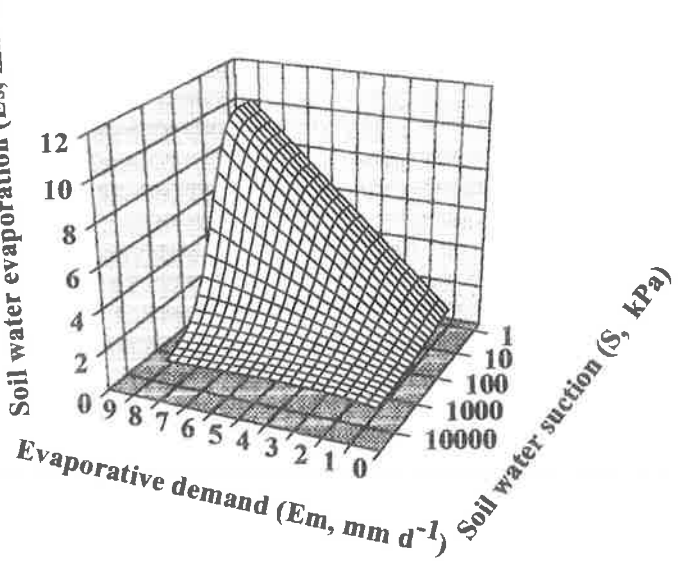
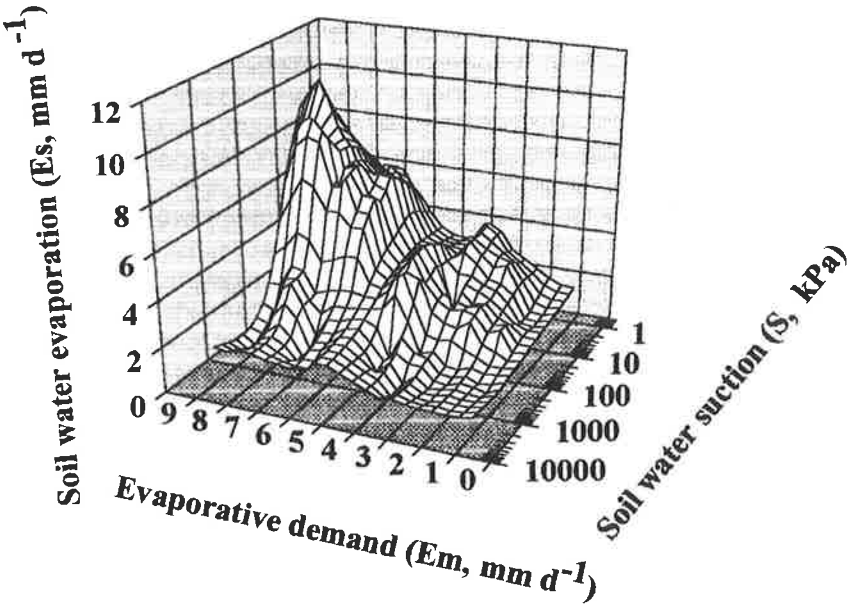


Figure 6.3 The influence of soil water suction (S) and evaporative demand (Em) on soil water evaporation (Es), **(a)** measured Es and **(b)** estimated Es using Equation 6.8, from the continuous wheat crop rotation (WWW) sown by direct drilling (DD) in 1994.

(a) Measured Es in CC-WWW, 1994



(b) Estimated Es in CC-WWW, 1994

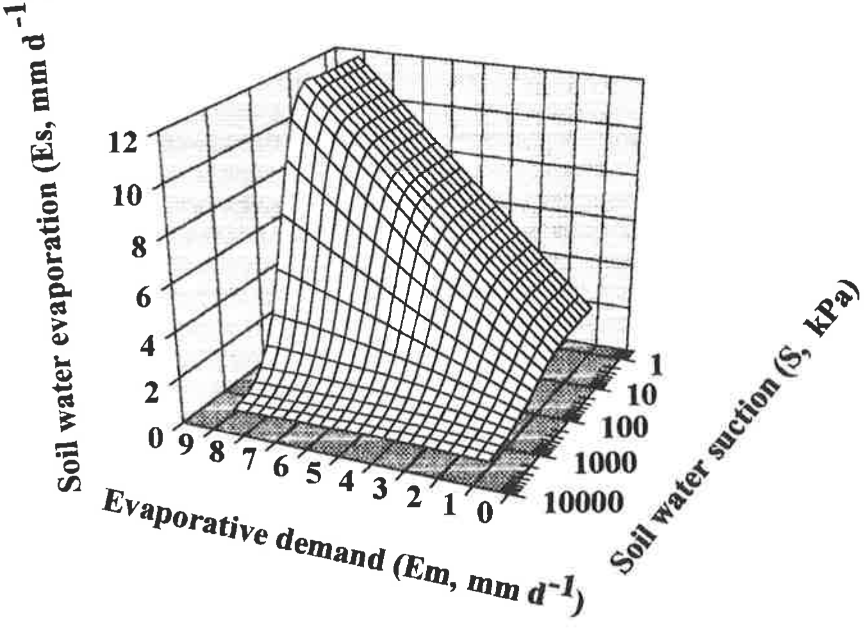


Figure 6.4 The influence of soil water suction (S) and evaporative demand (Em) on soil water evaporation (Es), **(a)** measured Es and **(b)** estimated Es using Equation 6.9, from the continuous wheat crop rotation (WWW) grown with conventional cultivation (CC) in 1994.

Figures 6.3a and 6.4a were created by fitting a surface mesh to measured Es and Em values obtained from either continuous wheat sown by direct drilling (DD-WWW) or conventional cultivation (CC-WWW) in 1994. Figures 6.3b and 6.4b are representations of Equations 6.8 and 6.9 fitted to the data in Figures 6.3a or 6.4a respectively.

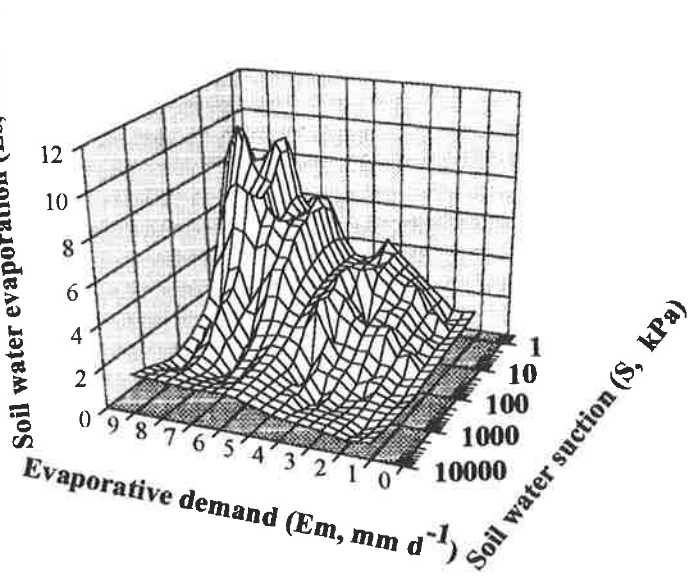
However, the dependencies (SigmaPlot, 1994) of coefficients k_1, k_2 k_3 k_4 and k_5 in each equation were close to 1.0 (varied from 0.88 to 0.98) implying that the coefficients were not independent and the number of coefficients could be reduced to three. Accordingly Equation 6.7 can be written as

$$\mathbf{Es} = \mathbf{Em / (1 + (\log_{10} S/\alpha\,)^{(\beta + \gamma Em)}).} \tag{6.10}$$

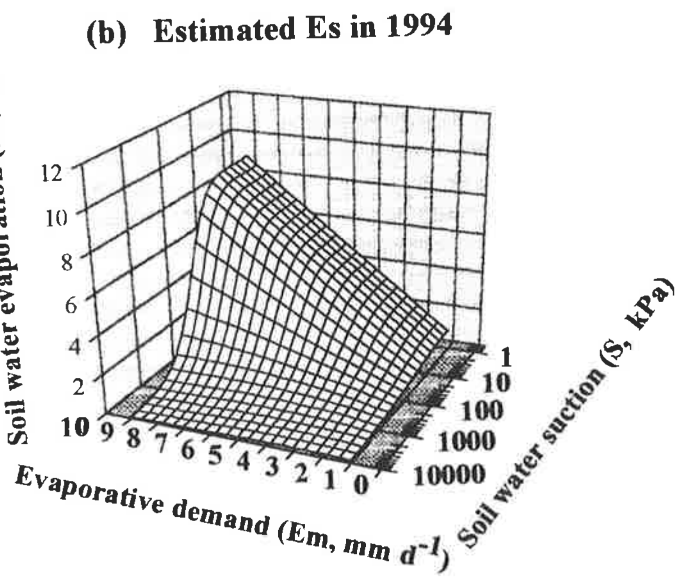
The statistical analysis of the two sets of measured data obtained from direct drilling and conventional cultivation in 1994 were not different at p = 0.05 (t - test value = 0.234, degrees of freedom = 334). Furthermore. the estimated Es generated by Equation 6.8 and 6.9 were not different either (t-test value = 1.572, degree of freedoms = 334). Surface soil structure, available water capacity and aggregate stability of DD and CC treatments were not different in 1994 (Chapter 4). Therefore, the total data set from DD and CC treatments were combined and fitted by a single function in the form of Equation 6.10. The result obtained was

$$\mathbf{Es} = \mathbf{Em / (1 + (\log_{10} S/2.04\,)^{(2.33 + 0.52Em)}).} \quad \mathbf{(R^2 = 0.84)} \tag{6.11}$$

Measured Es and estimated Es (Equation 6.11) were plotted against Em and $\log_{10}(S)$ values as shown in Figures 6.5a and b respectively.



(a) Measured Es in 1994



(b) Estimated Es in 1994

Figure 6.5 The influence of soil water suction (S) and evaporative demand (Em) on soil water evaporation (Es) for, **(a)** measured Es and **(b)** estimated Es using Equation 6.11 **($Es = Em / (1 + (\log_{10} S/2.04)^{(2.33 + 0.52Em)})$)**, in continuous wheat (WWW) sown by direct drilling or conventional cultivation (CC) in 1994.

6.4. Simplified soil water evaporation model

Equation 6.11 shows that Es is directly dependent on Em and inversely dependent on soil matric suction(S). The regression coefficient **b** in Equation 6.6, corresponding to ($\beta + \gamma$ Em) in Equation 6.11, indicates that **b** is a function of Em. However, in order to have a more valid, practical and simpler model, Equation 6.11 was simplified further by eliminating the Em term in the denominator and generalising the regression coefficients giving

$$\mathbf{Es} \quad = \quad \mathbf{Em / (1 + (\alpha \log_{10} S)^{\beta}).} \qquad (6.12)$$

The same set of data used in Equation 6.11 were refitted by Equation 6.12 giving

$$\mathbf{Es} \quad = \quad \mathbf{Em / (1 + 0.016 (\log_{10} S)^{5.77})} \qquad \mathbf{(R2 = 0.82).} \qquad (6.13)$$

This equation is plotted in Figure 6.6.

The regression coefficients α and β of Equation 6.13 are constant with values of 0.016 and 5.77 and gave only small dependencies (SigmaPlot, 1994) of 0.181 with low standard errors of 0.005 and 0.338 respectively. Figure 6.6 shows that this simplified equation can fit a soil water evaporation function for both direct drilled and conventional cultivation treatments with a coefficient of determination (R^2) of 0.82.

Equation 6.13 was used to predict soil water evaporation using a range of soil matric suction and evaporative demand values as shown in Table 6.2. The results are not shown graphically because they are similar to Figure 6.6 since the same function was used to estimate Es.

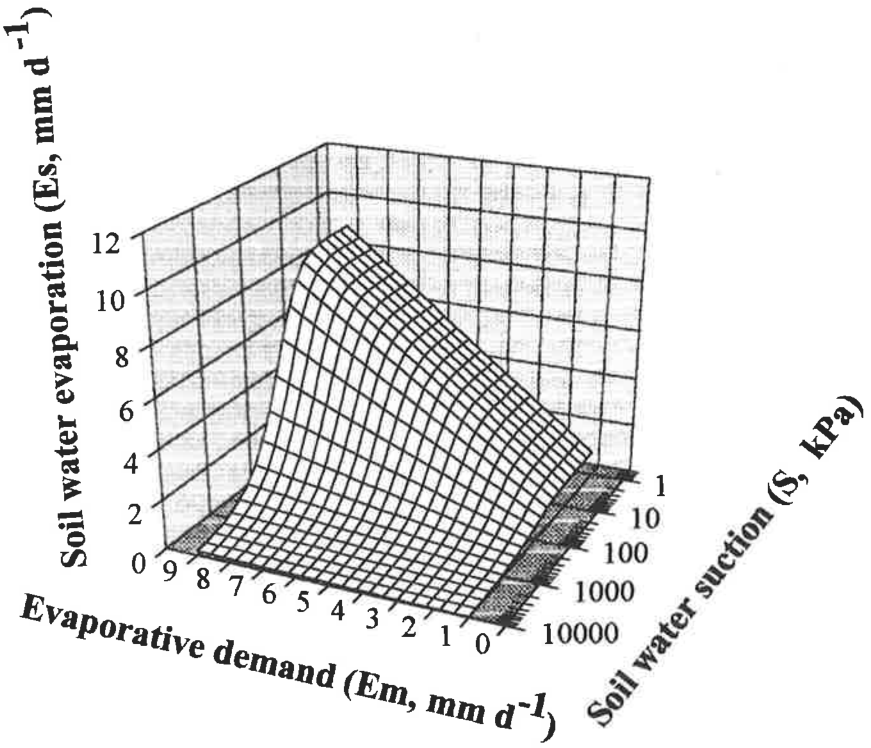


Figure 6.6 Estimated soil water evaporation (Es) using the simplified fitted function (Equation 6.13, $\mathbf{Es = Em / (1 + 0.016 (log_{10}S)^{5.77})}$) as influenced by the evaporative demand (Em) and soil matric suction (S) in continuous wheat sown by both direct drilling (DD) and conventional cultivation (CC) in 1994.

Table 6.2 shows that when soil matric suction (S) ranges from 1 to 10 kPa, soil water content is approximately at saturation and soil water evaporation (Es) is approximately equal to evaporative demand (Em). This result corresponds to Stage I of soil water evaporation as described by Ritchie (1972), Idso et al. (1974), Stroosnijder (1987) and Kutilek and Nielsen (1994).

Table 6.2 Predicted soil water evaporation (Es, mm d^{-1}) using Equation 6.13, Es = Em/(1+0.016 $(\log_{10}S)^{5.77}$) for a range of evaporative demand (Em) and soil matric suction (S) values and calculated relative soil water evaporation (Es/Em)

Matric suction		**Evaporative demand (Em, mm d^{-1})**							**Es/Em**
S **kPa**	**$\log_{10}$(S)**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**(Kes)**
1	**0.00**	1.000	2.000	3.000	4.000	5.000	6.000	7.000	**1.00**
5	**0.70**	0.998	1.996	2.994	3.992	4.990	5.988	6.986	**0.998**
10	**1.00**	0.984	1.969	2.953	3.937	4.921	5.906	6.890	**0.984**
30	**1.48**	0.868	1.736	2.604	3.472	4.341	5.209	6.077	**0.868**
60	**1.78**	0.693	1.386	2.079	2.772	3.465	4.158	4.851	**0.693**
100	**2.00**	0.534	1.068	1.602	2.135	2.669	3.203	3.737	**0.534**
300	**2.48**	0.250	0.500	0.750	1.000	1.250	1.500	1.750	**0.250**
600	**2.78**	0.147	0.293	0.440	0.587	0.734	0.880	1.027	**0.147**
1000	**3.00**	0.099	0.199	0.298	0.398	0.497	0.596	0.696	**0.099**
1500	**3.18**	0.074	0.147	0.221	0.294	0.368	0.441	0.515	**0.074**
2000	**3.30**	0.060	0.120	0.179	0.239	0.299	0.359	0.418	**0.060**
5000	**3.70**	0.032	0.064	0.096	0.128	0.160	0.191	0.223	**0.032**
10000	**4.00**	0.021	0.041	0.062	0.082	0.103	0.123	0.144	**0.021**

As soil dries over a matric suction range from 10 to 300 kPa, Es decreases sharply. For example more than 50% of the total Es is lost by the time that S reaches 300 kPa (Table 6.2). Es at this range of soil matric suction should be controlled by both Em and upward flow of soil water within the surface layers. The upward flux depends on hydraulic conductivity and the hydraulic suction gradient in these layers. This corresponds to Stage II in the Ritchie (1972) model. When the soil surface is very dry with a soil matric suction (S) greater than 1000 kPa (log S =3 kPa) at any level of Em, Es is close to zero and the result can be described as Stage III of soil water evaporation (Idso et al., 1974; Kutilek and Nielsen, 1994).

The relative soil water evaporation (the ratio of soil water evaporation to evaporative demand, Es/Em) was calculated at each soil matric suction and is presented in Table 6.2. The relative soil water evaporation decreases with increasing soil matric suction (S) and does not vary with evaporative demand.

6.5 Test of soil water evaporation function

A data set of measured soil water evaporation (Es), evaporative demand (Em) and associated soil water contents (θ) from the continuous wheat sown by direct drilling and conventional cultivation in 1995 were used to test the performance of Equations 6.11 and 6.13. The soil matric suctions were calculated using the soil water retention functions developed in 1994 (Equations 6.1 and 6.2) which could be linearised to ;

$$\log_{10}(S) = a - b\,\theta \qquad (6.15)$$

The intercept "**a**" and the slope "**b**" of this equation were recalculated over the available water content range from field capacity to wilting point (matric suctions, S of 10 and 1500 kPa respectively). The water contents corresponding to these suctions were 0.248 and 0.264 $m^3\ m^{-3}$ for direct drilled and 0.101 and 0.112 $m^3\ m^{-3}$ for conventionally cultivated treatments. The intercept "**a**" was approximately constant at 4 because wilting point water contents of the surface soil (0-75 mm) were similar in direct drilled and conventionally cultivated treatments during the 4 years of experimentation. Therefore the equations used to transform soil water content to soil matric suction are $\log_{10}(S) = 4 - 12\,\theta$ for direct drilled and $\log_{10}(S) = 4 - 11.4\,\theta$ for conventionally cultivated treatments.

6.5.1 Performance of the simplified function

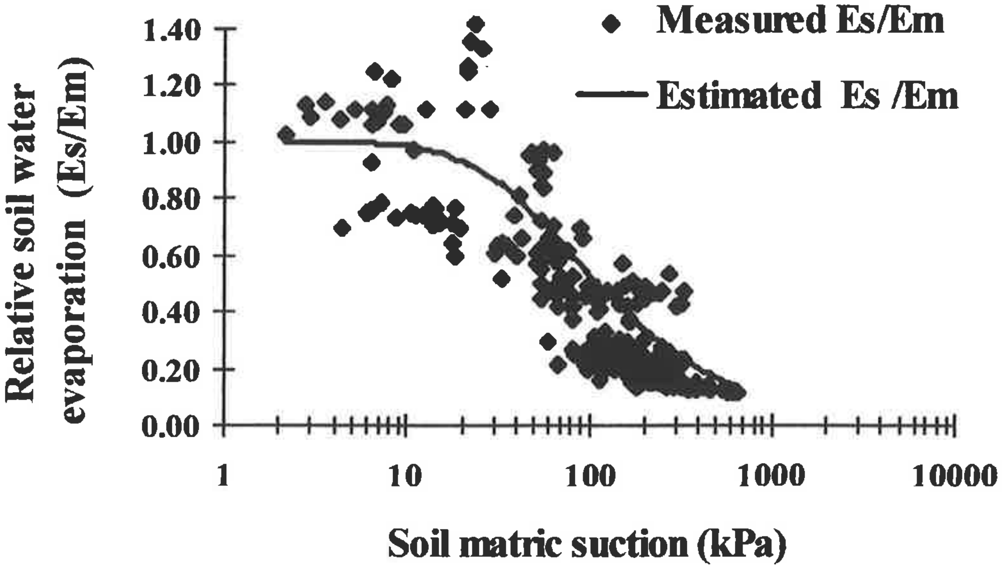
The simplified function (Equation 6.13) was tested based on the two dimensional function showing the relationship between relative soil water evaporation (Es/Em) and soil matric suction (S). The measured relative soil water evaporation for 1995 and the fitted function (Equation 6.13) are presented in Figure 6.7a and b for direct drilled and conventionally cultivated treatments respectively. Estimated relative soil water evaporation (Es/Em) from direct drilled treatments was approximately equal to the average measured Es/Em for moist soil ($S<100$ kPa) but exceeded measured values as the soil became drier ($S>100$ kPa) (Figure 6.7a). In conventionally cultivated treatments the model tended to overestimate Es/Em over most of the range of water contents, particularly $S<300$kPa for CC (Figure 6.7b).

