Deep Drainage and Nitrate Losses under Native Vegetation and Agricultural Systems in the Mediterranean Climate Region of Australia

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Preamble

Background

Increasingly, questions are being asked about the long-term sustainability of Australia's current agricultural practices. Without doubt, there have been changes to the hydrology and nutrient status of landscapes where agricultural crops have replaced native vegetation. In many cases, the effects have been subtle and incremental over a long term so that only recently have the associated problems become obvious.

The issue of sustainable agricultural practice is at the core of the LWRRDC/CSIRO initiative entitled 'Redesign of Plant Production Systems', with the proposed research focusing primarily on soil water and nutrient balances under native vegetation and agricultural systems that have replaced them.

The explicit purpose of this review is specified below, but an initial 'caveat' is worth highlighting. Natural systems by their very nature are highly complex, with many feedback loops. For example, soil acidification, salinisation and surface crusting may be linked through the process pathway—soil acidification results in poor root growth, which reduces evapotranspiration and increases recharge, leading to groundwater rise and mobilisation of salt. The build-up of salt in the root zone leads to plant death and further reductions in evapotranspiration, causing possible waterlogging and scalding of the soil surface. The scalded surface lacks protection from raindrop impact and so becomes susceptible to crusting. Of course, the effect of stocking pressure could be added to this scenario.

Hence, when an emphasis is placed on considering changes to hydrology and nitrate leaching under agricultural systems that have replaced native vegetation it is inevitable that some of the subtle interactions between plant, soil and climate will be overlooked.

In Australia, the situation is exacerbated by the extreme vagaries of climate. In many cases the records are simply not long enough to establish how the natural systems actually respond to climatic extremes. For example, since its discovery in 1840 Lake Eyre was considered to be permanently dry until its first recorded filling in 1949 and initial reports on the existence of water in the lake were considered to be observation errors. Not until the recent fillings of the lake has it been recognised that periodic inundation is a natural feature of the Lake Eyre system.

This example graphically highlights the need to proceed with caution when reviewing the hydrological functioning of natural systems in the Australian continent because most experimental programs are necessarily short term.

By contrast, most agricultural enterprises are characterised by high nutrient import, export and turnover, with stability achieved through the use of technology and input of energy (Slayter 1972). The systems are simple in terms of plant diversity, and net production is maximised at the expense of biomass accumulation, high gross productivity and natural stability (Johnston 1993). Nevertheless, the vagaries of climate can have a substantial impact on reported experimental results and therefore it is still relevant to place field observations in the context of long-term climatic conditions.

Purpose of the study and terms of reference

The purpose of this study is to review existing information and data sets concerning water and nutrient use by natural plant communities and agricultural plant production systems that have replaced them in southern (primarily mediterranean) Australia. The purpose of the review is to provide a sound starting base for R&D projects within the CSIRO/LWRRDC R&D Program on 'Redesign of Plant Production Systems'.

The major activities in the review were:

1. Review and summarise from published literature, work that quantifies the availability, uptake and loss of water and nitrogen (especially via deep drainage) from within natural vegetation ecosystems and from the agricultural plant production systems that have largely replaced them, across southern Australia.
2. Identify as far as possible, similar work in the 'grey' literature or as unpublished technical reports, etc.

3. Summarise the information available in those reports, including a brief description of the location of natural or agricultural vegetation type, the representativeness of climatic conditions during data collection, trends in water-use-efficiency, together with a collation and summary of the quantitative data collected.
4. Provide, wherever possible, contact details on the location of those data sets for use by others.
5. Draw out any general conclusions arising from the reviewed results.
6. Arrange and hold a workshop at a suitable location to review the results of the project so far, including discussion of the sites and plant systems, the measurement techniques used, and the data obtained.
7. Prepare a written summary of the project, to include the review of past work and data sets, general conclusions drawn, and results of the workshop.

Part of objective (6) was achieved by holding two preliminary working group meetings in Western Australia and Adelaide. In Western Australia, preliminary results were discussed in a forum with the following participants from CSIRO: Dr J. Williams, Dr F.X. Dunin, Dr I. Fillery, Dr B. Keating, Dr K. Verburg and Dr P. Ward.

In Adelaide, discussions were held with former staff of CSIRO Water Resources who were intimately involved with estimation of recharge across the Mallee region and the south-east of the State. My thanks are extended to Mr F. Leaney, Mr I. Jolly, Mr A. Kennett-Smith and Dr V. Snow for these discussions.

Further discussions were held in Melbourne with Professor R.E. White, Dr A. Western, Dr R. Grayson and Mr Fredrick Watson.

Following these working group meetings, input was obtained from Professor J. Pate (University of Western Australia), Dr Ted Lefroy (CLIMA) and Drs R. George and E. Barrett-Lennard (Agriculture W.A.). A previously unpublished internal review of tree water use that has been undertaken by Dr Barrett-Lennard and colleagues is included as Chapter 4 in this review.