Figure 6.7a and b also show that the large variation of measured Es/Em at high values of evaporative demand (high Es/Em) and soil water content (low S) in both direct drilled and conventionally cultivated treatments indicating that relative soil water evaporation was not only dependent on soil matric suction but also on evaporative demand and soil surface roughness.

6.5.2 The compatibility of the estimated and the measured values of soil water evaporation

The compatibility between the measured soil water evaporation values and the estimated values in 1995 are graphically illustrated in Figures 6.8 and 6.9. The estimated Es and Es/Em using Equations 6.11 and 6.13 were plotted against the measured Es and Es/Em for continuous wheat sown by direct drilling and conventional cultivation as shown in Figure 6.8a and b and Figure 6.9a and b respectively. Estimated Es using Equation 6.13 gave similar results (the graph is not presented).

(a) Es/Em ratio in direct drilled plots (1995)



(b) Es/Em in Conventionally cultivated plots (1995)

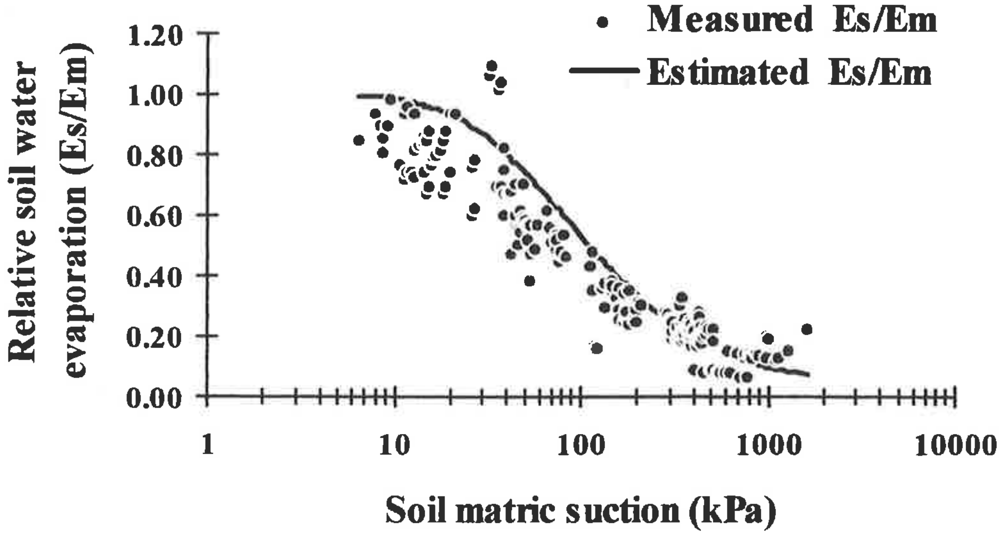
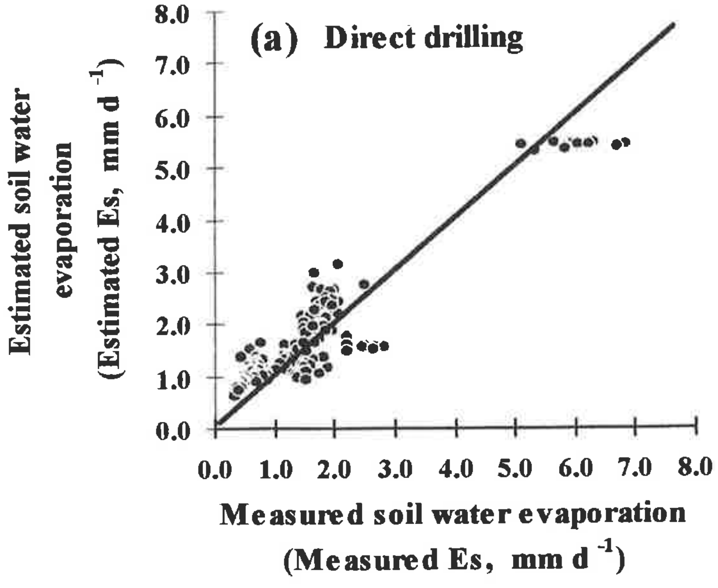


Figure 6.7 Comparison of measured and estimated relative soil water evaporation (Es/Em) using Equation 6.13 at different values of soil matric suction (S) for continuous wheat sown by **(a)** direct drilling (DD) or **(b)** conventional cultivation (CC) in 1995.

Equations 6.11 and 6.13 tended to overestimate soil water evaporation (Figure 6.8 and 6.9) in 1995 because Equations 6.11 and 6.13 were developed using data obtained in 1994 which was an exceptionally dry year and the soil surface was not sealed or crusted by the effects of rainfall impact (Chapter 4). In 1995, with higher rainfall, surface sealing may have been more pronounced on conventionally cultivated treatments whereas the better soil structure in direct drilled treatments would have been less affected. The overestimated Es/Em (Figure 6.9) may indicate that the soil water evaporation was limited by increased surface sealing in 1995. On the other hand, the surface soil thickness (particularly the tilled layer in CC) may have been less than 75 mm due to cumulative compaction of wheel traffic in 1995. This could have caused more variability in the results obtained from Equations 6.13 in that year. To increase the precision of estimated Es or Es/Em, the soil matric suction of the soil surface should be measured directly in the surface soil layer of 0 to 50 mm depth where water contents are most uniform.

The Chi-square test was used to test the compatibility between the measured values of soil water evaporation (Es and Es/Em) and the estimated values using Equations 6.11 and 6.13 for continuous wheat sown by direct drilling or conventional cultivation in 1995. The coefficient of determination (R^2) and the chi-square values (χ^2) are presented in Table 6.3. These data show that Equations 6.11 and 6.13 gave reliable estimates of Es and Es/Em with regression coefficient significance values of 0.05 and Chi-square significance values of 0.01 probability (Table 6.3).



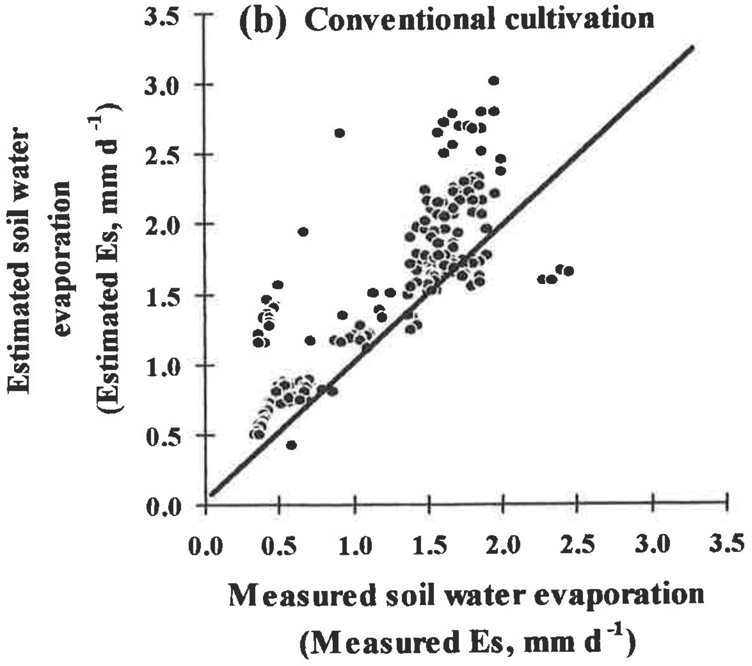
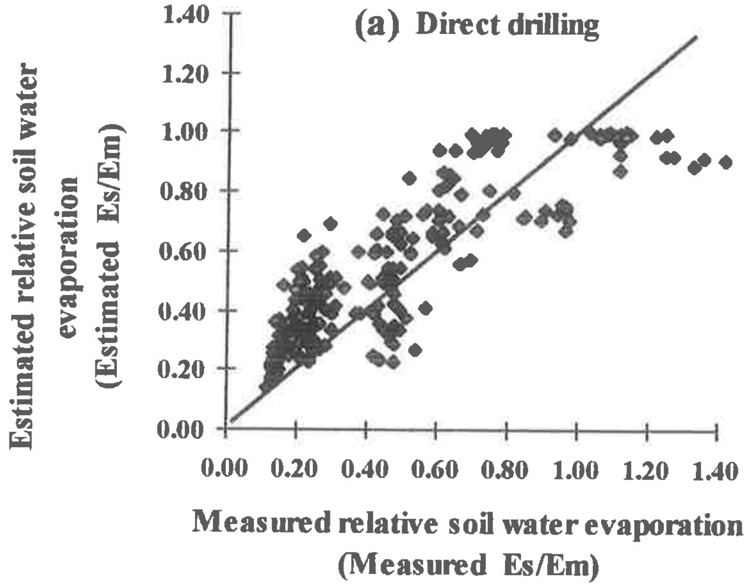
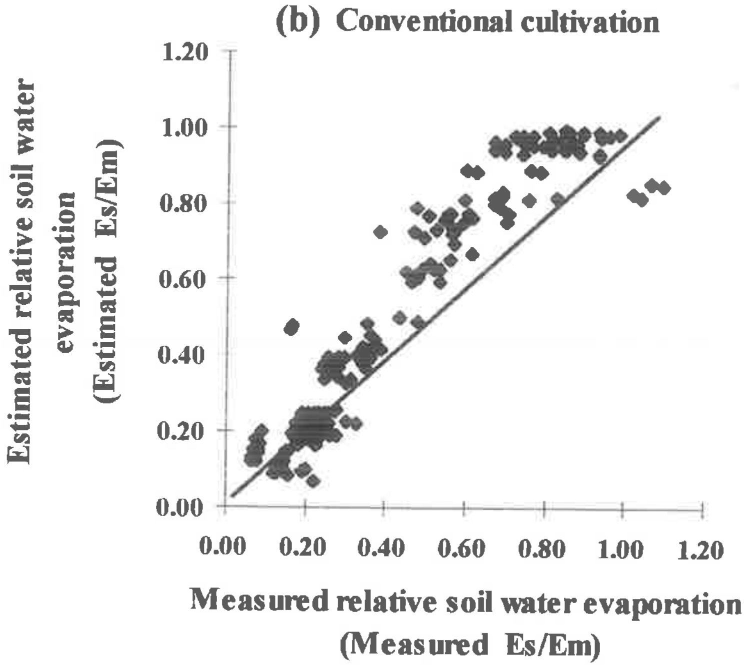


Figure 6.8 Comparison of measured and estimated evaporation using Equation 6.11 $(\mathbf{Es = Em/(1+((log_{10}S)/2.04)^{(2.33+0.52\ Em)}})$ and a data set of Em and the soil water content of the surface soil layer (0-75 mm) under continuous wheat sown by **(a)** direct drilling (DD) and **(b)** conventional cultivation (CC) in 1995. The test of

goodness gave Chi-square values (χ^2) of 40.28 and 25.40 significant at $p = 0.05$ for **(a)** and **(b)** respectively. The line shows the 1:1 relationship.



(a) Direct drilling



(b) Conventional cultivation

Figure 6.9 Comparison of measured and estimated evaporation using Equation 6.15 (**$Es/Em = 1/(1+0.016\ (\log_{10}S\ )^{5.77})$**) and a data set of Em and the soil water content of the surface soil layer (0-75 mm) under continuous wheat sown by **(a)** direct drilling (DD) and **(b)** conventional cultivation (CC) in 1995. The test of goodness of fit gave Chi-square values (χ^2) of 12.95 and 5.47 significant at $p = 0.05$ for **(a)** and **(b)** respectively. The line shows the 1:1 relationship.

Table 6.3 Statistical tests of the goodness of fit of soil water evaporation functions in 1995.

Fitting Equation and the performance of fitted function	**Coefficient of Determination (R^2 Chi-square test (χ**	**Degree c freedon**	**Significant level at p**
Test of fitting Equation 6.11	**$R^2 = 0.84^*$**	178	0.05
Test of fitting Equation 6.13	**$R^2 = 0.82^*$**	360	0.05
Comparison of the measured field data in 1995 and the estimated values (Es, Es/Em)			
Estimated Es			
Using Eq. 6.11 for Direct drilling	**$\chi^2 = 40.28^{**}$**	230	0.01
Using Eq. 6.11 for Conventional Cultivation	**$\chi^2 = 25.40^{**}$**	205	0.01
Estimated Es			
Using Eq. 6.13 for Direct drilling	**$\chi^2 = 35.86^{**}$**	230	0.01
Using Eq. 6.13 for Conventional Cultivation	**$\chi^2 = 18.94^{**}$**	205	0.01
Estimated Es/Em			
Using Eq. 6.13 for Direct drilling	**$\chi^2 = 12.95^{**}$**	230	0.01
Using Eq. 6.13 for Conventional Cultivation	**$\chi^2 = 5.47^{**}$**	205	0.01

The statistical results in Table 6.3 show that there were no significant differences between the estimated Es obtained from Equations 6.11 and 6.13. Both equations gave similar estimates of Es. This confirms that the simplified soil water evaporation function (Equation 6.13) is not inferior to the original developed function (Equation 6.11). In fact Equation 6.11 should be more sensitive to evaporative demand than Equation 6.13 because the variable "Em" was included in the power term of soil matric suction ($S^{(2.33+0.52Em)}$). However, the simplified Equation 6.13 tended to give estimated Es closer to the measured values ($\chi^2 = 35.86$ and 18.94 in DD and CC plots respectively) than

Equation 6.11 ($\chi^2 = 40.28$ and 25.40 in DD and CC plots respectively) which indicates that the simplified soil water evaporation function is more preferable for predicting soil water evaporation. Equation 6.13 will be referred to as the "Roseworthy Soil Water Evaporation" (RSWE) model and was used to predict daily water lost from the soil surface during the growing seasons from 1992 to 1995 in Chapter 7.

6.6 Discussion and conclusions

(i) Soil water evaporation was modelled in order to predict water loss from the soil surface under a crop canopy during different growing seasons with different rainfall and weather conditions. The procedures were generation of the model, model simplification and testing of the model performance.

(ii) Generation of the model was accomplished by using a data set of evaporative demand (Em) and soil matric suction (S) measured by microevaporimeters and microlysimeters placed under the canopy of a wheat crop in a continuous wheat rotation and sown by direct drilling or conventional cultivation in 1994. The model was developed from the relationships between soil water evaporation rate and the soil matric suction at different fixed levels of evaporative demand. Four fitted functions were obtained from four different ranges of evaporative demand and the regression coefficients were plotted as functions of the evaporative demand. The first model was a sigmoid function of soil water evaporation varying with evaporative demand as a power of soil matric suction and had three regression coefficients.

(iii) The model was reduced to two independent variables, evaporative demand and soil matric suction and simplified to two regression coefficients. The simplified model was used in the form of a relative soil water evaporation function varying as a function of a single variable, soil matric suction.

(iv) The model was tested with a data set of soil water evaporation measured under the canopy of the continuous wheat rotation sown by direct drilling and conventional cultivation in 1995. The chi-square test was used to judge compatibility between measured and estimated values of soil water evaporation .

(v) Model performance testing showed that the two models generated from 1994 data performed similarly and tended to overestimate Es and Es/Em in 1995 particularly for the conventionally cultivated treatments.

(vi) The Roseworthy Soil Water Evaporation model (RSWE, Equation 6.13) which predicts soil water evaporation, was developed from a set of field data under low rainfall and unusual climatic conditions in 1994. For this reason, the model was less precise in predicting soil water evaporation in wetter years because of more extensive surface sealing and crusting caused by rainfall impact. For example, in 1995 measured soil water evaporation was lower than the estimated values using the RSWE model developed from a field data set obtained in 1994 because surface soil structure was adversely influenced by the higher rainfall in 1995.

(vii) The regression coefficients of Equations 6.11 and 6.13 may vary with surface soil properties such as sealing (crusting) and surface roughness conditions. The surface soil matric suction may not provide a good measure of soil water evaporation if the surface soil layer is not uniform. Using the soil water characteristic for depths less than 50 mm may avoid the error in average matric suction of the soil surface and provide a better estimate of evaporation.

(viii) The RSWE model was not tested continuously under field conditions throughout the growing season and may need to be modified for different types of soil and different climatic conditions. However, this model is easier use and has better theoretical support, (based on energy status of the atmosphere, the soil water characteristic, and soil matric suction), compared with the two widely used soil water evaporation models, Ritchie (1972) model and Stroosnijder (1987) model (Chapter 2, Section 2.5.3).

(ix) The transition from Stage I to Stage II soil water evaporation in the Ritchie (1972) and Stroosnijder (1987) models are not well defined. Furthermore, the models used to predict soil water evaporation in the two stages are not linked and are quite different (Section 2.5.3). The Roseworthy Soil Water Evaporation model uses only one equation which can predict all the three stages of daily soil water evaporation regardless of the transition from one stage to another.

(x) The RSWE model estimates daily soil water evaporation based on daily evaporative demand and the surface soil matric suction with the two constant soil parameters (α and β) which may be varied with soil type and surface roughness.

$$\mathbf{Es = Em / (1+\alpha (\log_{10} S)^{\beta}} .$$

The advantages of the RSWE model are (1) The model can be used at any day and any stage of soil water evaporation regardless of day number or time when soil drying began. (2) The model is based on evaporative demand (Em) and soil matric suction (S) which are the two main factors that control soil water evaporation. These two factors are related directly to the energy balance affecting water evaporation from the soil surface. (3) The soil matric suction may be easily estimated from soil water content by using a soil water retention curve. (4) The RSWE model is a sigmoid function of soil water evaporation and soil matric suction at a given evaporative demand. The various segments of the sigmoid function in the soil water evaporation model correspond to the three stages of soil water evaporation described earlier (Chapter 2, Section 2.4.1).

(xi) In 1994, predicted soil water evaporation from direct drilled treatments was similar to that from conventionally cultivated treatments. In 1995, the same model overestimated soil water evaporation. The reason for this was thought to be that the change in soil surface properties due to rain drop impact (Chapter 4) were sufficient to change the evaporation characteristic. This difference may have been reduced by using a soil moisture characteristic for the 1995 soil condition, but this was not available. Only estimated soil water suction based on soil water content at field capacity (matric suction at 10 kPa) using the soil water retention function developed in 1994 was available. While the technique used here has some promise for general application, further examination of the relationship between model predictions and changes in soil surface structure are required.

CHAPTER 7

PARTITIONING EVAPORATION AND TRANSPIRATION BY MODELLING

7.1 Introduction

Modelling is useful in describing complex, time dependent processes such as the soil water balance. Chapters 5 and 6 have shown that the interactions between tillage, crop growth and climatic conditions in dryland farming systems are complex. This complexity has prompted considerable effort to develop models of water balance and crop growth over the past 20 years. Only with the use of such models can research questions and hypotheses relating to such complex systems be properly investigated.

A wide range of models have been developed, ranging from simple regression relationships between rain and yield (eg French and Schultz, 1984) to full scale water balance simulations but with varying scales of complexity (Ritchie, 1974; Greacen and Hignett, 1976; Monteith, 1981; Lhomme and Katerji, 1991). The most reliable soil water balance models address soil water evaporation and crop transpiration separately. These processes are substantially different in character and have opposing effects on crop water use efficiency.

Most models described in Chapter 2 (Section 2.5) do not account for differences in topsoil properties which result from different tillage practices (Chapter 4). Furthermore, the more complex models such as the Penman-Monteith model (Monteith, 1981) (Section 2.5) are often impractical to use because of the great detail required in input data (for example, net radiation and surface resistance, for each crop canopy, relative humidity, soil heat flux density, wind speed and leaf area index) which are difficult and expensive to measure reliably. Very often only approximate data are available and the results often do not explain treatment differences. For this reason simple models that require less complex data are often more practical.

The aim of the work reported in this chapter was to develop a simple soil water balance model (Roseworthy Water Use model, RWU) to simulate some of the hydrological aspects of a dryland farming system as affected by different tillage practices. The model focuses on aspects of soil water evaporation and crop transpiration which affect the water use efficiency of wheat crops sown by direct drilling or conventional cultivation during a succession of seasons with different weather conditions.

7.2 Model development and description

The soil water balance model described here focuses on daily water use in terms of soil water evaporation (E_{si}), crop transpiration (T_{ci}) and the available soil water within 2 m soil depth. The processing sequences for the Roseworthy Water Use (RWU) model (this chapter) and the Roseworthy Soil Water Evaporation (RSWE) model (Chapter 6) are presented in Figures 7.1 and 7.2 respectively. A general description of the development and properties of the model follow.

(i) Daily rainfall data input was obtained from daily rainfall data collected at the experimental site as described in Chapter 3 (Section 3.5.3).

(ii) Evaporative demand was calculated from daily Class-A pan evaporimeter data from Turretfield weather station located approximately 15 km from the experimental plot.

Roseworthy Water Use (RWU) model

Input data file of
daily rainfall and pan evaporation

↓

Calculation of the pan factor (Kp)
at average maximum water use (ETpm)
$Kp = ETpm / Epetm$
$Kp = 4.44 / 4.48 = 0.99$

↓

Calculation of daily potential evapotranspiration (ETpi)
$ETpi = Kp\ Epi = 0.99\ Epi$

↓

Calculation of the maximum crop transpiration factor (Kt)
at average maximum potential crop transpiration
(with full cover, no-stress, dry soil surface)
$Kt = Tcpm / ETptm = Tcpm / Kp\ Eptm$
$Kt = 5.38 / 0.99 \times 5.60 = 0.97$

↓

Calculation of daily dry matter (DMi)
from a fitted crop growth function for each year

↓

Generate daily fresh weight (Fwi)
$Fwi = (6.68 \exp(-0.012)\ Di)\ DMi$

↓

Calculation of daily crop factor (Kci)
$Kci = Fwi / Fwp$

↓

Calculation of the daily potential transpiration (Tcpi)
$Tcpi = Kt\ ETpi\ Kci$
$= 0.96\ Kp\ Epi\ Kci$
$Tcpi = 0.97\ Epi\ Kci$

↓

Calculation of the daily soil water factor (Ksi)
$AWf = AWi / AWm$
$AWf = (SWi - WP) / (SWm - WP)$
$Ksi = 1 \quad (AWf > 0.5)$
$Ksi = 2\ AWf \quad (AWf < 0.5$

↓

Calculation of the daily actual crop transpiration (Tcai)
$Tcai = Ksi\ Tcpi$

Figure 7.1 Flow chart of daily Roseworthy Soil Water Use model.

Roseworthy Soil Water Evaporation (RSWE) model

Input data file of daily rainfall and daily potential soil water evaporation (Espi)

$Espi = ETpi - Tcpi$

↓

Input data for the surface soil (tilled layer)
Surface soil depth (SD, mm) ?
Soil water content at 10 kPa (FC, $m^3\ m^{-3}$) ?
Soil water content at 1500 kPa (WP, $m^3\ m^{-3}$) ?
Initial soil water content at sowing date, (θo, $m^3\ m^{-3}$) ?

↓

Calculation of intercept 'a' and slope 'b' for soil water retention function

$a = 1 + b\ FC$

$b = 2.18 / (FC - WP)$

↓

Calculation of maximum stored soil water (SWm) and initial stored soil water (SWo)

$SWm = FC \times SD$

$SWo = \theta o \times SD$

↓

Calculation of daily stored soil water (SWi)

$SWi = SWi_{-1} + Pi - Esi_{-1}$

↓

Calculation of daily soil water content (θi)

$\theta i = SWi / SD$

↓

Calculation of the daily soil matric suction (Si)

$\log_{10}Si = a - b\ \theta i$

$\log_{10}Si = 4 - b\ \theta i$

↓

Calculation of daily soil water evaporation

$\mathbf{Esi = Espi / (1 + 0.016\ (\log_{10}Si)^{5.77})}$

End of day

Figure 7.2 Flow chart for the daily Roseworthy Soil water Evaporation model.

This site was chosen as it had a complete daily data set for 4 years of the experiment and correlated highly ($R^2 > 0.95$) with the intermittent readings at the experimental site.

(iii) A function to interpolate daily dry matter production was fitted to measured dry matter data at different crop growth periods as described in Chapter 3.

(iv) Potential crop transpiration (T_{cp}) and actual crop transpiration (T_{ca}) were calculated from evaporative demand (Class A pan evaporimeter), fresh biomass above ground level and available soil water within 2 m soil depth.

(v) Calculation of daily soil water evaporation was based on surface (0 to 75 mm) matric suction measurements and evaporative demand using the simplified soil water evaporation model developed in Chapter 6. The surface soil water suction was estimated from daily volumetric water content at the soil surface (0 to 75 mm) using the soil water retention function measured in 1994. Because the water retention curve varied from year to year, slope was modified to take account of this by using water content at field capacity and wilting point for each year. The daily soil water content was estimated from soil water content from the previous day plus measured rainfall minus modelled evaporation (Equation 6.13).

(vi) The actual water used by the crop or total soil water lost through actual evapotranspiration was calculated as the summation of the daily simulated actual soil water evaporation (using matric suction and evaporative demand) and the daily simulated actual crop transpiration (using fresh biomass and available soil water content).

(vii) Relative dry matter water use efficiency was calculated from maximum water use efficiency, cumulative actual evapotranspiration and cumulative dry matter production.

(viii) Daily available water left in the soil profile was calculated from the total available soil water within 2 m depth left from the previous day, plus the amount of daily rainfall and minus the amount of water lost through actual evapotranspiration.

Data from two growing seasons, 1993 and 1994 for continuous wheat sown by direct drilling or conventional cultivation were used to develop the model and its various components. The data used were soil water content, evaporative demand, daily rainfall, and dry matter production. The soil water balance was computed from daily rainfall data as water gain and evaporation and transpiration as water losses. Water loss from the crop canopy was based on daily evaporative demand. The pan coefficient (K_p), the crop factor (K_c) and the soil water factor (K_s) which influenced crop water use were developed as described below.

7.2.1 Pan factor and daily potential evapotranspiration

Average maximum potential evapotranspiration of a crop canopy (ET_{pm}, 4.44 mm d^{-1}) was obtained from average water lost from the field during full crop cover when the soil surface was wet (observed in 1992, 142 to 160 days after sowing, Chapter 5). This value of ET_{pm} was divided by the average evaporation from a Class-A pan during the same period (E_{pctm}, 4.48 mm d^{-1}) to obtain a pan coefficient, K_p

$$\mathbf{K_p = ET_{pm} / E_{petm} = 4.44 / 4.48 = 0.99.} \qquad (7.1)$$

The daily potential evapotranspiration (ET_{pi}) was calculated as the product of daily evaporation from a Class A pan (E_{pi}) and the pan coefficient

$$\mathbf{ET_{pi} = K_p E_{pi} = 0.99 E_{pi} \sim E_{pi}.} \qquad (7.2)$$

Equation 7.2 shows that evaporation from a Class-A pan could be directly used as daily potential evapotranspiration. A full range of daily potential evapotranspiration on day i after sowing (ET_{pi}) for each growing season from 1992 to 1995 was equal to daily evaporation from a Class-A pan.

7.2.2 Crop transpiration factor

Maximum potential crop transpiration (T_{cpm}, 5.38 mm d^{-1}) occurred from 122 to 138 days after sowing in 1993 (Chapter 5) under conditions of full crop cover from the fully developed crop, fully supplied with subsurface soil water but with a dry surface. Soil water evaporation was assumed to be negligible during this period. The corresponding average daily potential evapotranspiration (ET_{ptm}) estimated from the corresponding E_{pi} (5.60 mm d^{-1}) (Equation 7.2) during this period of maximum potential crop transpiration (T_{cpm}) was used to calculate a transpiration factor (K_t)

$$\mathbf{K_t = T_{cpm} / ET_{ptm} = T_{cpm} / K_p\, E_{ptm} = 5.38 / (0.99 \times 5.60) = 0.97.} \qquad (7.3)$$

7.2.3 Crop growth function

Dry matter (DM) production of wheat at different stages of crop growth in the continuous wheat crop rotation sown by direct drilling and conventional cultivation in 1993, 1994 and 1995 are presented in Figure 7.3.

Dry matter production in 1992 was measured only twice during maturity. Daily dry matter for that year was then estimated from these data, measured cumulative water use and a function dependent on time (days after sowing) (Equations 7.4 and 7.5) for direct drilling and conventional cultivation respectively.

Polynomial functions were fitted to the measured cumulative dry matter of the other years (1993 to 1995) from tillering to maturity (Figure 7.1). The functions are shown in Equations 7.6 to 7.11.

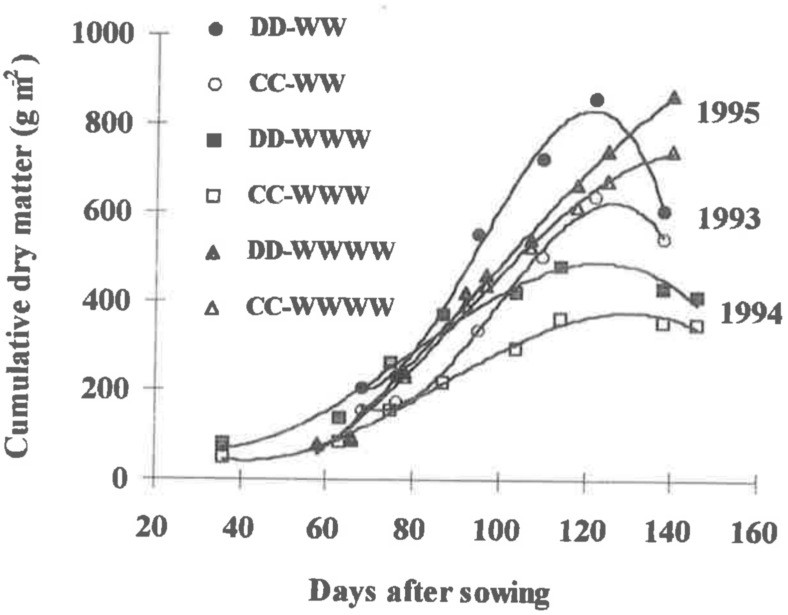


Figure 7.3 Cumulative dry matter of wheat as influenced by the length of time under wheat and sowing method (direct drilling, DD and conventional cultivation, CC) in 1993, 1994 and 1995. Data were fitted by Equations 7.6 to 7.11.

Daily dry matter production (DM) of wheat was calculated as polynomial functions of time, ie days after sowing (Di) for direct drilling and conventionally cultivated treatments

1992 **DD-Wheat** $\mathbf{DM = 59 - 3.8\,D_i + 0.12\,D_i^{\,2} - 0.0004\,D_i^{\,3}}$ $\mathbf{R^2 = 0.98}$ (7.4)

CC-Wheat $\mathbf{DM = 47 - 3.4\,D_i + 0.10\,D_i^{\,2} - 0.0004\,D_i^{\,3}}$ $\mathbf{R^2 = 0.98}$ (7.5)

1993 **DD-WW** $\mathbf{DM = 5721 - 201\,D_i + 2.31\,D_i^{\,2} -0.008\,D_i^{\,3}}$ $\mathbf{R^2 =0.99}$ (7.6)

CC-WW $\mathbf{DM = 4804 - 160\,D_i + 1.74\,D_i^{\,2} -0.006\,D_i^{\,3}}$ $\mathbf{R^2 = 0.99}$ (7.7)

1994 **DD-WWW** $\mathbf{DM = 1262 - 64\,D_i + 1.02\,D_i^{\,2} -0.005\,D_i^{\,3}}$ $\mathbf{R^2 = 0.99}$ (7.8)

CC-WWW $\mathbf{DM = 561 - 28\,D_i + 0.44\,D_i^{\,2} -0.002\,D_i^{\,3}}$ $\mathbf{R^2 = 0.99}$ (7.9)

1995 **DD-WWWW** $\mathbf{DM = 65 - 6\,D_i + 0.18\,D_i^{\,2} -0.0006\,D_i^{\,3}}$ $\mathbf{R^2 = 0.99}$ (7.10)

CC-WWWW $\mathbf{DM = 333 - 20\,D_i + 0.34\,D_i^{\,2} -0.001\,D_i^{\,3}}$ $\mathbf{R^2 = 0.99}$ (7.11)

Total fresh biomass was measured several times during crop development in 1993 and 1995. The ratio of fresh and dry biomass (Fw/DM) was regressed as a function of time after sowing (t, days)

$$\mathbf{Fw / DM} = \mathbf{6.68\,exp(-.012t)} \qquad R^2 = 0.97 \qquad (7.12)$$

Equations 7.4 to 7.11 and Equation 7.12 were used to calculate daily fresh biomass of wheat above the soil surface for each year and each treatment. Crop transpiration is really dependent on leaf area index (Ritchie, 1972) rather than fresh biomass. However, the fresh biomass (Fw, g m^{-2}) is closely related to leaf area index (Equation 7.13) (LAI) and this justified Equation 7.12.

$$\mathbf{Fw} = \mathbf{322.8\,LAI + 83.26} \qquad R^2 = 0.94 \qquad (7.13)$$

Daily fresh biomass of the crop also varied with the available water during drought periods but this effect was considered to be negligible. Therefore crop transpiration was mainly dependent on fresh biomass above the ground surface.

7.2.4 Daily potential crop transpiration

Daily potential crop transpiration (T_{cpi}) was estimated from relative fresh biomass and daily potential evapotranspiration (ET_{pi}). The daily fresh biomass was divided by a maximum fresh biomass obtained in 1993 (1396 g m^{-2}), which corresponded to the maximum crop transpiration. This ratio gave a relative fresh biomass which is defined as a daily crop factor (K_{ci}). Daily potential crop transpiration (T_{cpi}) without soil water stress was calculated as

$$\mathbf{T_{cpi} = K_t\,ET_{pi}\,K_{ci} = 0.96\,ET_{pi}\,K_{ci}.} \qquad (7.14)$$

7.2.5 Soil water factor

Maximum available soil water (AW_m) and the daily available soil water (AW_i) in the soil profile to a depth of 2 m was used to calculate the daily soil water factor (K_{si}) which limited crop transpiration. Crop transpiration was not limited until the daily available water (AW_i) was less than 50 % of maximum available water (AW_m). The available soil water fraction (AW_f) was used to calculate a daily soil water factor (K_{si}) based on a general soil water availability function (Greacen and Hignett, 1976; Jensen et al., 1990)

$$\mathbf{AW_f = AW_i / AW_m = (SW_i - SW_w) / (SW_m - SW_w)} \qquad (7.15)$$

$K_{si} = 1$ for $AW_f \geq 0.5$ and $K_{si} = 2\,AW_f$ for $AW_f < 0.5$.

SWi is daily stored soil water (mm), SWm is maximum stored soil water at field capacity (782 mm) and SWw is stored soil water at wilting point (427 mm). SW_m and SW_w were obtained from the field at maximum stored soil water in 1992 and the minimum stored soil water when the crop wilted permanently in 1994 respectively. This gave AWm equal to 355 mm which was used for all 4 years of the experiment because maximum soil water holding capacity was not affected by different treatments and climatic conditions as shown in Chapter 5.

7.2.6 Actual crop transpiration

Daily actual crop transpiration (T_{cai}) was calculated as the product of daily potential crop transpiration (T_{cpi}) and the corresponding daily soil water factor (K_{si})

$$\mathbf{T_{cai} = K_{si}\, T_{cpi}}. \qquad (7.16)$$

7.2.7 Soil water evaporation

Daily actual evaporation (E_{sai}) was estimated from daily matric suction and daily potential evaporation (E_{spi}) as an evaporative demand (E_m) at the soil surface. The difference between daily potential canopy evapotranspiration (ET_{pi}) and potential crop transpiration (T_{cpi}) was used as daily potential soil water evaporation (E_{spi})

$$\mathbf{E_{spi} = ET_{pi} - T_{cpi}} . \qquad (7.17)$$

7.2.7.1 Estimation of soil matric suction

The daily soil water content (θ_i) of the surface soil (0-75 mm) was calculated from the daily stored water (SWi, mm) in the surface soil (0 to 75 mm) divided by surface soil depth (SD, mm). SWi was calculated from the initial soil water content or the soil water content on a previous day, surface soil thickness (SD, mm), the daily rainfall (Pi, mm) and the soil water evaporation loss from the previous day (Es_{i-1}, mm)

$$\boldsymbol{\theta_i = (\theta_{i-1} / SD + Pi - Es_{i-1}) / SD.} \qquad (7.18)$$

Soil matric suction (S_i, kPa) was then estimated from the soil water content (θ_i, $m^3\ m^{-3}$) using Equation 6.15

$$\mathbf{\log_{10} (S_i) = a - b\,\theta_i} \qquad (7.19)$$

Regression coefficients **a** and **b** for each treatment were dependent on surface soil structure which varied depending on the method of sowing and rainfall conditions (Chapter 4). The soil water contents at field capacity (matric suction 10 kPa) and wilting point (1500 kPa) were used to calculate the slope **b** of the soil water retention function.

$$\mathbf{b = (4 - \log_{10} S) / FC = (4-1) / FC.} \qquad (7.20)$$

Because the wilting point was independent of treatment and rainfall, the intercept **a** of Equation 7.19 assumed a constant value of 4 (equivalent to a matric suction 10,000 kPa).

Field capacity values, initial soil water contents at the time of sowing and the calculated slope values (**b**) of the soil water retention function of the surface soil for continuous wheat sown by direct drilling and conventional cultivation from 1992 to 1995 are presented in Table 7.1.

Table 7.1 Field capacity water contents (matric suction 10 kPa), initial soil water contents at the time of sowing and the slope (**b**) of the soil water retention function for successive crops of wheat sown by direct drilling (DD) or conventional cultivation (CC).

Experimental Year	Treatment	Field capacity ($m^3 m^{-3}$)	Initial soil water content ($m^3 m^{-3}$)	Slope values (b)
1992	DD-Wheat	0.230	0.212	12.88
	CC-Wheat	0.278	0.223	10.79
1993	DD-WW	0.225	0.225	13.33
	CC-WW	0.310	0.310	9.68
1994	DD-WWW	0.233	0.212	12.88
	CC-WWW	0.256	0.223	11.72
1995	DD-WWWW	0.248	0.214	12.10
	CC-WWWW	0.264	0.225	11.36

7.2.7.2 Estimation of actual soil water evaporation

The soil water evaporation function developed in Chapter 6, Equation 6.13, was used as a sub-model in this soil water balance model but rewritten as

$$E_{si} = E_{spi} / (1 + 0.016 (\log_{10} S_i)^{5.77}) \quad (7.21)$$

where E_{si} is the actual daily soil water evaporation (mm), E_{spi} is daily potential soil water evaporation or evaporative demand (E_{mi}) on day i (mm), and S_i is the surface soil (0 to 75 mm) matric suction (kPa) calculated on day i after sowing.

7.2.8 Estimation of the available stored soil water

The daily change of stored soil water resulting from rainfall or evaporation was calculated

$$
\begin{aligned}
\mathbf{SW_i - SW_{i-1}} &= \mathbf{E_{si} - T_{ci} - D_{ri}} \\
\mathbf{AW_i} &= \mathbf{P_i + AW_{i-1} - E_{si} - T_{ci} - D_{ri}} \qquad (7.22)
\end{aligned}
$$

where SW_i and SW_{i-1} are the stored soil water (mm) within 2 m soil depth on day i and day i-1 respectively, P_i is rainfall (mm), AW_i is available soil water (mm), E_{si} is soil water evaporation (mm), T_{ci} is transpiration and D_{ri} is deep drainage (mm) beyond 2 m depth from day i-1 to day i.

7.3 Model assumptions

(i) Surface runoff was negligible on the research site because of the low slope (<2 %). Deep drainage below 2 m only occurs when water contents exceed field capacity values which was observed only for a short time in 1992. For this reason surface runoff and canopy interception loss terms in the water balance model were neglected.

(ii) Deep drainage beyond 2 m depth were assumed to be negligible for all growing seasons. Except for short periods in 1992, this assumption seems justified.

(iii) The available water capacity within 2 m soil depth was calculated from the actual maximum stored soil water at field capacity in the wettest year and wilting point as the driest soil profile in the driest year when permanent wilting commenced.

(iv) Daily rainfall was added to the surface soil layer (0-75 mm), but when the water content was higher than the field capacity value, excess water was allowed to drain to deeper layers. When this occurred soil water evaporation was assumed to be equal to the smaller of evaporative demand or potential soil water evaporation.

(v) Evaporation of water from soil occurred at the potential rate when the surface soil (0 to 75 mm) matric suction was equal to or lower than 10 kPa or when the soil water content was equal to or higher than field capacity.

7.4 Model performance

The Roseworthy Water Use (RWU) model was used to predict the soil water evaporation, crop transpiration and the available soil water for continuous wheat sown by direct drilling and conventional cultivation. Simulations were based on daily rainfall and evaporation from a Class-A pan from 1992 to 1995. The performance of the model in predicting soil water evaporation, crop transpiration, available soil water and cumulative water use or cumulative evapotranspiration of wheat was evaluated.

7.4.1 Simulation of soil water evaporation and crop transpiration

Simulated daily actual soil water evaporation (E_{si}), daily crop transpiration (Tca) and daily available stored soil water (ASW), as influenced by rainfall in continuous wheat (WWWW) sown by direct drilling (DD) or conventional cultivation (CC), are presented in Figure 7.4, 7.5, 7.6 and 7.7 for 1992, 1993, 1994 and 1995 respectively. Simulated growing season total evaporation, transpiration, evapotranspiration and dry matter water use efficiency are shown in Table 7.2. Measured evapotranspiration and dry matter water use efficiency are also shown for comparison.

In 1992 (Figure 7.4) the daily actual soil water evaporation (E_{sa}) from direct drilled treatments was predicted to be higher during the first week after sowing and lower during tillering to maturity compared with evaporation from conventionally cultivated treatments. By contrast, daily actual crop transpiration (Tca) predicted from direct drilled treatments was higher than from conventionally cultivated treatments during tillering to maturity. Daily available stored soil water in direct drilled treatments was predicted to be less than that in conventionally cultivated treatments throughout the growing period. However, the model showed that daily actual evapotranspiration (ETa) from direct drilled and conventionally cultivated treatments was not different. These results suggested that the water lost from the direct drilled soil surface before crop emergence was higher due to lower soil matric suction compared to that lost from the bare soil surface of conventionally cultivated soil. This apparent contradiction can be explained by the higher soil water content of direct drilled treatments (Chapter 4). When the crop water use was simulated, soil water evaporation was then dependent on the evaporative demand at the soil surface under a crop canopy. Under these conditions, (direct drilling having greater biomass and therefore a higher leaf area index), transpiration increased and evaporative demand at the soil surface was reduced due to increased shading compared to conventional cultivation. A similar result was obtained for simulations done for 1993 when soil water evaporation from direct drilled treatments was predicted to be higher than that from conventionally cultivated treatments.

In 1993 (Figure 7.5) daily actual soil water evaporation (Esa) was predicted to be lower and daily actual crop transpiration (Tca) higher on direct drilled treatments throughout the growing period compared to the conventionally cultivated treatments. The available stored soil water was shown to decrease because of increased evapotranspiration from both direct drilled and conventionally cultivated treatments. However, available soil water in direct drilled treatments was predicted to be lower than in conventionally cultivated treatments due to higher transpiration by the crop as it used water from deeper soil layers. These simulated outcomes suggest that water use efficiency in direct drilled treatments will be higher than in conventionally cultivated treatments under conditions where rainfall is limited during tillering to flowering but less limiting during flowering to yield formation. The correspondence between these predictions and the results reported in Chapter 5 invoke confidence in the Roseworthy Water Use (RWU) model.

Figure 7.6 shows the simulations for the 1994 season. Direct drilled and conventionally cultivated treatments were predicted to lose approximately the same amount of water by evaporation (Esa) during the first three weeks after sowing (1 to 21 days). Twenty five mm of rain fell on day 28 and after this event, the model predicted that direct drilled treatments would lose less water by evaporation and more by transpiration than conventionally cultivated treatments because biomass production in the former treatments was higher.

1992

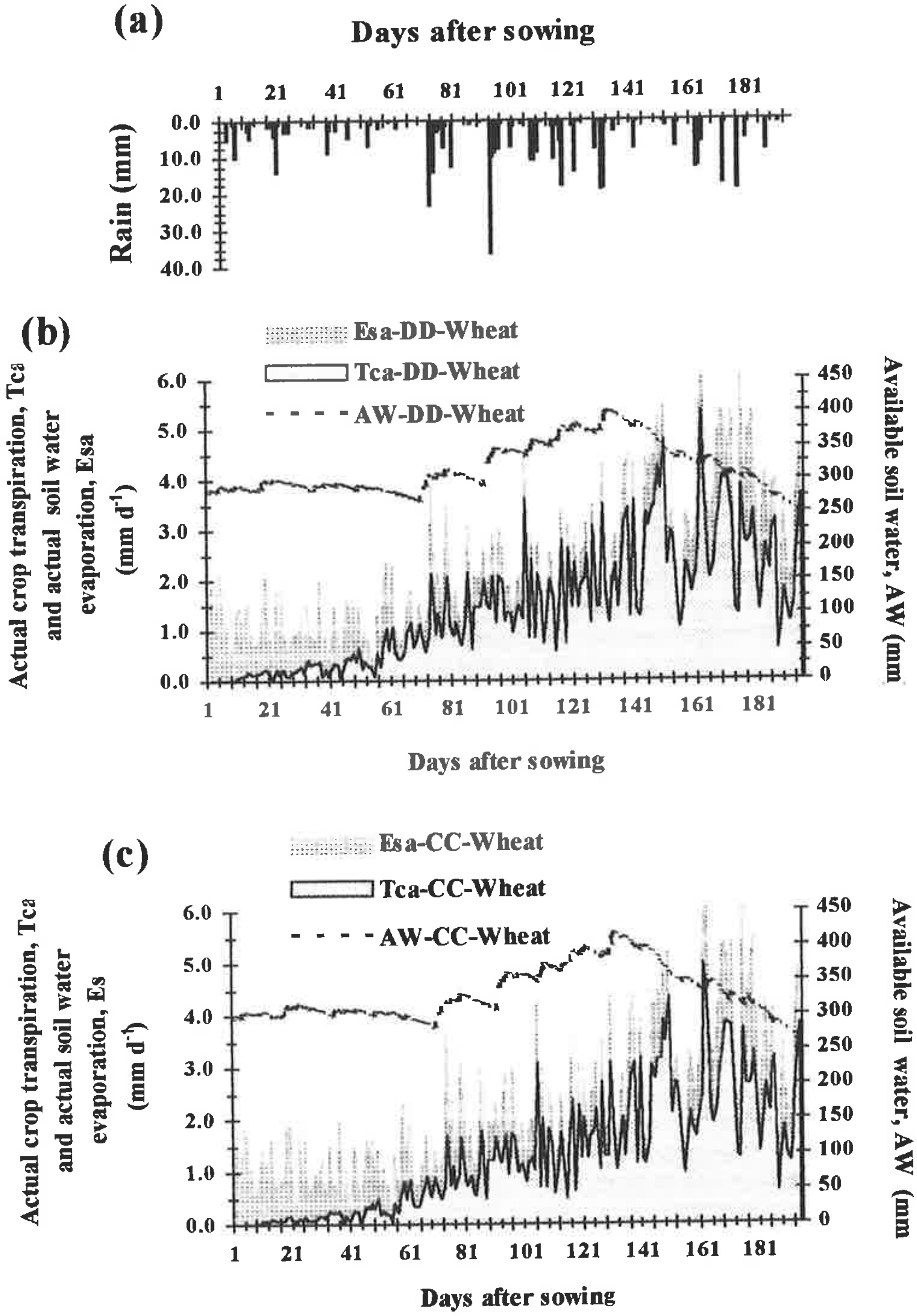


Figure 7.4 Daily actual crop transpiration (Tca), actual soil water evaporation (Esa) and available stored soil water (AW) for wheat estimated by the Roseworthy Water Use model as influenced by **(a)** growing season rainfall **(b)** direct drilling, DD and **(c)** conventional cultivation, CC in 1992.

1993

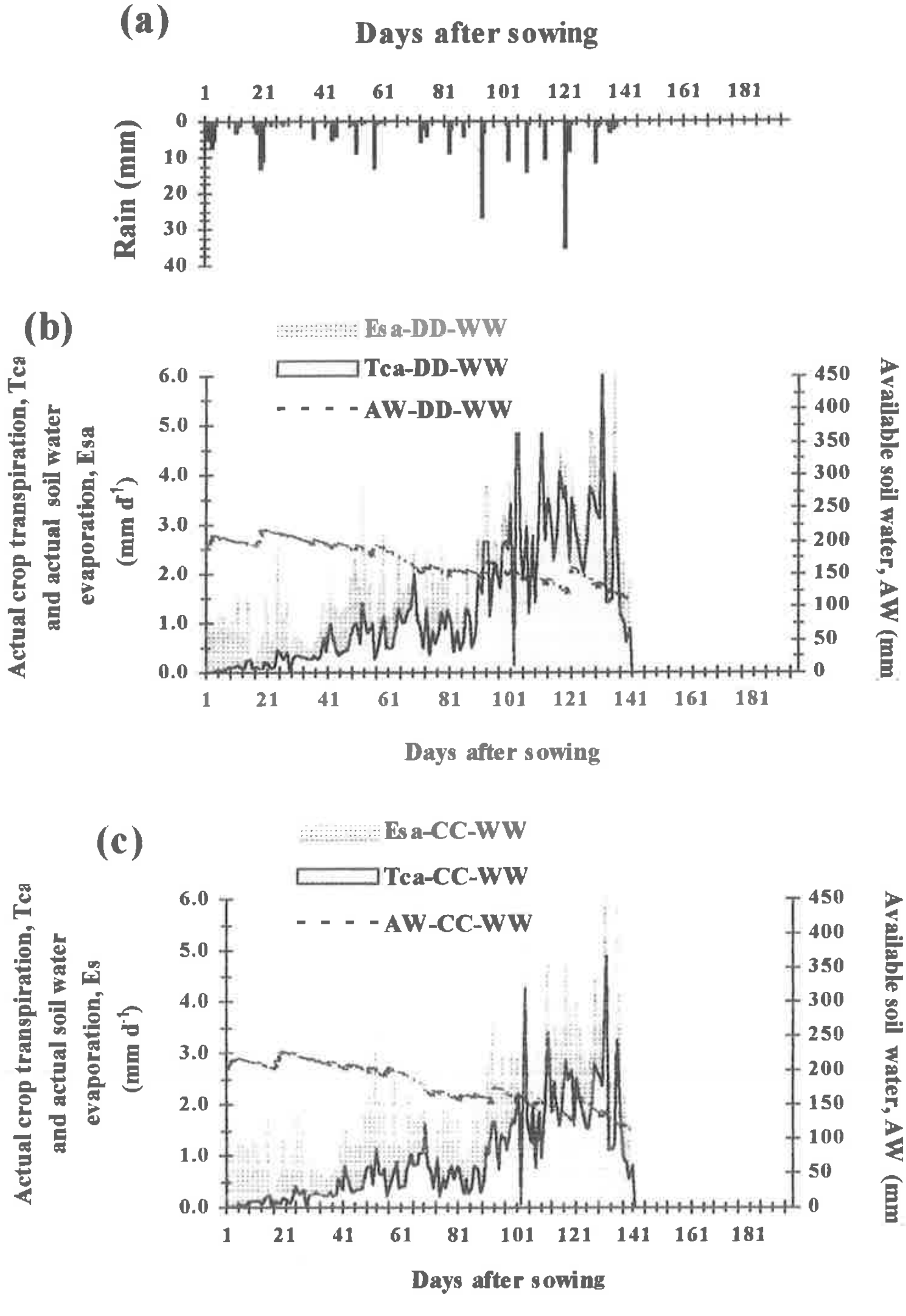


Figure 7.5 Daily actual crop transpiration (Tca), actual soil water evaporation (Esa) and available stored soil water (AW) for wheat estimated by the Roseworthy Water Use model as influenced by **(a)** growing season rainfall **(b)** direct drilling, DD and **(c)** conventional cultivation, CC in 1993.

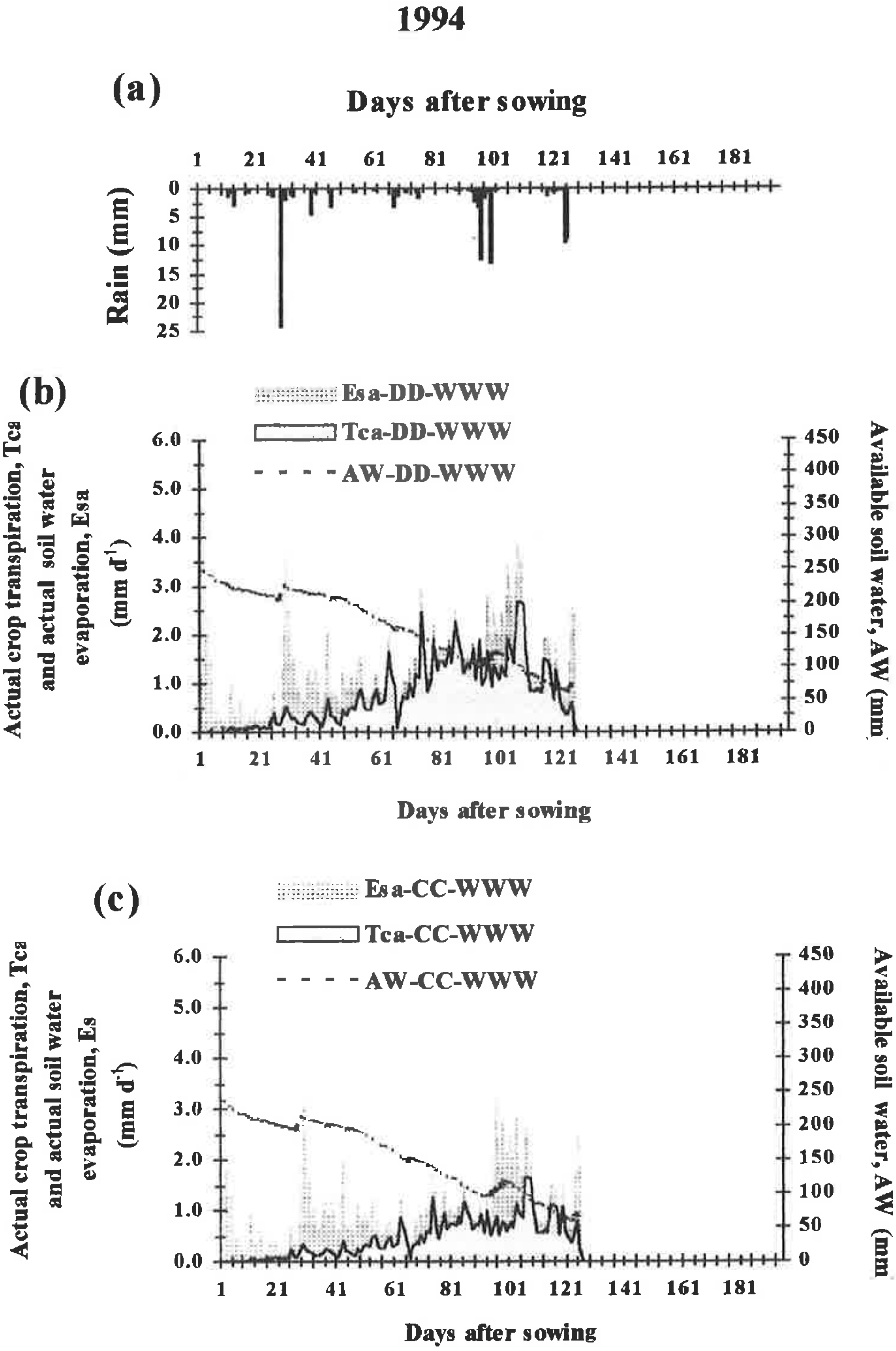


Figure 7.6 Daily actual crop transpiration (Tca), actual soil water evaporation (Esa) and available stored soil water (AW) for wheat estimated by the Roseworthy Water Use model as influenced by **(a)** growing season rainfall **(b)** direct drilling, DD and **(c)** conventional cultivation, CC in 1994.

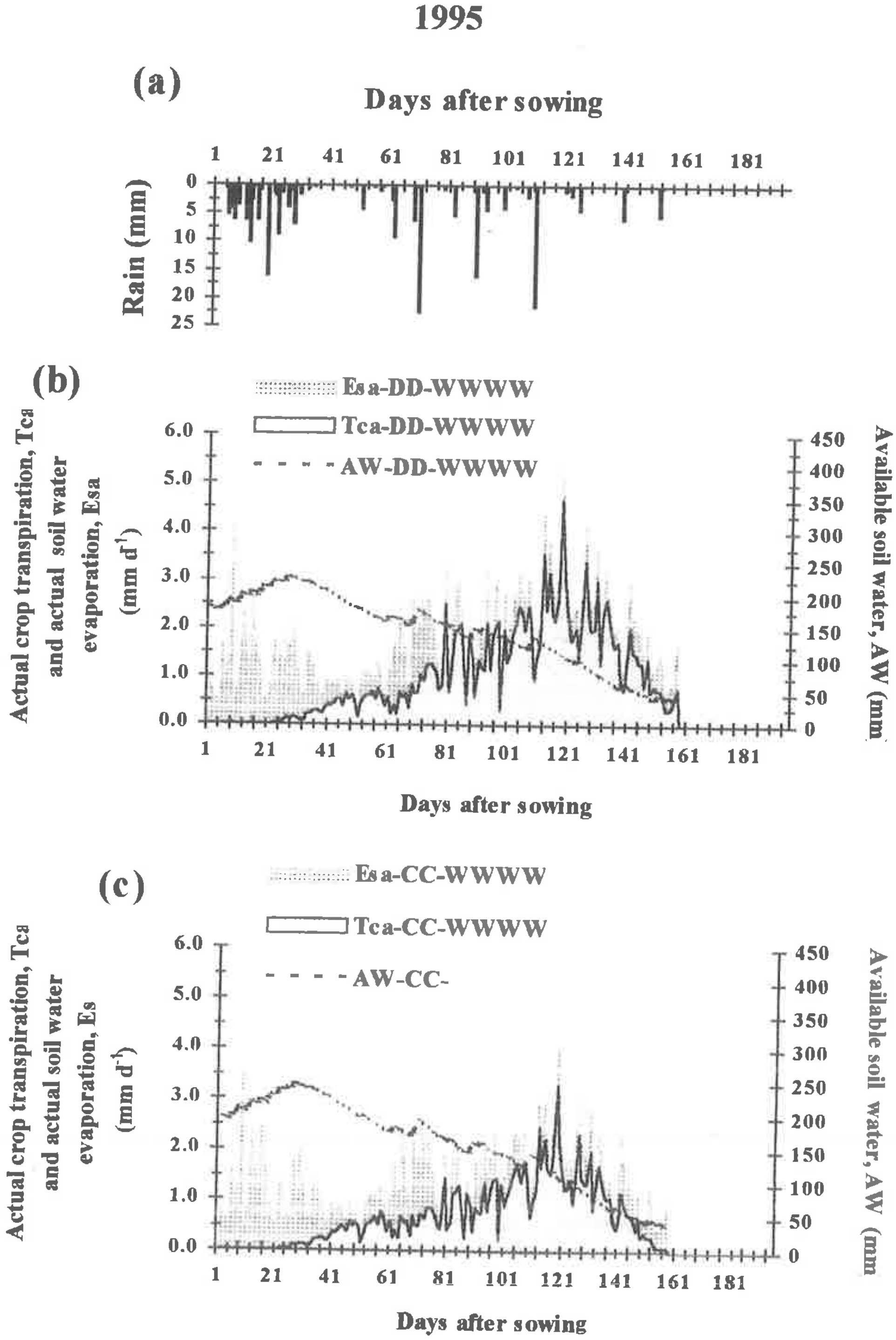


Figure 7.7 Daily actual crop transpiration (Tca), actual soil water evaporation (Esa) and available stored soil water (AW) for wheat estimated by the Roseworthy Water Use model as influenced by **(a)** growing season rainfall **(b)** direct drilling, DD and **(c)** conventional cultivation, CC in 1995.

The amount of available stored soil water predicted in the direct drilled treatments was similar to that in conventionally cultivated treatments. The available soil water was predicted to decrease as evapotranspiration increased in both direct drilled and conventionally cultivated treatments throughout the whole growing period. This result suggests that soil water use in direct drilled and conventionally cultivated treatments will be similar under conditions of moisture stress. Low rainfall resulted in higher soil water evaporation and lower crop transpiration being predicted from conventionally cultivated treatments because the latter had poorer soil conditions for seedling establishment and crop development (lower surface soil water holding capacity with higher aeration porosity, Chapter 4).

Figure 7.7 shows the simulations for 1995. The model indicated that soil water evaporation from direct drilled treatments and conventionally cultivated treatments were similar during sowing to tillering (1 to 60 days after sowing). After this time, direct drilling appeared to have less daily Esa and high daily Tca from tillering to maturity. The available soil water was predicted to be lower for the whole growing period compared with conventional cultivation. These results suggest that wheat sown by direct drilling uses water more efficiently under a uniform rainfall distribution during tillering to flowering . When rainfall was low from flowering (120 days) to harvesting (158 days), wheat sown by direct drilling tended toward using more water from deeper layers of the soil profile. Under these conditions transpiration is expected to be greater due to greater biomass production and lower evaporative demand compared with conventional cultivation.

Table 7.2 Simulated cumulative transpiration (CTca, mm) by wheat, actual evaporation (CEsa, mm) from soil and actual evapotranspiration (CETa, mm) and dry matter water use efficiency (WUE, kg ha^{-1} mm^{-1}) and measured values of evapotranspiration (CET*, mm) and dry matter water use efficiency (WUE*, kg ha^{-1} mm^{-1}) for three stages of crop growth and two sowing methods.

Days*	**Direct drilling**						**Conventional cultivation (CC)**					
1992	**CTca**	**CEsa**	**CETa**	**WUE**	**CET***	**WUE***	**CTca**	**CEsa**	**CETa**	**WUE**	**CET***	**WUE***
(1) 75	**27**	**68**	**95**	**30**	116	-	**20**	**73**	**93**	**24**	124	-
(2) 115	**84**	**94**	**178**	**34**	160	-	**68**	**107**	**175**	**30**	165	-
(3) 185	**261**	**162**	**422**	**23**	405	-	**231**	**187**	**418**	**23**	437	-
1993												
(1) 75	**37**	**65**	**102**	**21**	134	16	**30**	**74**	**104**	**14**	130	13
(2) 110	**99**	**88**	**187**	**37**	269	33	**70**	**117**	**187**	**24**	248	24
(3) 138	**181**	**115**	**296**	**17**	354	17	**130**	**163**	**293**	**14**	312	18
1994												
(1) 68	**22**	**42**	**64**	**30**	98	23	**13**	**44**	**171**	**18**	80	22
(2) 100	**66**	**55**	**121**	**36**	186	20	**35**	**62**	**97**	**27**	179	20
(3) 125	**96**	**73**	**169**	**12**	200	12	**57**	**80**	**137**	**15**	198	17
1995												
(1) 58	**8**	**57**	**65**	**9**	77	10	**8**	**57**	**65**	**10**	63	10
(2) 97	**52**	**91**	**143**	**33**	201	23	**54**	**92**	**146**	**32**	231	19
(3) 140	**148**	**115**	**263**	**36**	239	36	**150**	**119**	**269**	**31**	273	27

Days* is number of days after sowing and (1) is Tillering , (2) is Flowering , (3) is Ripening

The modelled actual transpiration, evaporation and their sum, the actual evapotranspiration, were totalled over the growing season and listed in Table 7.2 for three growth stages and the years 1992 to 1995. Measured actual evapotranspiration is also listed in this table for comparison with modelled values. Dry matter water use efficiency is also shown at the same growth stages.

Comparison of simulated and measured actual evapotranspiration (CETa) over tillage treatments generally showed little difference between the two sowing methods (Table 7.2). However, comparison of measured versus simulated values for a particular sowing method showed larger differences with measured values being generally greater, but not invariably so. The largest differences were observed in 1992, but it should be noted that this was the first year of experimentation and monitoring commenced rather late in the season and the importance of those data need to be downgraded. The estimated evapotranspiration in conventionally cultivated treatments was lower than in direct drill treatments in 1994. This result suggests that wheat may not use water from deeper soil layers in dry conditions such as in 1994.

Although differences between the sowing methods were small for actual evapotranspiration, this was not the case for transpiration and evaporation. These quantities were not separately measured, but could be separately modelled. Simulated transpiration from direct drilled treatments was greater than that from conventional cultivation, except for 1994 when they were similar. In contrast, actual soil water evaporation was greater from conventionally cultivated treatments. These differences probably arise from the differences in biomass between the treatments and the consequent effects on soil shading and leaf area index. In this respect, the model has shown considerable worth in partitioning evaporation and transpiration.

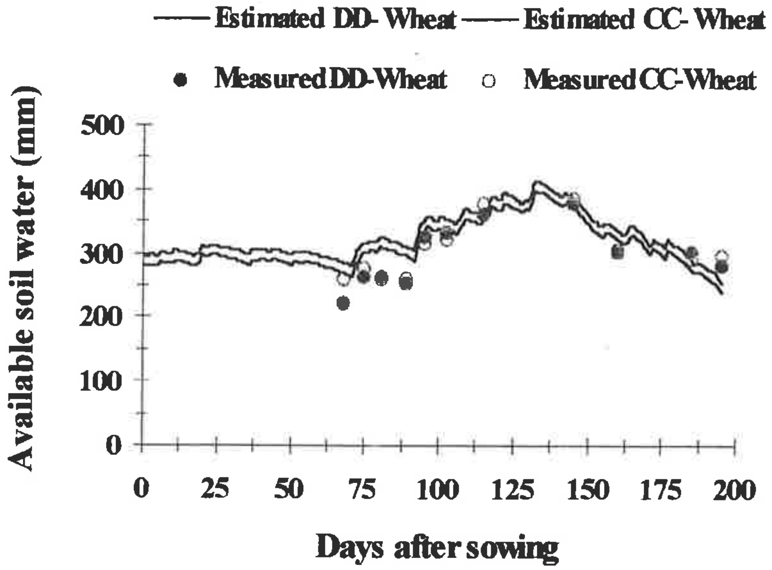
Measured dry matter water use efficiency was generally greatest for direct drilling treatments compared to conventionally cultivated treatments except for 1994, where it was similar at all growing stages. Simulated water use efficiency followed the same general trend as for measured water use efficiency, ie DD > CC. The reason for this was that yields of dry matter were greater in DD than CC.

Difference between simulated and measured water use efficiency were generally small for any particular sowing method, except for those at flowering in 1994 and 1995. The reason for this is not known, but the correspondences between measured and simulated water use efficiency at tillering and ripening lend confidence to the model.

7.4.2 Prediction of available soil water and cumulative water use

Comparison of predicted and measured available soil water for direct drilled and conventionally cultivated treatments in 1992 to 1995 (Figures 7.8 and 7.9) shows close similarity. This was particularly true for years with higher rainfall (1992 and 1995) (Figure 7.8a and b respectively). In drier years prediction of available soil water tended to be somewhat erratic. In 1993 it was higher than the measured values (Figure 7.9a) while in 1994 it was lower (Figure 7.9b). This erratic behaviour may have been caused by the assumption that water was available to 2 m soil depth whereas the effective root zone was probably shallower than this in dry years. For this reason in a dry year, the model will withdraw water from deeper soil layers than occurs in practice, giving higher estimates of available soil water. This, however, does not explain why measured available water was higher than that simulated in 1994, a dry year. The model predicted consistently lower available soil water for direct drilled compared to conventionally cultivated treatments except for 1994. The reversal of the trend in that year cannot readily be explained.

(a) 1992



(b) 1995

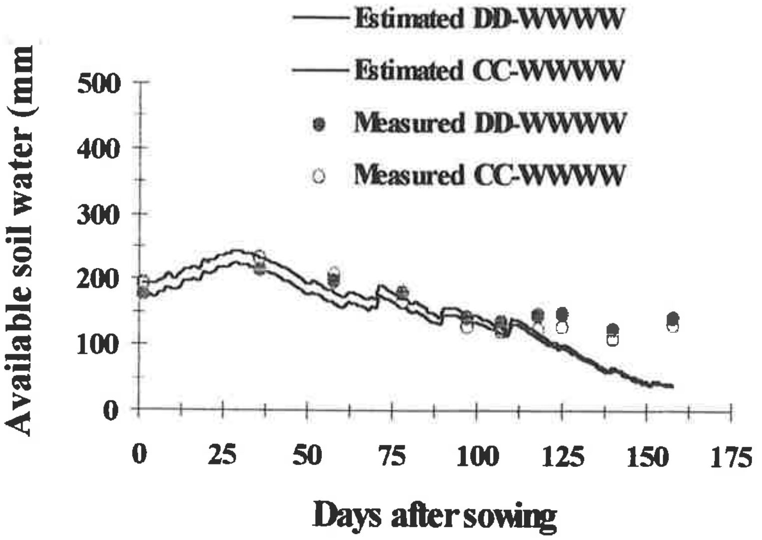
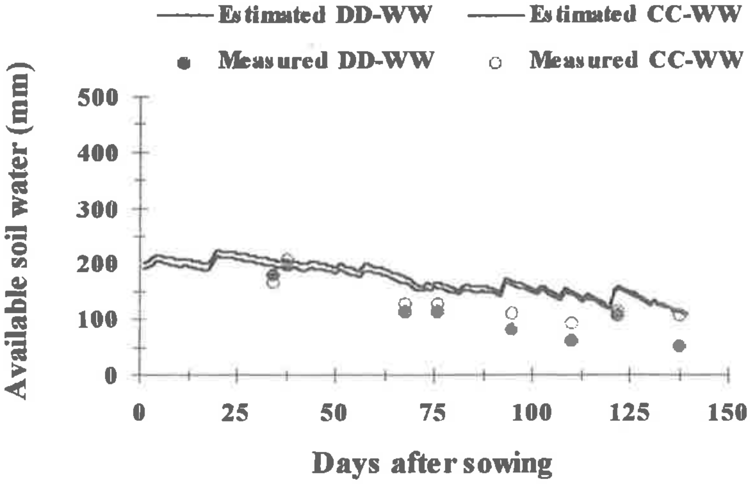


Figure 7.8 Estimated (Roseworthy Water Use model) and measured values of available water for wheat sown by direct drilling or conventional cultivation in years with **high** rainfall **(a)** 1992 and **(b)** 1995.

(a) 1993



(b) 1994

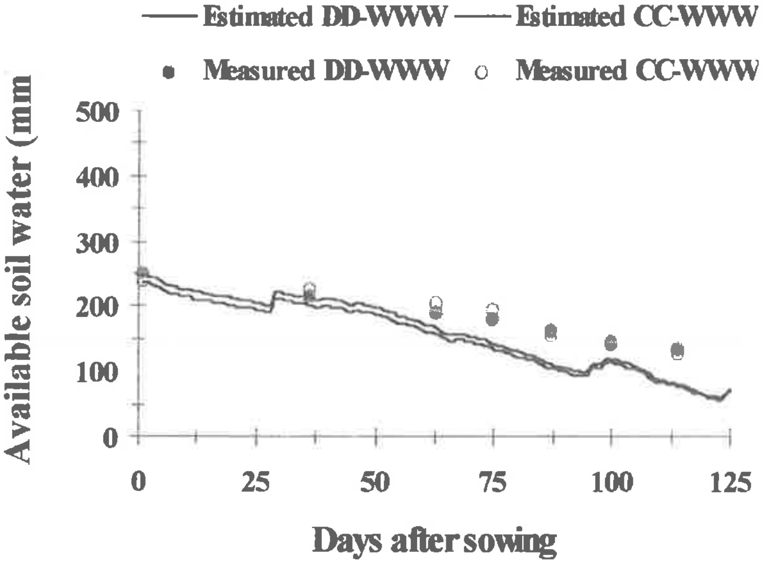


Figure 7.9 Estimated (Roseworthy Water Use model) and measured values of available water for wheat sown by direct drilling or conventional cultivation in years with **low** rainfall **(a)** 1993 and **(b)** 1994

7.4.3 Simulated transpiration water use efficiency and grain yield

Simulated values daily crop transpiration (CTc) and calculated cumulative dry matter (CDM, Equation 7.4 to 7.11) for all years of experimentation were regressed using a polynomial function

$$\mathbf{CDM = 0.20 + 0.086\,CTc - 0.0002\,CTc^2 \quad R^2 = 0.98.} \qquad (7.23).$$

The relationship is plotted in Figures 7.10 with the simulated values for each year of experimentation.

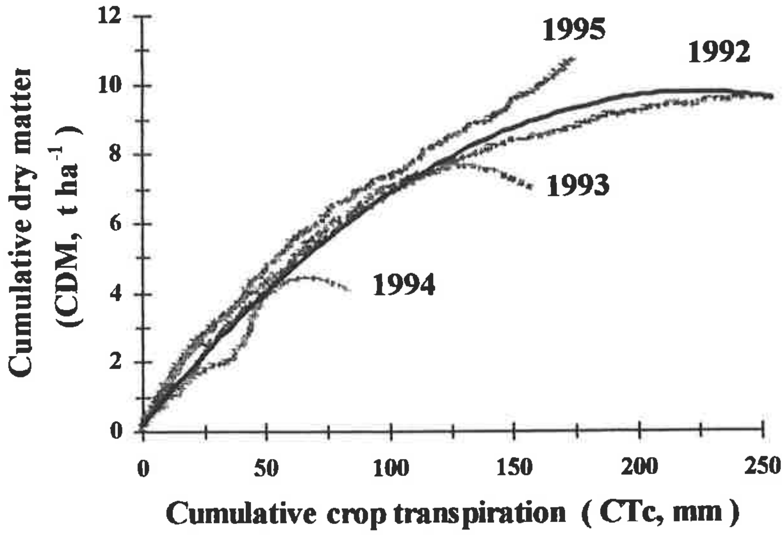


Figure 7.10 The relationship between cumulative dry matter production and cumulative crop transpiration with the fitted function (unbroken line), for wheat sown by direct drilling from 1992 to 1995.

Figure 7.10 shows that the model predicts dry matter production to be dependent on the cumulative water use through transpiration. This relationship is accepted with confidence because the actual crop transpiration was calculated from fresh biomass production and the available soil water (Equation 7.12 and 7.16) was used for estimating dry matter water use efficiency based on crop transpiration.

The transpiration water use efficiency was not constant through the growing season nor from year to year. When the crop was not under moisture stress the transpiration water use efficiency was approximately constant (1995 data). Transpiration over the period from just before tillering to late flowering (approximately 30 to 110 days after sowing) is used to produce dry matter and develop a well distributed root system. Accordingly, one would expect a close relationship between grain yield and dry matter transpiration efficiency (over the period from sowing to 110 days). This is confirmed by the relationship shown in Figure 7.11.

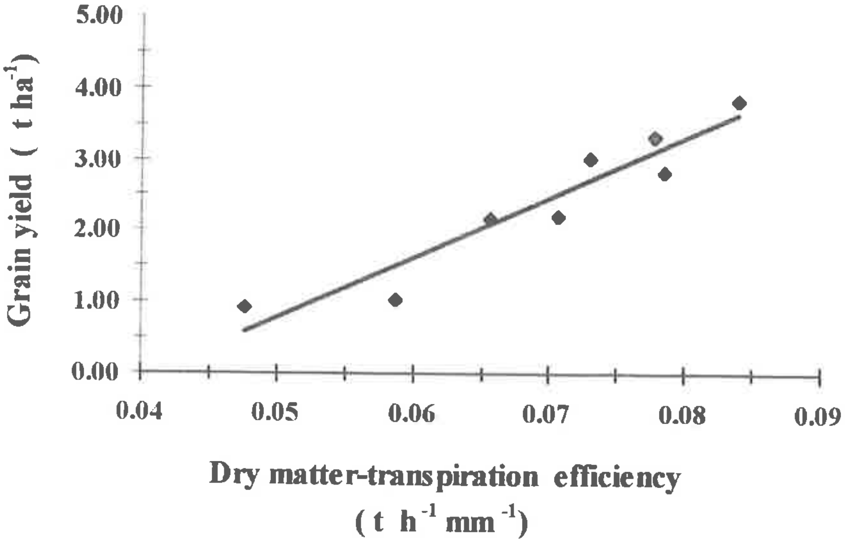


Figure 7.11 The relationship between simulated dry matter transpiration efficiency (110 days after sowing) and measured grain yield for wheat sown either direct drilling or conventional cultivation in 1992 to 1995.

Figure 7.11 shows that the dry matter transpiration efficiency (t ha^{-1} mm^{-1}) which is the cumulative dry matter per unit cumulative transpiration from sowing to 110 days was closely related to grain yield production in both direct drilled or conventionally cultivated treatments over all years of experimentation. The relationship is described by a linear regression function

$$\mathbf{Ya = 83.42\ DTE - 3.385} \qquad R^2 = 0.90 \qquad (7.24)$$

where Ya is the actual grain yield at any soil moisture condition (t ha^{-1}) and DTE is dry matter transpiration efficiency (t ha^{-1} mm^{-1}) calculated as the cumulative dry matter per unit area per unit cumulative transpiration during the first 110 days of crop growth.

This relationship allows grain yield to be predicted from a knowledge of the cumulative dry matter production and cumulative transpiration expressed as dry matter transpiration water use efficiency). These quantities can be obtained from field measurements and the type of model discussed here. This is a useful predictive tool. However, some caution needs to be exercised before this result can be accepted without question. Further testing of the model is required to verify the soundness of the computational procedures.

7.5 Summary and conclusions

A model of crop water use was developed in which soil water evaporation and crop transpiration were partitioned. The data used to develop the model was obtained from wheat crops sown by direct drilling and conventional cultivation under different weather conditions from 1992 to 1995. Modelling procedure, assumption and performance are summarised as follows.

(i) The model used (1) measured values of maximum evapotranspiration (ETm) and corresponding evaporation from a class-A pan (Epetm) were used to calculate the pan factor (Kp), (2) maximum potential crop transpiration (Tcpm) with corresponding maximum fresh biomass (Fwm) and the corresponding estimated potential evapotranspiration (ETptm) were used to calculate the crop transpiration factor (Kt), (3) daily fresh biomass (Fwi) was calculated from a crop growth function of dry matter for each year and the ratio of the daily crop fresh weight and the maximum fresh weight (Fwi/Fwm) was used as the daily crop factor (Kci), (4) daily evaporation from a class-A pan (Epi), the crop factor (Kci) and the crop transpiration factor (Kt) were used to generate the daily potential evapotranspiration (ETpi) and the daily potential crop transpiration (Tcpi), (5) daily soil factor (Ksi) calculated based on the daily available soil water (AWi) was used to generate the daily actual crop transpiration. (Tcai).

(ii) The Roseworthy Soil Water Evaporation model (Chapter 6) was used to compute daily soil water evaporation (Esi) based on the daily soil water content and the evaporative demand for soil water evaporation using (1) soil water content at field capacity and at wilting point to calculate the soil water retention function for estimating soil water matric suction, (2) daily evaporative demand at the soil surface was calculated based on the daily potential evapotranspiration minus the daily potential crop transpiration.

(iii) The assumptions of the model were (1) water gain in the water balance system was from rainfall only while the water losses were accounted for by crop transpiration and soil water evaporation, (2) daily rainfall was added to the surface soil layer and water in excess of field capacity drained to deeper soil layers within one day, (3) available soil water was assumed to be stored in a depth of 2 m and no drainage losses occurred beyond 2 m, (4) soil water evaporation was assumed to take place from the surface layer of 0 to 75 mm depth only.

(iv) The model performance was illustrated by the following: (1) effect of rainfall and tillage practices on partitioning soil water evaporation and crop transpiration for each growing season from 1992 to 1995 showed that soil water evaporation was high during the early growing season and under poor crop growth conditions with wet surface soil conditions and with high evaporative demand at the soil surface, (2) direct drilling resulted in better water use efficiency by inducing lower cumulative soil water evaporation and causing higher crop transpiration compared with the conventional cultivation because the former treatment caused greater biomass production as shown in Chapter 5, (3) prediction of available soil water within the soil profile and cumulative evapotranspiration showed similar trends to field measurements.

(v) The model displayed inaccuracy in predicting the cumulative available soil water in dry conditions in relation to total water consumption estimates. This might have arisen from assuming that soil water was available to 2 m depth rather than 1 to 1.5 m.

(vi) More work is required to advance development and verification, of the model. In particular the output should be compared with the Penman-Monteith combination model or the Ritchie model.

(vii) The relationships developed between cumulative dry matter and cumulative crop transpiration, and grain yield production and dry matter transpiration efficiency are benefits from the modelling exercise. These relationships are useful for predicting dry matter transpiration efficiency and hence grain yield. Transpiration efficiency can be used to indicate the efficiency of dry matter and crop yield production under rainfed conditions which is an improvement on the evapotranspiration efficiency or the conventionally used term "water use efficiency".

CHAPTER 8

GENERAL DISCUSSION AND CONCLUSIONS

This research has examined the response of wheat to two sowing methods (tillage systems) and a selection of crop rotation systems suitable for South Australia. Results have shown that the interaction of tillage practices with crop rotation systems over 4 years gave significantly different surface soil structural properties in most years which translated into differences in soil mechanical and hydrological properties, water balance, dry matter production, wheat grain yield and finally water use efficiency. These effects were particularly noticeable in 1993 and 1995 but less obvious in 1992 and 1994. Rainfall in the former years was closer to the norm than the latter years which were either unusually wet (1992) or unusually dry (1994). Experimental differences between treatments in 1992 and 1994 were muted and difficult to interpret. However, apart from this difficulty, results over the four years of experimentation showed significant differences between treatments, and generally the differences were consistent over the four year period. Anticipation of soil and weather variability indicated that the aims of the thesis would only be achieved by a combination of field monitoring, laboratory experimentation and computer modelling. While additional experimentation and modelling needs to be done to resolve some of the issues examined in this thesis, the aims of the project have been achieved.

8.1 Sowing method and soil structural improvement

The hypothesis which guided this aspect of the research was that it is possible to improve the aggregate structural properties and thence soil hydrological properties of the Roseworthy loam soil by adopting appropriate tillage and sowing methods. Results of the experimental and modelling work have shown this to be true. However the expression of the improvement was dependent on rainfall patterns during the growing season.

In general, the changes of soil physical properties from 1992 to 1995 showed that direct drilling improved both surface and sub surface soil structure by improving air-filled porosity, increasing the rate of water infiltration and reducing bulk density and penetration resistance compared to the conventional cultivation. These improvements in direct drilling treatments came about because this technique avoided development of tillage pans and promoted better aggregation (fewer fine aggregates).

8.1.1 Tillage pan formation

Treatments sown by conventional cultivation rapidly developed a tillage pan beneath the tilled layer (below about 75 mm). The tillage pan had higher values of bulk density and penetration resistance and lower values aeration porosity compared to treatments sown by direct drilling. This difference persisted throughout the period of experimentation but was more pronounced in years when the early growing season rainfall was high (1992 and 1995). When the soil was wetter, compaction by wheel traffic and tines was greater. The tillage pan reduced the infiltration rate of the surface soil which limited accession of rainfall to deeper soil layers. Root growth was also observed to be restricted in deeper layers in conventionally cultivated treatments. These effects were particularly noticeable in 1992, the wettest of the four years of experimentation.

8.1.2 Surface aggregate size and stability

Treatments sown by direct drilling had a higher proportion of water stable aggregates with a larger mean weight diameter in the surface layer (0-75 mm depth) than conventionally cultivated treatments. Direct drilling promoted surface conditions in which aggregates were more resistant to rapid wetting by rainfall and raindrop impact, resulting in better surface aeration and a higher rate of infiltration of water compared to conventional cultivation.

Treatment differences in surface soil properties at ripening (one month before harvesting) were dependent on the amount and distribution of rainfall after sowing. Although conventionally cultivated treatments had lower bulk density immediately after sowing in 1992 and 1993, this was rapidly reversed by the destructive effect of rainfall on the less stable aggregates. Consequently at the end of those growing periods, direct drilled treatments had greater aeration porosity and only slightly less available water capacity than conventional cultivation treatments. This trend was reversed in 1994 showing that under low rainfall conditions, conventional cultivation retained better surface structure with a low bulk density, until the end of the growing season.

8.1.3 Soil structure and water loss by evaporation

In most years a measurable improvement of soil structure in both the surface soil (0-75 mm) and the subsurface soil (75-150 mm) as a residual effect of direct drilling at crop ripening was observed. The only disadvantage of direct drilling was that soil water lost from the bare soil surface during dry periods exceeded conventional cultivation. Lacking a tillage pan, the surface soil layer (0-75 mm) in direct drilled treatments was wetter during dry periods due to the greater continuity of soil porosity between the surface and subsurface. However, this did not measurably change the total stored soil water during the four cropping seasons.

8.2 Dependence of crop production on rainfall or stored soil water

The hypothesis on which this aspect of the research was based is that wheat production (dry matter accumulation and grain yield) could be increased by improving rainfall accession and storage arising from improved soil structure. This has been shown to be true although the magnitude of the improvement is again dependent on rainfall patterns during the growing season. The part played by soil structure in this dependence was discussed in the previous section.

Improved soil structure by direct drilling led to better accession of rainfall to the soil profile where it was used more efficiently by the crop compared to conventional cultivation. However, biomass production and grain yield on this site were controlled in most years of experimentation by the amount and distribution of rainfall more than the total stored soil water. However, stored soil water is clearly important in buffering variation in distribution of rainfall during the growing season.

8.2.1 Growing season rainfall

There was no difference in total stored soil water to 2 m depth between direct drilling and conventional cultivation in any year of the trial. At any time direct drilled treatments tended to have less stored soil water than conventionally cultivated treatments because of the greater biomass production and the greater rate of water consumption of direct drilled crops. However, biomass production was more dependent on the amount and distribution of rainfall than on the stored soil water, particularly during pre-tillering to late flowering. The higher the rainfall in the early stages of crop growth, the greater the biomass production.

8.2.2 Efficient use of rain by direct drilled crops

Crops sown by direct drilling had greater yields in most years of the trial (exception was 1994). The magnitude of this yield advantage over 4 years for all crops was 7 % and 2 % for continuous wheat, depending on rainfall. Only in 1994, with low growing season rainfall, did conventional cultivation out yield direct drilling (by 12 %). The improved yields obtained from direct drilling resulted from the two possible processes: (i) improved accession of water and/or (ii) improved root penetration, to subsurface soil layers.

(i) It is likely that the accession of rainfall in conventionally cultivated treatments was reduced by a sealed soil surface because of the relatively unstable aggregates found and the pan formed below the tilled layer. These factors combined to retain water near the surface in conventionally cultivated plots where loss by evaporation, especially during wet periods, was more likely than in direct drilled treatments where rain water penetrated more deeply. This reduced the water available for transpiration and hence crop production in conventionally cultivated treatments .

(ii) The higher root length density and deeper penetration of wheat roots induced by direct drilling tended to enhance more efficient use of soil water, resulting in greater dry matter production at all growing stages from tillering to maturity. This led to higher grain yield compared to conventional cultivation. Higher yield did not always translate into higher water use efficiency. However, direct drilling of all crops in the rotations studied tended to have higher water use efficiencies than crops sown by conventional cultivation. The reason for this was the better soil structural conditions of direct drilled treatments which enhanced soil water availability.

8.3 Dependence of wheat yield on preceding crops

The hypothesis associated with this component of the research was that wheat yield could be improved by using rotations which optimised storage of soil water for use by the crop in the next season. Total stored soil water in the early part of the growing season depends on water stored in soil after harvest in the previous cropping season. Early season water storage was lowest after a preceding season with the highest water consumption and the greatest dry matter production. Rotations of wheat after wheat or faba bean or canola showed significantly different effects on biomass and grain yield production.

8.3.1 Wheat yield improvement after faba bean

Biomass production of wheat following faba bean was higher than wheat following canola or wheat following wheat during tillering to heading in 1993 and 1994. This resulted in the highest grain yield production in 1993, a season with high rainfall from flowering to ripening. The rapid biomass production in 1994 did not eventuate in high grain yield because of lack of rain later in the season (Chapter 7).

After a high faba bean yield in 1992, wheat grain yield in 1993 increased by 18 % compared with wheat after wheat. This response was even more enhanced (35 % compared with wheat after wheat) if subsequent crops were sown by direct drilling. However, in contrast to 1994, in other years an average of 15% decrease in yield was observed in wheat following faba bean compared to wheat following wheat.

8.3.2 Wheat yield improvement after canola

No effect on wheat grain yield by a preceding canola crop was found in 1994 and 1995. However, in 1993, the yield of wheat preceded by canola was higher than if preceded by wheat. The lack of rain in 1994 reduced biomass production and seed yields of canola considerably and this may have affected wheat grain yield in 1995. In 1992 canola yields were higher than other years and in 1993 succeeding wheat yield (preceded by canola) was 20 % higher than wheat preceded by wheat. Wheat crops following poor canola crops displayed a 13% reduction in yield making the overall benefit of canola over 4 years negligible.

However, a contrasting result was obtained if biomass at tillering, rather than the grain yield, was used to assess the effect of the previous crop. Grain yield is dependent on the current season's rainfall while biomass production at tillering is more dependent on soil water storage, including carry over from the previous season.

Biomass production by wheat at tillering was on average 24 % greater following canola compared to wheat. In some years differences in the interactive effect of the preceding canola rotation and the tillage practices were observed, but these were dependent on seasonal weather. Generally the effect was due mainly to crop rotations. It may be inferred from this that the preceding canola crop has had an effect on the early growth of the succeeding wheat crop, but the limiting effect of subsequent water stress nullified this initial advantage.

The soil surface shielding accorded by canola canopies exceeds that of wheat during the vegetative growth stages. However, a poor canola crop canopy resulting from low rainfall was less effective in preventing surface sealing and wheat following canola under these conditions did not yield as well. Wheat preceded by faba bean should give the best yield response when rainfall was limiting during some stages of growth because faba bean has a short growing period. Continuous wheat crop rotations gave the best grain yields in dry years compared to other crops and this overrode disadvantages of disease development and fertility problems experienced by canola and faba bean.

8.4 Modelling soil water evaporation and transpiration

The advantages of direct drilling in terms of improved soil surface structure and increased crop yield compared to conventional cultivation are clear. The higher water use efficiency obtained by direct drilling of the crop meant that more soil water was used by the crop for transpiration and less water was lost from the soil by evaporation. This was the basic hypothesis of the research aims for this thesis. The two quantities, transpiration and evaporation, could not be measured independently in this project but were partitioned by modelling (Chapters 6 and 7). The results obtained from the model, together with empirical data obtained in the field (Chapters 4 and 5) showed that this hypothesis was probably true.

The Roseworthy Soil Water Evaporation model was developed to estimate daily soil water evaporation using the data set of evaporative demand, soil water evaporation and soil water content measured under field conditions. The model combined the three stages of soil water evaporation into a single sigmoid function with the two independent variables as evaporative demand and the soil matric suction The model has several advantages over others, chiefly that it is driven by the main factors governing evaporation, atmospheric demand and soil matric suction and accounts for soil structure and texture variations.

A particular strength of this model is that it can deal with evaporation under conditions of frequent, recurring light rain, a characteristic of the early part of the South

Australian growing season. Other models are less suited to this wetting pattern. While beyond the scope of this thesis, there is a need for further research to develop the relationship between the soil moisture retention characteristic of structured soils (such as a tilled surface soil) and the evaporation function with the aim of developing a theoretical basis replace the empirical approach used here. Albedo is an important factor in soil water evaporation and it needs to be included in the model.

The perception that an increase in crop transpiration and a decrease in soil water evaporation explained the superiority of direct drilling over conventional cultivation was the basis for developing the Roseworthy Crop Water Use model. This model computes progressive crop transpiration and dry matter accumulation using measured fresh biomass data taken through the season from emergence to ripening. Together with the Roseworthy Soil Evaporation model, the two important components of the soil water balance, crop transpiration and soil water evaporation, can be separated and described as a function of time (Chapter 7). In this thesis a daily time step was used. This proved a valuable tool for interpreting the empirical results obtained from field experiments.

The model showed that (i) soil water evaporation was high during the early part of the growing season, particularly if canopy growth was poor which lead to development and exposure of wet soil surface conditions, often under a high evaporative demand, (ii) improvement of crop water use efficiency was due to the greater biomass production by crops sown by direct drilling.

Some of the simulated outcomes could be matched with field observations and this inspired confidence in the model. However this process also showed that the model was inaccurate under dry conditions in relation to total water consumption estimates which might be due to the assumption that soil water was available to 2 m depth. More testing and sensitivity analysis of the model is obviously required. The model would be strengthened by developing predictive capability for fresh biomass production, thereby reducing its empiricism.

8.5 Dry matter production and yield

Simulations by the model of daily soil water evaporation, dry matter production and cumulative crop transpiration showed that dry matter transpiration efficiency during pre-tillering to late flowering was closely related to grain yield production (Chapter 7). This finding is supported by empirical data gathered over 4 years showing the correlation between grain yield and maximum dry matter production (Figure 8.1). Grain yield is clearly dependent on development of an adequate crop as judged by the production of dry matter through the growing season. Simulation of dry matter accumulation is thus a valid estimation of yield potential.

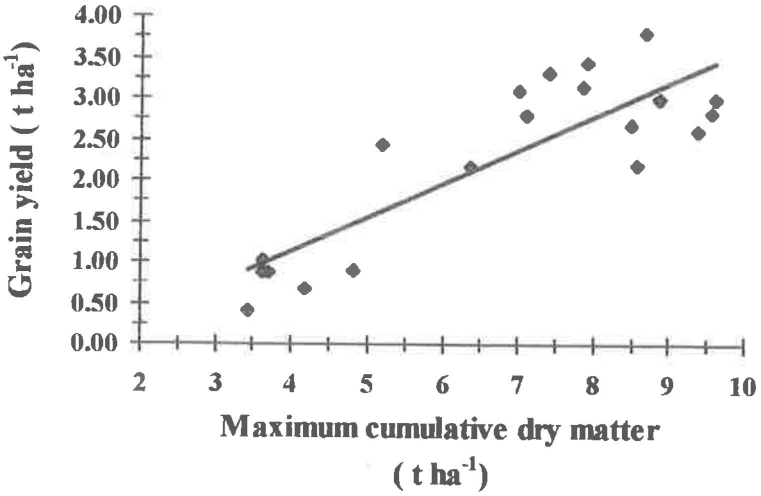


Figure 8.1 The relationship between grain yield (Ya) and maximum dry matter production (CDM_{max}) of wheat sown after wheat, faba bean and canola by direct drilling and conventional cultivation from 1992 to 1995. The relationship is described by **Ya = 0.41 CDM_{max} + 0.49**, with **R^2 of 0.72.**

8.6 Effect of rainfall and transpiration on dry matter and grain yield

The variability of both rainfall and rainfall distribution during this project provided an opportunity to study the response of crops to variability of water availability and water stress conditions. While a larger data set is clearly required to establish the widespread application of the finding, there seems to be a strong relationship between yield, dry matter transpiration efficiency and maximum biomass production during pre-tillering to late flowering. While post flowering rainfall has often been cited as a reason for reduced yields from otherwise large and healthy crops, water stress during pre-tillering to flowering is accepted as being more critical.

During four years of experimentation from 1992 to 1995, the amount and distribution of rainfall from sowing to ripening interacted with transpiration to affect dry matter production and ultimately grain yield. In 1992 excess rainfall throughout the growing period (total of 482 mm) caused prolonged anaerobic conditions in much of the root zone. This probably lead to the unexpected yield reduction and low water use efficiency observed in that year. The years 1993 and 1995 had similar total rainfall (Chapter 5). However, in 1993 cumulative rainfall during seeding to ripening (258 mm) was higher than in 1995 (206 mm) and the distribution of rain during this period in 1993 differed from 1995. This caused different patterns of cumulative dry matter production by wheat, culminating in different yields (Chapter 5). In 1994 rainfall was exceptionally low throughout the growing season (192 mm) which caused low wheat yields. These patterns of weather and soil interactive effects on dry matter production are illustrated graphically by a combination of modelled transpiration and measured rainfall in Figure 8.2 for each of the four years of research and in Figure 8.3 for the four-year combined data.

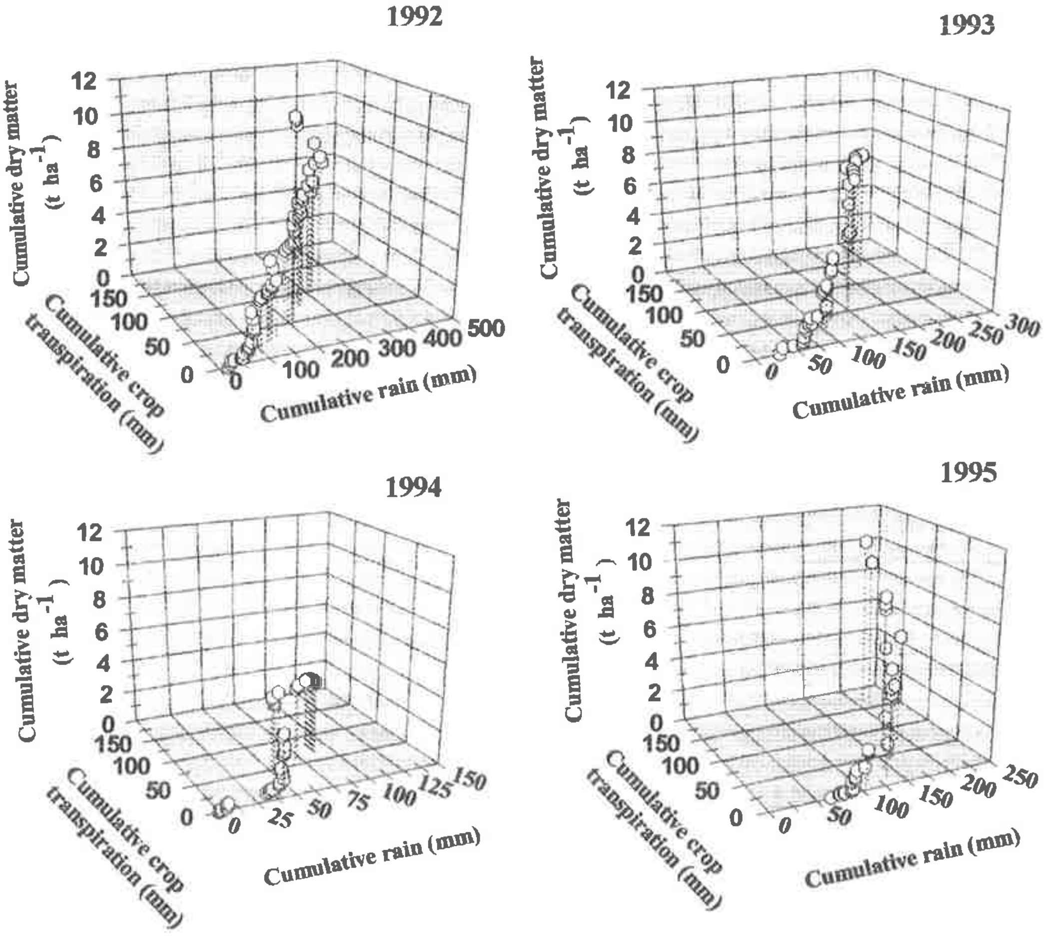


Figure 8.2 The influence of cumulative crop transpiration and rain on dry matter production from sowing to ripening during each year of experimentation (1992 to 1995).

Figure 8.2 illustrates several important features:

(i) In 1992, dry matter production was driven by cumulative rainfall and crop transpiration up to grain filling (140 days after sowing) and finally by crop transpiration drawing on stored soil water because of a decline in rainfall (Figure 7.4).

(ii) In 1993, low rainfall and low soil water during early tillering to early heading (21 to 76 days after sowing) reduced transpiration and slowed dry matter production but, during heading to flowering (80 to 110 days), dry matter increased when some rain fell allowing transpiration to proceed (Figures 5.3 and 7.5).

(iii) In 1994 rainfall was very low throughout the growing season, dry matter production was low and was driven by rainfall during early growing season. From tillering to heading (63 to 87 days after sowing), dry matter was driven by transpiration from stored soil water. When some rain fell during heading to flowering, transpiration and dry matter production did not change due to severe water stress. Transpiration was minimal in that season (Figure 5.6 and 7.6).

(iv) In 1995, sowing date was late and germination was slow, dry matter production was retarded until 30 days after sowing. Dry matter was driven by rainfall and transpiration between tillering and heading (58 to 100 days after sowing). After heading (100 days), absence of rain shifted dry matter production back to reliance on soil water (Figure 5.9 and 7.7).

The data in Figures 8.1 and 8.2 show that grain yield development occurs in a three dimensional space bounded by rain (or, in general, weather), transpiration of soil water and dry matter production. The data for the 4 years (Figure 8.2), although barely sufficient for the purpose, were combined in Figure 8.3 giving a first approximation of this three dimensional yield response surface for the experimental site. This figure indicates that grain yield development is the end product of a series of interdependent events driven primarily by crop water supply. The maximum rate of production for biomass during any part of this process is determined by biomass already present and the efficiency with which it accesses and transpires water.

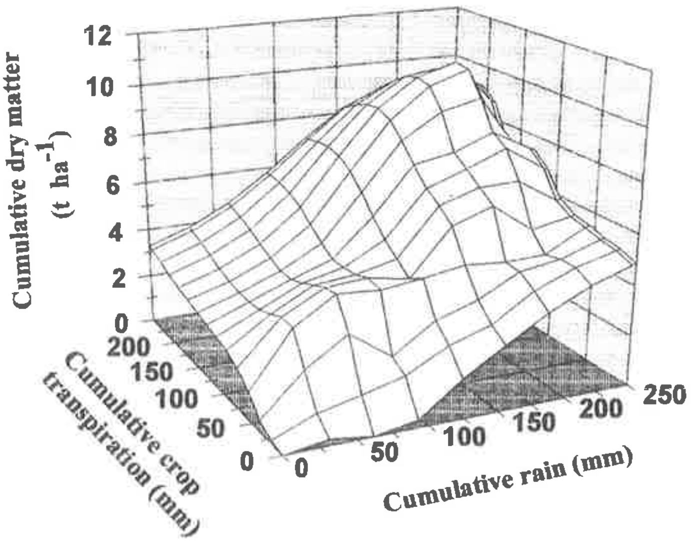


Figure 8.3 Yield response surface for Roseworthy loam estimated from 4 years of climatic data (1992 to 1995) and modelled crop transpiration and dry matter production.

Clearly the rate of production of biomass of any stage of crop development depends on the biomass accumulated in the previous stage. The ultimate performance of the crop as measured by grain yield, is the product of all growing stages. If any stage suffers impeded development, potential grain yield will be diminished. Therefore for optimum grain yield to be achieved, there must be an optimum balance between rainfall (the main driving force), transpiration (the effective part of the rainfall) and biomass production throughout the growing season. The development of high yield is dependent on developing a good crop which in turn is dependent on a balance of appropriate rainfall and sufficient soil water storage to drive transpiration, which in turn is dependent on good germination. Figure 8.3 defines this relationship for the experimental site over the 4 years of experimentation.

APPENDICES

Appendix 1 Weekly rainfall data at the experimental site from 1992 to 1995

WEEKLY RAINFALL

Week Number	Experimental year			
	1992	1993	1994	1995
1	0	10	25.6	10.6
2	0.4	0	2.4	0
3	0	9	1	9.6
4	0	40	0	4
5	0.6	0	0	6
6	7.8	2	6	8.6
7	8.4	0	0	16.4
8	1.2	5.1	3.6	0
9	0	6.4	2.8	10.8
10	40.8	0.2	0	0.2
11	0	0	0	1.5
12	0.1	5.2	0	0
13	13.6	0	0	0.1
14	0.1	0	0	10.4
15	8.2	0	10.8	6
16	4.2	0.1	0	8.8
17	8.2	0	0	3.4
18	10.9	0	1.8	13.4
19	8	2.2	0	14.8
20	31.6	4.4	0	2
21	10.1	3.5	8.4	0
22	3.2	4	7.8	14.6
23	15	6.6	33	4.3
24	8	18.2	19.3	36.6
25	20.6	10.6	3.8	3.3
26	6.4	12.7	19.8	7.4
27	1.7	5	0.2	13.1
28	14	27.6	1.4	5.8
29	4.8	2.9	4.1	30.8
30	9.7	0	0.2	25.4
31	2.7	10.4	28.3	17
32	0.6	5.4	6	9.8
33	53.8	22.6	4	0.3
34	14	1.4	0	0.4
35	1.7	0	1	4.4
36	63.6	12.5	3.4	13.2
37	10.2	11	2.6	6.3
38	31.2	4.4	1.5	22.7
39	37.2	30.4	0.4	5.8
40	15.8	11	0.7	0
41	45	14.4	30	21.6
42	3.2	10.3	0	4.1
43	8.4	44.2	0	23.5
44	2	13.7	3	0
45	8.4	7.2	21	3.4
46	32	0.2	7.6	4.2
47	18.6	3.6	0	0
48	24.9	9.2	5.4	5.8
49	8.4	1	8.6	0
50	0.8	0	3.7	0
51	7.6	12.6	0.1	0
52	0	0	0	0
Growing season rain (mm) (April to October or week 14 to 44)	**454**	**290**	**194**	**329**
Week number from sowing to ripening	**22 to 48**	**25 to 44**	**27 to 46**	**27 to 49**
Rain from sowing to ripening (mm)	**457**	**251**	**115**	**218**
Yearly total rain (mm)	**628**	**401**	**279**	**410**

Appendix 2 The average values of soil water evaporation (mm d^{-1}) as influenced by direct drilling (DD), conventional cultivation (CC) and crop rotations of wheat (W), faba bean (B) and canola (C) as WW, BW, CW, WB and WC at selected time of measurement during crop growth in 1993.

	Tillage practices and crop rotation systems							Standard deviation	
Days after sowing	DD	CC	WW	BW	CW	WB	WC	DD	CC
28	1.630	1.021	0.989	1.469	1.573	0.555	1.262	0.159	0.100
29	1.950	0.699	1.020	1.003	1.011	1.029	1.164	0.062	0.108
41	1.950	0.851	1.704	1.140	1.430	1.407	1.326	0.072	0.200
47	1.100	0.862	0.776	0.878	0.923	0.971	1.037	0.045	0.030
48	1.380	0.748	1.111	1.073	0.793	1.117	0.982	0.057	0.046
55	1.254	1.079	1.137	1.218	1.052	1.145	1.281	0.031	0.077
62	1.486	1.084	1.210	1.165	1.255	1.405	1.390	0.108	0.065
67	0.697	0.619	0.577	0.662	0.597	0.7205	0.691	0.052	0.110
69	0.732	0.673	0.641			0.779	0.689	0.030	0.034
90	1.689	1.209	1.500			1.453	1.3945	0.040	0.044
97	1.276	1.449	1.373			1.3485	1.3675	0.084	0.094
99	1.283	0.548	0.655			1.271	0.8205	0.180	0.100
117	0.874	0.450	1.120			0.4625	0.402	0.150	0.170

Appendix 3 The average values of soil water content ($m^3\ m^{-3}$) of the surface soil layer (0-75 mm depth) and sub-surface layer (75-150 mm depth) as influenced by direct drilling (DD), conventional cultivation (CC) and crop rotaion of wheat (W), faba bean (B) and canola (C) as WW, BW, CW, WB and WC at selected times during crop growth in 1993

	Surface soil (0-75 mm)							Standard deviation	
Days after sowing	Tillage practices and crop rotation systems								
	DD	CC	WW	BW	CW	WB	WC	DD	CC
28	0.223	0.207	0.208	0.212	0.211	0.214	0.220	0.010	0.006
29	0.188	0.166	0.172	0.178	0.164	0.193	0.189	0.005	0.023
41	0.178	0.158	0.177	0.158	0.139	0.177	0.157	0.025	0.025
47	0.217	0.191	0.222	0.203	0.200	0.206	0.196	0.009	0.026
48	0.170	0.161	0.157	0.175	0.174	0.176	0.181	0.026	0.018
55	0.180	0.181	0.190	0.180	0.179	0.182	0.188	0.017	0.021
62	0.198	0.193	0.216	0.192	0.178	0.206	0.214	0.012	0.019
67	0.167	0.140	0.154	0.162	0.165	0.160	0.173	0.003	0.028
69	0.122	0.112	0.106			0.119	0.109	0.018	0.011
90	0.170	0.132	0.139			0.142	0.152	0.020	0.014
97	0.238	0.231	0.227			0.243	0.216	0.011	0.016
99	0.179	0.154	0.156			0.153	0.196	0.035	0.027
117	0.115	0.105	0.112			0.095	0.115	0.019	0.021

	Subsurface soil (75-150 mm)								
	Tillage practices and crop rotation systems							Standard deviation	
Days after sowing	DD	CC	WW	BW	CW	WB	WC	DD	CC
28	0.278	0.304	0.29	0.240	0.224	0.250	0.270	0.015	0.024
29	0.235	0.245	0.25	0.246	0.235	0.258	0.260	0.038	0.059
41	0.223	0.232	0.24	0.221	0.200	0.238	0.250	0.016	0.023
47	0.271	0.281	0.29	0.220	0.269	0.270	0.300	0.017	0.010
48	0.207	0.243	0.241	0.224	0.193	0.225	0.221	0.015	0.024
55	0.220	0.260	0.280	0.201	0.197	0.240	0.283	0.038	0.059
62	0.239	0.270	0.264	0.257	0.228	0.263	0.287	0.016	0.023
67	0.202	0.313	0.240	0.172	0.207	0.268	0.279	0.017	0.010
69	0.181	0.203	0.173			0.197	0.207	0.019	0.006
90	0.163	0.200	0.167			0.169	0.208	0.037	0.007
97	0.278	0.281	0.260			0.266	0.312	0.033	0.016
99	0.218	0.192	0.177			0.200	0.238	0.024	0.028
117	0.187	0.156	0.155			0.169	0.191	0.027	0.014

Appendix 4 Soil water characteristics of surface soil (0-75 mm depth) and subsurface soil (75-150 mm depth) as influenced by tillage practices (direct drilling , DD and conventional cultivation, CC) and crop rotation systems (wheat-wheat- wheat, WWW, wheat-faba bean-wheat, WBW, wheat-canola- wheat, WCW, canola-wheat-faba bean, CWB and faba bean-wheat-canola, BWC) in 1994

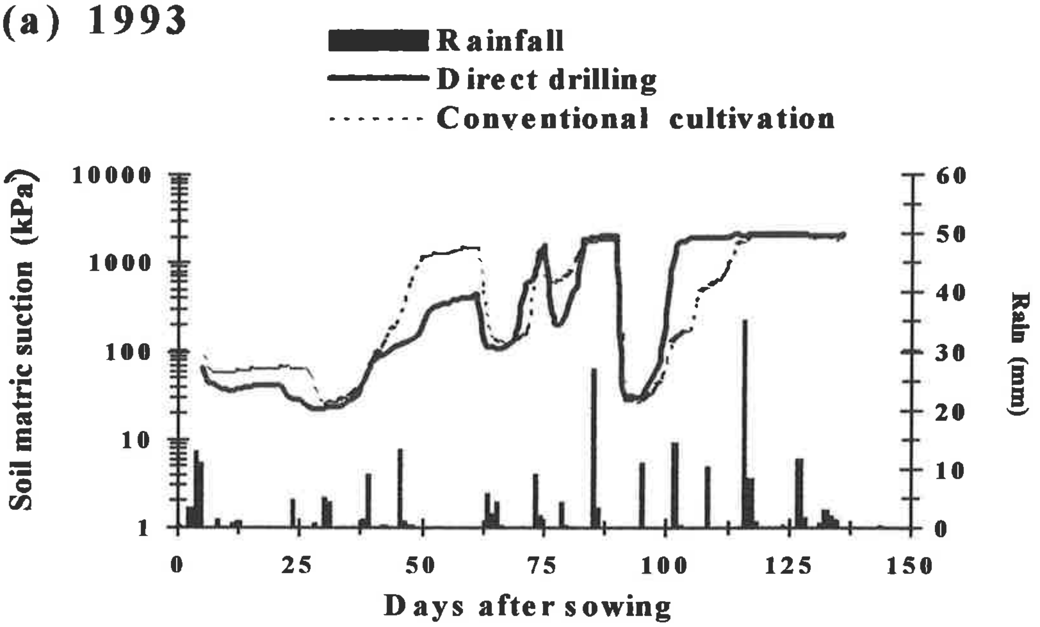
Soil matric suction (kPa) 0-75 mm	**Tillage practices**			**Crop rotation systems**					
	DD	**CC**	**l.s.d T**	**WWW**	**WBW**	**WCW**	**CWB**	**BWC**	**l.s.d S**
0	0.508	0.563	ns	**0.533a**	**0.515a**	**0.522a**	**0.574b**	**0.531a**	0.043*
0.1	**0.330a**	**0.355b**	0.022*	**0.365a**	**0.328a**	**0.324a**	**0.38b**	**0.318a**	0.053**
1	**0.316a**	**0.338b**	0.022*	**0.337a**	**0.317a**	**0.311a**	**0.355b**	**0.314a**	0.033*
2	0.299	0.317	ns	0.314	0.301	0.295	0.331	0.300	ns
5	0.265	0.276	ns	0.273	0.267	0.262	0.284	0.266	ns
10	0.237	0.243	ns	0.244	0.239	0.235	0.249	0.233	ns
30	0.213	0.216	ns	0.217	0.215	0.211	0.225	0.206	ns
60	0.188	0.191	ns	0.194	0.192	0.190	0.193	0.182	ns
100	0.168	0.158	ns	0.167	0.161	0.156	0.171	0.160	ns
300	0.123	0.125	ns	0.128	0.122	0.123	0.126	0.121	ns
1500	0.105	0.106	ns	0.104	0.112	0.104	0.107	0.100	ns
75-150 mm	**DD**	**CC**	**l.s.d T**	**WWW**	**WBW**	**WCW**	**CWB**	**BWC**	**l.s.d S**
0	0.491	0.435	ns	0.462	0.450	0.459	0.468	0.475	ns
0.1	0.367	0.380	ns	0.379	0.370	0.373	0.380	0.364	ns
1	0.337	0.359	ns	0.355	0.343	0.346	0.358	0.339	ns
2	**0.317a**	**0.347b**	0.019*	0.339	0.326	0.331	0.343	0.324	ns
5	**0.287a**	**0.324b**	0.035**	0.312	0.300	0.304	0.313	0.299	ns
10	**0.255a**	**0.283b**	0.022*	0.279	0.268	0.268	0.273	0.255	ns
30	**0.24a**	**0.265b**	0.022*	0.265	0.255	0.254	0.251	0.235	ns
60	**0.216a**	**0.238b**	0.022*	0.241	0.229	0.230	0.226	0.211	ns
100	**0.206a**	**0.227b**	0.025*	0.232	0.221	0.216	0.214	0.201	ns
300	0.165	0.185	ns	0.190	0.188	0.176	0.171	0.161	ns
1500	0.126	0.133	ns	0.138	0.138	0.130	0.126	0.117	ns

l.s.d * T and S are the least significant differences of the means caused by tillage practices and crop rotation systems for comparison at probability of 0.05 (*) and 0.01 (**)

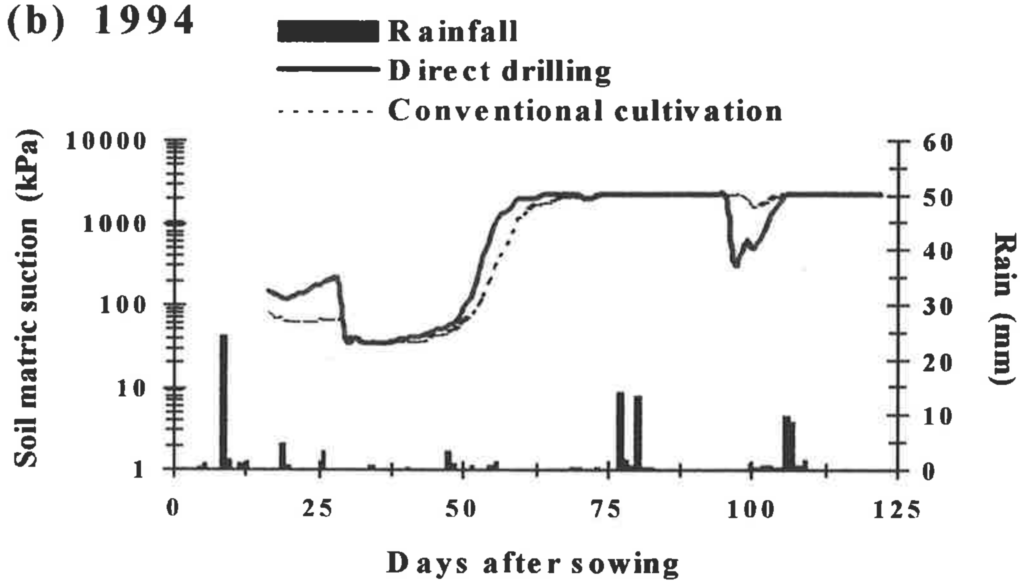
In any row, different letters (a and b) represent significant differences between the means of water content

ns : is non-significant differences between different tillage practices, and among different cropping systems

(a) 1993



(b) 1994



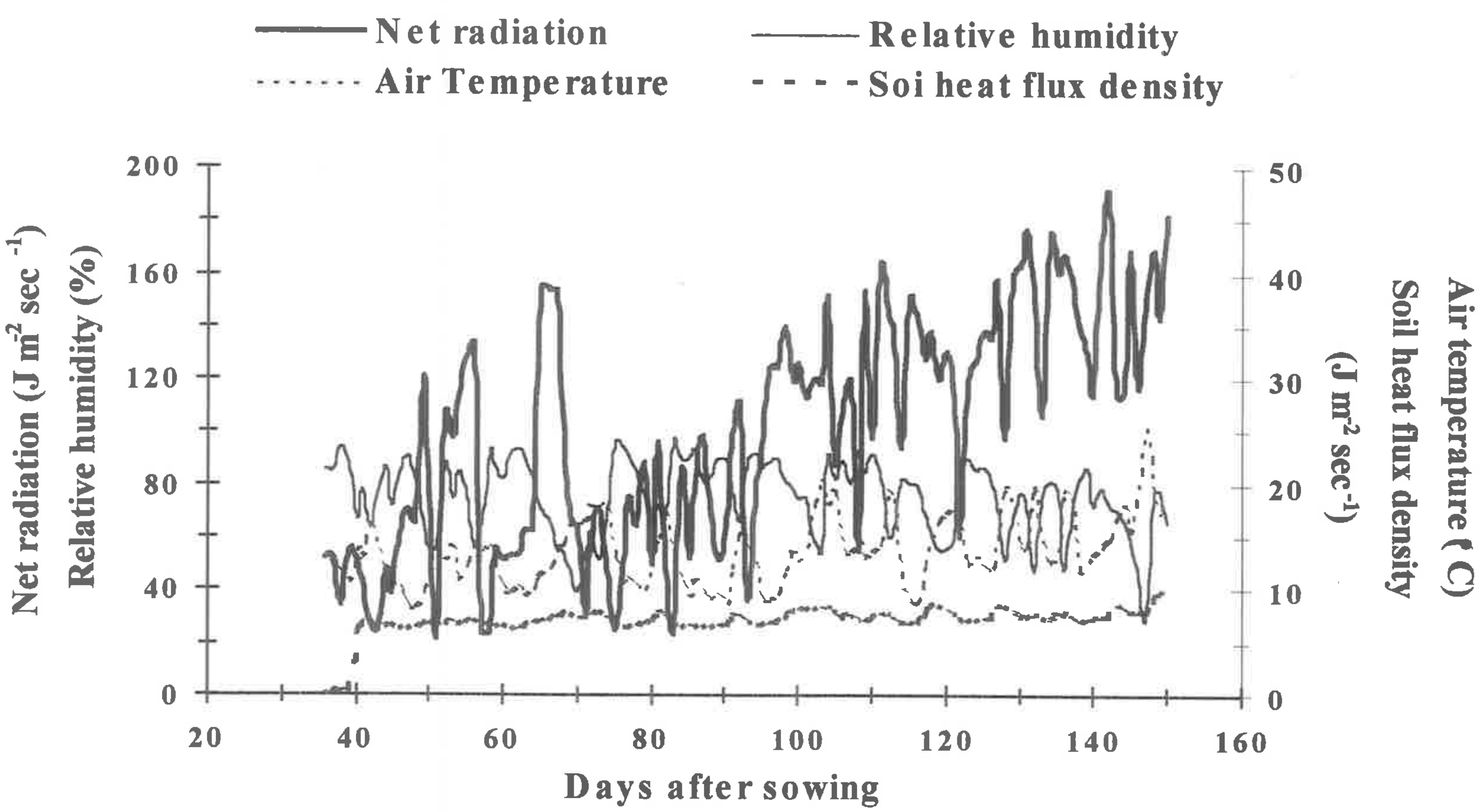
Appendix 5 Average soil matric suction at 200 mm soil depth as influenced by direct drilling and conventional cultivation measured by electronic moisture sensor recorded on a data logger at mid-day, 12.00 , during growing season in (a) 1993 and (b) 1994.

Appendix 6 The realtionship between soil water evaporation (Es) and soil water suction (S) at different evaporative demand (Em) as influenced by continuous wheat crop rotation sown by direct drilling (DD-WWW) in 1994

Continuous wheat sown by direct drilling																	
Em mm d^{-1}	**S kPa**	**Es mm d^{-1}**	**Em mm d^{-1}**	**S kPa**	**Es mm d^{-1}**	**Em mm d^{-1}**	**S kPa**	**Es mm d^{-1}**	**Em mm d^{-1}**	**S kPa**	**Es**	**Em mm d^{-1}**	**S kPa**	**Es mm d^{-1}**	**Em mm d^{-1}**	**S kPa**	**Es mm d^{-1}**
1.600	6.5	0.803	**2.603**	250.6	0.789	**3.651**	4.8	4.308	**3.935**	12.3	4.683	**4.594**	47.0	3.740	**7.432**	21.8	3.612
1.600	8.3	0.803	**2.603**	196.8	1.218	**3.651**	19.3	3.103	**3.935**	1064.1	0.338	**4.594**	62.1	3.583	**7.432**	370.7	1.917
1.600	299.9	0.115	**2.603**	258.2	1.005	**3.651**	33.3	2.738	**3.935**	50.7	3.038	**6.396**	48.9	3.742	**7.432**	501.2	1.799
1.600	266.1	0.115	**2.603**	258.2	1.005	**3.651**	30.4	2.556	**4.126**	59.0	4.489	**6.396**	13.8	6.447	**7.432**	29.5	4.861
1.600	38.6	0.344	**2.603**	202.8	0.716	**3.651**	21.2	2.775	**4.126**	11.2	4.951	**6.396**	95.5	4.458	**7.432**	6.7	5.797
1.600	16.6	0.918	**2.603**	129.1	0.895	**3.665**	18.7	3.299	**4.126**	84.7	4.394	**6.396**	679.2	1.433	**7.432**	72.8	2.742
1.691	9.1	1.062	**2.603**	154.5	0.716	**3.665**	174.6	0.880	**4.126**	1202.3	1.052	**6.396**	824.1	1.356	**7.432**	274.2	1.583
1.691	2877.4	0.107	**2.603**	243.2	0.716	**3.665**	13.5	4.010	**4.126**	45.0	4.299	**6.396**	26.9	5.494	**7.969**	3.9	9.164
1.691	11.2	1.167	**2.782**	34.3	1.305	**3.665**	159.6	0.817	**4.126**	889.2	1.432	**6.396**	36.2	5.334	**7.969**	1.8	9.850
1.691	863.0	0.213	**2.782**	472.1	0.479	**3.665**	154.5	1.114	**4.210**	5.8	3.440	**6.396**	2.3	7.164	**7.969**	12.3	8.766
1.691	657.7	0.213	**2.782**	619.4	0.398	**3.665**	107.6	1.041	**4.210**	2552.7	1.242	**6.396**	15.8	7.004	**7.969**	13.9	8.925
1.691	2.1	0.955	**2.782**	47.8	1.193	**3.665**	101.4	0.964	**4.210**	6.3	4.585	**6.396**	227.0	3.025	**7.969**	299.9	3.777
1.691	47.8	0.742	**2.782**	14.3	2.835	**3.665**	77.3	1.041	**4.210**	582.1	1.053	**7.144**	916.2	0.607	**7.969**	266.1	4.184
1.691	129.1	0.531	**2.782**	98.4	1.018	**3.665**	129.1	0.817	**4.210**	1.0	4.585	**7.144**	719.4	0.336	**7.969**	34.3	3.833
1.691	92.7	0.318	**2.782**	338.8	0.398	**3.805**	10.6	3.105	**4.210**	698.2	1.528	**7.144**	763.8	1.007	**7.969**	137.1	3.833
1.691	638.3	0.318	**3.120**	141.3	2.306	**3.805**	201.4	2.549	**4.210**	32.3	2.770	**7.144**	319.2	1.064	**7.969**	107.6	4.120
1.691	154.5	0.213	**3.120**	2.0	3.073	**3.805**	756.8	0.556	**4.210**	101.4	1.815	**7.144**	458.1	0.879	**8.577**	811.0	0.660
1.845	3.9	1.906	**3.120**	619.4	0.306	**3.805**	1364.6	0.556	**4.210**	75.0	1.625	**7.144**	370.7	1.322	**8.577**	619.4	0.789
1.845	37.5	0.188	**3.120**	381.9	0.365	**3.805**	301.3	2.549	**4.210**	417.8	1.339	**7.144**	229.1	1.465	**8.577**	638.3	0.926
1.845	169.4	0.563	**3.120**	43.7	2.562	**3.805**	1361.4	0.635	**4.210**	532.1	1.053	**7.144**	349.1	1.029	**8.577**	266.1	1.269
1.957	15.8	1.910	**3.120**	185.4	1.732	**3.935**	338.8	2.027	**4.210**	118.0	1.911	**7.144**	164.4	1.322	**8.577**	393.6	1.038
1.957	274.8	0.955	**3.120**	59.0	2.337	**3.935**	1202.3	0.252	**4.594**	543.3	0.639	**7.144**	159.6	1.322	**8.577**	319.2	1.269
1.957	820.4	0.382	**3.120**	34.3	2.711	**3.935**	1096.5	0.252	**4.594**	18.3	3.822	**7.144**	150.0	1.064	**8.577**	95.5	1.750
1.957	1462.2	0.192	**3.120**	1002.3	0.150	**3.935**	70.6	2.448	**4.594**	349.1	0.639	**7.144**	77.3	3.479	**8.577**	185.4	1.913
1.957	429.5	0.955	**3.120**	972.7	0.378	**3.935**	101.4	2.699	**4.594**	392.6	0.400	**7.144**	46.3	5.387	**8.577**	282.5	1.432
1.957	14.0	1.528	**3.120**	222.3	0.225	**3.935**	23.2	3.290	**4.594**	17.9	3.583	**7.144**	59.0	3.365	**8.577**	133.0	1.510
1.957	1276.4	0.382	**3.651**	19.3	0.573	**3.935**	145.5	2.617	**4.594**	5.7	4.617	**7.144**	944.1	1.343	**8.577**	121.6	1.990
1.957	185.4	1.528	**3.651**	18.2	0.982	**3.935**	1396.4	0.338	**4.594**	8.6	4.856				**8.577**	121.6	1.595
1.957	1475.7	0.382	**3.651**	26.9	0.654	**3.935**	89.9	2.530	**4.594**	4.4	3.583						

Appendix 7 The relationship between soil water evaporation (Es) and soil water suction (S) at different evaporative demand (Em) as influenced by continuous wheat crop rotation sown by conventional cultivation (CC-WWW) in 1994

Continuous wheat crop rotation sown by conventional cultivation																	
Em mm d^{-1}	$\log_{10}$ S log kPa	Es mm d^{-1}	Em mm d^{-1}	$\log_{10}$ S log kPa	Es mm d^{-1}	Em mm d^{-1}	$\log_{10}$ S log kPa	Es mm d^{-1}	Em mm d^{-1}	$\log_{10}$ S log kPa	Es mm d^{-1}	Em mm d^{-1}	$\log_{10}$ S log kPa	Es mm d^{-1}	Em mm d^{-1}	$\log_{10}$ S log kPa	Es mm d^{-1}
1.600	1.722	1.032	**2.603**	2.726	0.424	**3.651**	1.487	2.778	**3.896**	2.218	2.388	**4.594**	1.912	3.919	**7.144**	2.795	0.529
1.600	0.799	1.205	**2.603**	2.691	0.742	**3.651**	1.320	3.647	**3.896**	2.333	2.291	**4.594**	2.557	0.818	**7.144**	2.760	1.057
1.600	1.953	0.602	**2.603**	2.576	0.742	**3.651**	1.775	3.560	**3.896**	2.829	0.764	**4.594**	2.749	0.602	**7.144**	1.538	8.001
1.600	1.791	0.774	**2.603**	0.834	2.548	**3.665**	1.526	2.848	**3.896**	2.322	1.718	**4.594**	1.717	5.007	**7.144**	1.192	7.580
1.600	2.610	0.086	**2.782**	1.584	2.164	**3.665**	0.961	4.050	**4.061**	2.714	0.954	**4.594**	2.049	4.819	**7.144**	2.841	0.314
1.600	2.218	0.774	**2.782**	2.472	0.796	**3.665**	2.518	1.708	**4.061**	2.414	0.954	**4.594**	1.361	4.713	**7.432**	1.295	7.083
1.600	2.599	0.258	**2.782**	2.841	0.462	**3.665**	2.391	1.708	**4.061**	2.506	0.954	**4.594**	2.095	4.406	**7.432**	2.368	2.557
1.600	0.926	0.946	**2.782**	3.037	0.334	**3.665**	0.177	4.325	**4.061**	2.668	1.348	**4.594**	1.135	4.920	**7.432**	2.772	1.501
1.600	2.126	0.602	**2.782**	2.656	0.732	**3.665**	0.396	4.079	**4.061**	2.218	1.405	**4.594**	2.701	0.818	**7.432**	2.991	1.315
1.744	2.783	0.410	**2.782**	2.333	1.004	**3.665**	0.742	4.325	**4.061**	1.122	3.598	**6.396**	0.721	6.844	**7.432**	2.541	2.542
1.744	2.483	0.410	**2.782**	1.561	2.724	**3.665**	1.941	2.038	**4.061**	2.829	0.954	**6.396**	3.235	0.793	**7.432**	2.241	2.401
1.744	2.587	0.546	**2.782**	3.002	0.303	**3.665**	1.745	1.484	**4.061**	2.426	1.519	**6.396**	2.390	1.433	**7.432**	1.249	7.127
1.744	2.760	0.410	**2.782**	2.333	0.876	**3.665**	1.826	2.833	**4.061**	1.445	4.215	**6.396**	2.562	1.196	**7.432**	2.945	1.367
1.744	2.322	0.682	**2.782**	1.711	2.504	**3.665**	1.895	2.767	**4.061**	2.160	1.572	**6.396**	2.659	1.356	**7.432**	1.388	6.399
1.744	2.899	0.410	**2.782**	3.048	0.334	**3.665**	2.114	1.514	**4.061**	2.656	0.845	**6.396**	2.316	1.912	**7.432**	2.230	2.482
1.744	2.541	0.410	**3.120**	2.553	0.268	**3.665**	2.172	1.778	**4.061**	1.641	3.314	**6.396**	2.682	1.593	**7.432**	1.434	6.614
1.744	2.276	0.546	**3.120**	2.368	0.268	**3.809**	1.275	1.912	**4.061**	2.679	1.011	**6.396**	0.786	7.407	**7.432**	3.002	1.397
1.744	2.726	0.682	**3.120**	2.333	0.334	**3.809**	2.369	0.956	**4.337**	3.002	1.132	**6.396**	2.455	2.789	**7.969**	1.215	10.041
1.744	2.783	0.546	**3.120**	1.480	2.069	**3.809**	2.787	0.381	**4.337**	3.037	1.054	**6.396**	2.763	1.356	**7.969**	1.272	9.563
1.845	1.607	1.832	**3.120**	1.376	2.134	**3.809**	3.008	0.190	**4.337**	2.414	4.068	**6.396**	1.457	7.087	**7.969**	1.145	9.722
1.845	1.745	1.832	**3.120**	1.272	2.402	**3.809**	2.540	0.956	**4.337**	2.899	0.902	**6.396**	2.739	1.356	**7.969**	1.318	9.794
1.845	2.483	0.611	**3.120**	2.287	0.399	**3.809**	2.244	0.766	**4.337**	2.207	4.294	**6.396**	2.643	2.072	**7.969**	1.272	9.722
1.845	2.426	0.203	**3.120**	1.457	2.069	**3.809**	1.230	1.527	**4.337**	1.941	4.294	**6.396**	2.192	2.949	**7.969**	1.457	9.563
1.883	2.982	0.557	**3.120**	2.737	0.268	**3.809**	2.957	0.381	**4.337**	2.691	2.637	**6.396**	2.445	2.232	**7.969**	2.391	3.937
1.883	2.941	0.318	**3.120**	2.126	2.000	**3.809**	1.359	2.103	**4.337**	2.010	5.274	**6.396**	2.223	2.386	**7.969**	2.391	3.698
1.883	2.981	0.636	**3.120**	2.841	0.243	**3.809**	2.218	1.527	**4.594**	1.206	4.828	**6.396**	1.780	6.370	**7.969**	2.333	3.227
2.603	1.607	2.447	**3.120**	1.192	2.923	**3.809**	1.407	2.483	**4.594**	1.970	4.511	**6.396**	2.188	3.345	**8.577**	2.726	0.455
2.603	0.649	3.207	**3.120**	0.488	3.351	**3.809**	3.012	0.381	**4.594**	1.806	3.758	**6.396**	1.762	5.174	**8.577**	2.668	0.500
2.603	1.837	2.280	**3.120**	1.676	2.742	**3.896**	3.060	0.288	**4.594**	2.667	0.446	**6.396**	2.860	1.196	**8.577**	2.806	0.832
2.603	2.587	0.422	**3.651**	2.231	0.694	**3.896**	3.095	0.191	**4.594**	1.788	3.845	**7.144**	2.772	0.529	**8.577**	2.529	0.700
2.603	2.380	0.338	**3.651**	2.267	0.610	**3.896**	2.633	0.861	**4.594**	2.301	3.400	**7.144**	2.714	0.421	**8.577**	2.737	0.600
2.603	2.656	0.505	**3.651**	2.106	0.610	**3.896**	2.956	0.191	**4.594**	1.885	3.845	**7.144**	2.852	0.629	**8.577**	2.726	0.580
2.603	2.576	0.505	**3.651**	2.294	0.957	**3.896**	2.483	1.434	**4.594**	2.449	0.804	**7.144**	2.772	1.050	**8.577**	1.272	7.170
2.603	2.737	0.424	**3.651**	1.380	4.257	**3.896**	2.183	1.909	**4.594**	1.406	4.475	**7.144**	2.772	0.421	**8.577**	0.949	10.464
2.603	2.599	0.211	**3.651**	2.126	1.303	**3.896**	1.826	3.249	**4.594**	2.616	0.923	**7.144**	2.587	0.629	**8.577**	2.829	0.635



Appendix 8 Average daily net radiation, relative humidity, air temperature and soil heat flux density at 200 mm soil depth measured by electronic sensors recorded on a data logger under direct drilling during growing season in 1993.

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RWUE	relative water use efficiency
RY	relative yield
S	cropping rotation system
S	general soil matric suction (kPa)
Si	daily soil matric suction (kPa)
SAD	stable aggregate as a fraction or percentage by weight
SAT	stable aggregate as a fraction or percentage by weight of total dry aggregate (g g^{-1} or %)
SD	surface soil depth (mm)
SWi	daily stored soil water (mm)
SWm	maximum stored soil water (at field capacity, mm)
SWw	stored soil water at wilting point (mm)
T	tillage practice
Tc	general crop transpiration (mm)
Tcai	daily actual crop transpiration (mm d^{-1})
Tcpi	daily potential crop transpiration (mm d^{-1})
TSW	total stored soil water (mm)
TxS	interactive effect between tillage practice and crop rotation system
Uz	wind speed (m s^{-1})
WP	soil water content at wilting point or 1500 kPa matric suction (m^3 m^{-3})
WU	general water use (mm)
WUE	water use efficiency (kg ha^{-1} mm^{-1})
Yp	potential or maximum yield (t ha^{-1})
Zi	soil depth of each horizon (mm)
Zw	the height of wind measurement (m)

THE EFFECTS OF TILLAGE PRACTICES AND CROP ROTATION SYSTEMS ON SOIL PROPERTIES AND WATER USE EFFICIENCY

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CHAPTER 1

GENERAL INTRODUCTION

Dryland wheat production in Southern Australia is limited by soil hydrological imbalances which are controlled by soil physical properties and climatic conditions. In general, wheat growth under rainfed conditions depends mainly on the available water within the root zone which is governed by the amount and distribution of rainfall on the one hand (French and Schultz, 1984) and storage and supply of available water in soil on the other hand (Greacen, 1981b; Hamblin, 1993).

Southern Australia enjoys a Mediterranean climate where rainfall predominates in the early part of the growing season (April to August) and is minimal during the latter part of the season (September to December). Only a small amount of water (<20 %) is used by wheat during the early growing season up to tillering. After tillering to maturity, approximately 80 % of total water use is needed for transpiration, especially during the anthesis stage. However, the amount of rainfall is high during the early growing season (>60 % of the total from April to October), generally exceeding the water requirement of wheat but there is insufficient rainfall during the post-tillering stage. The critical period of wheat production, between anthesis to maturity, falls during this stage. Therefore, wheat growth during the middle to the end of the growing season depends mainly on water stored in the root zone. (Greacen and Hignett, 1976).

The proportion of rainfall stored water within the soil profile and the soil water regime through the season is controlled by the surface and subsurface soil physical properties. The accession of rainfall to the soil profile, water holding capacity of the root zone, drainage below root zone, soil water evaporation and crop transpiration are all dependent on soil structural quality. Optimum total storage of water and maximum availability of water for the crop production demands optimum soil structural qualities. The methods available to improve soil properties under rainfed conditions are generally restricted to improved tillage practices and crop rotation systems.

Adaptation of tillage practices have been used to improve soil structure in dryland farming systems. Both direct drilling and conventional cultivation have both been used to increase water use and water use efficiency on dryland farming systems. However, the soil responses to either direct drilling or conventional cultivation depends on other soil management practices and the cropping systems (Denton and Wagger, 1992). Factors such as soil type, soil wetness, types of tillage machinery and tillage systems play a role in determining the response.

Conventional tillage has been used primarily to provide a fine seedbed to ensure optimum seed germination and also to control weeds, increase infiltration, enhance topsoil aeration, increase water stored in the soil profile, reduce surface runoff and reduce water evaporation loss by capillary rise to the soil surface during drying (Baver, 1968). However, it is now accepted that excessive tillage may induce soil structural deterioration (Cresswell et al., 1991). Conventional tillage may lead to decreased infiltration and hydraulic conductivity due to the decrease in the number of large pores in the subsurface layer (Lindstorm and Onstad, 1984). Generally, tillage tends to temporarily decrease the bulk density and increase the total porosity of the tilled layer. At the same time, soil below the tilled layer suffers increased bulk density from the pressure and remoulding applied by the tillage machinery (Klute, 1982). In time, because of increased oxidation of organic matter, structural stability changes and the physical condition of the tilled layer deteriorates. To minimised these adverse effects, tillage is confined to the sowing operation (direct drilling) by many wheat growers in the cropping areas of South Australia

(Hamblin and Kyneur, 1993). Weed control is achieved by use of herbicides and appropriate crop rotations.

Direct drilling may improve soil structure by retarding the development of a tillage pan and by promoting more stable surface soil aggregates and associated pores. These improved soil structural conditions promote increased infiltration, reduced surface runoff, decreased penetration resistance, increased aeration porosity and improved soil water characteristics (Datiri and Lowery, 1991).

In South Australia there is a need to develop improved farming systems that will optimise water storage and increase crop rooting depth. The factors that provide the means to do this include direct drilling or conventional cultivation and rotations of wheat (*Triticum aestivum L.*), canola (*Canola cache*) and faba bean (*Vicia faba L.*). These elements of a management system have the capacity to improve surface, subsurface and subsoil structure. The improved surface soil aggregate stability, lower bulk density, better aeration, greater available water storage capacity and increased infiltration rate can be expected to increase the accession of rainfall to the root zone and increase the availability of stored soil water. Ultimately these improvements are expected to increase crop water use efficiency. An additional benefit that could account from these advances is that deep drainage to the ground water table would decrease because of improved water storage and increased crop rooting depth.

The single most important step in improving crop productivity in Southern Australia is to improve water use efficiency. Crop water use is defined as the total volume of water (m^3) lost from a unit area (m^2) of crop canopy by evapotranspiration (usually expressed as millimetre of water). Water use efficiency is the mass of dry matter or grain produced per unit area per unit depth water use (kg ha^{-1} mm^{-1}). Water use efficiency in Southern Australia ranges from 16 to 54 kg $ha^{-1}mm^{-1}$ for dry matter and from 4 to 19 kg ha^{-1} mm^{-1} for grain (French and Schultz, 1984). This very large range of values reflect variations of climate (rainfall) and also different soil physical and environmental conditions and management.

Attempts to improve water use efficiency by crops under rainfed conditions assume that any increase in water use efficiency is dependent on increasing crop transpiration and decreasing soil water evaporation. However, few studies have been conducted in which transpiration has been measured separately from evaporation. Crop water use efficiency should therefore be expressed as transpiration efficiency instead of evapotranspiration efficiency. The difficulty in measuring this lies in partitioning total crop water use into soil water evaporation and crop transpiration. One method of doing this is to model soil water evaporation and crop transpiration separately. Crop production (dry matter or grain yield) per unit area per unit depth of water used for crop transpiration is called "transpiration efficiency" which is a better index for crop water use efficiency measurement than the commonly used evapotranspiration efficiency (Tanner and Sinclair, 1983). In South Australia, French and Schultz (1984) obtained maximum transpiration efficiencies of 55 and 20 kg ha^{-1} mm^{-1} for dry matter and grain yield of wheat respectively. Measurement of dry matter transpiration efficiency during sensitive growing stages of the crop may lead to improved understanding of the potential grain yield of wheat for specific soils under different climatic conditions.

Generally, there is little knowledge available to guide development of improved farming systems in Southern Australia which links soil structural quality to relative losses of water by transpiration as opposed to evaporation. The role of different tillage systems and crop rotations is also not clear in this distinction. An understanding of these interactions should provide a clearer basis for devising farming systems uniquely suited to Southern Australia conditions.

Aims of the research

The objective of the research reported in this thesis was to provide information to improve the productivity of dryland farming systems by improving surface and subsurface soil structure using tillage practices and crop rotation systems which can be expected to improve water use efficiency of crops.

Specific aims were to:

(i) compare the effects of direct drilling and conventional cultivation on surface and subsurface soil structural properties which effect crop production (dry matter and water use efficiency),

(ii) compare the effects of direct drilling and conventional cultivation on soil water evaporation, total stored soil water and cumulative water use (crop evapotranspiration),

(iii) compare the effects of different rotations of wheat, canola and faba bean on surface and subsurface soil structural properties which effect water use efficiency of wheat,

(iv) use modelling to study the effects of direct drilling and conventional cultivation on transpiration efficiency of wheat.

Thesis outline

This thesis consists of eight chapters. The literature review (Chapter 2) deals mainly with the effects of agricultural practices (tillage practices and crop rotations) and rainfall on soil properties, root distribution, crop growth, water use (soil water evaporation and crop transpiration) and water use efficiency including water use models. The experiments and results from this study are presented in three parts. The first part (Chapter 3) describes methodology, experimental and statistical design and computational procedures during 4 years of the experimentation from 1992 to 1995. The experimental results are presented in two sections: empirical results and modelling. Chapters 4 and 5 deal with field and laboratory experimental results. Chapter 4 covers the effects of tillage practices and crop rotation systems on surface and subsurface soil properties and field soil water evaporation. Chapter 5 covers stored soil water, cumulative water use, water use efficiency and crop production (dry matter and grain yield) including root length density distribution. Chapters 6 and 7 deal with modelling of water use to analyse the water use efficiency of wheat by generating and developing a soil water evaporation model (Chapter 6) and partitioning of evapotranspiration into soil water evaporation and crop transpiration (Chapter 7). Chapter 8 provides a general summary of the results and conclusions from the work.