1 Native vegetation systems

1.1 What is known about the hydrology of Australia's natural systems in the Mediterranean climate region?

The following statements were drawn from a literature search and interviews with experienced scientists. The statements were then presented to the first working group meeting in Western Australia and subsequently refined to reflect the consensus of that meeting.

1. Net rainfall is always less than gross rainfall due to canopy interception and interception by the surface organic litter layer. The understorey of many Australian remnant systems in agricultural regions has been denuded by grazing animals so the systems no longer reflect the interception capacity of the original native ecosystem.
2. Evaporation from leaf surfaces can greatly exceed potential evaporation (by up to five times) during and immediately after rainfall (Sharma 1984). This direct evaporation can account for 10–20% of gross annual rainfall (Dunin and Mackay 1982; Greenwood et al. 1985).
3. The canopy modifies the spatial distribution of water arriving at the ground surface, leading to highly variable infiltration, and hence spatial variations of soil water content. This variability can be further enhanced by non-wetting behaviour arising from the hydrophobic nature of many natural gums and resins.
4. Remnant vegetation patches can be impacted by incursion of groundwater from the surrounding agricultural land. Groundwater levels under remnants may therefore be unrepresentative of the original pre-clearing groundwater level.
5. The hydrology of natural systems is subject to periodic modification by fire. Bushfires are common throughout the mediterranean region and controlled burning is a common bushfire prevention strategy. Controlled burning to reduce the fuel load leads to a periodic complete modification of the understorey architecture and hence the near-surface heat and water balance.

1.2 Broad classification of vegetation types

The distribution of natural vegetation in the mediterranean region broadly follows a rainfall gradient with the following general groups prevailing:

Rainfall (mm)	Vegetation type
>800	Tall mesic wet sclerophyll forest
600–800	Dry sclerophyll forests and woodlands
400–600	Mallee woodlands and grasslands
<400	Shrub woodlands and hummock grasslands

Perennial sclerophyllous plants include eucalypts, banksias, acacias, casuarinas and xeric grasses.

The general characteristics of natural sclerophyllous vegetation include a reduced plant nutrient status, particularly phosphorus (Specht and Rundel 1990); an evergreen character with growth extended over most of the year, with flowering and shoot growth in spring (Specht 1969) and low nutrient loss rates and efficient nutrient cycling (Burrows 1976; Guthrie et al. 1978).

2 Methods of estimating recharge (deep drainage)

2.1 Introduction

Before reviewing the literature reporting on water balances and nitrate leaching it is pertinent to consider the major methods of measuring components of the water balance that are currently available. The inherent errors in the methods constrain the accuracy to which results can be reported.

Since this review began, the CSIRO has initiated publication of a series entitled ‘Physical and Chemical Techniques for Discharge Studies’. The objective of this series is to provide in an easy-to-read and practically orientated form, the techniques used by CSIRO scientists for detecting and measuring groundwater recharge and discharge. Part 1 of the series, entitled ‘The basics of recharge and discharge’, has been published (Salama 1996).

In this review, a brief documentation of the main methods of recharge estimation, with emphasis on their limitations, is presented. Readers are directed to the CSIRO series for more detailed information.

2.2 Relative chloride concentrations

For steady-state conditions, the rate of recharge can be estimated from a chloride mass balance of the unsaturated zone (Allison and Hughes 1978). If rainfall is the only source of chloride then the average flux of chloride below the root zone will equal the average flux of chloride from rainfall (provided runoff is negligible). The recharge rate, (*R*) follows from

$$R = C_p P / C_r \qquad (1)$$

where C_p is the average chloride concentration in rainfall (including ‘dryfall’), C_r is the chloride concentration of soil water below the root zone and *P* is precipitation (mm/year).

Under native vegetation systems in the mediterranean region, recharge is usually very low and results in a high level of chloride below the root zone. After clearing of native vegetation, the deep drainage is increased, resulting in leaching of the stored chloride. After a time, a new steady-state condition is reached and equation (1) can be used to estimate the rate of recharge since clearing. In practice, some chloride remains unleached from the soil profile during the establishment of the new steady-state. Hence, this method is useful only when recharge since clearing is very high and very little water is stored in the zone of evapotranspiration. Calculations of recharge using this method should, under all circumstances, be regarded as underestimates (Leaney and Herczeg 1995).

If recharge occurs through preferential flow, then much of the salt bulge will be by-passed by the invading water and the movement of the salt front will be considerably less than the rate of recharge.

Walker et al. (1991) modified the salt bulge displacement approach to estimate recharge for situations when ‘piston flow’ does not occur. For such circumstances, the following approximation applies

$$R = Qd/t \qquad (2)$$

where *t* is time since clearing and Q_d is the amount of water that has drained below the root zone. *Qd* is determined from water content of the soil profile above the displaced chloride front.

The method integrates recharge over a number of years and so does not provide any information on response to episodic extreme events.

2.3 Groundwater level fluctuation

It is generally assumed that in pristine catchments the groundwater recharge and discharge are in equilibrium and therefore there is no net change to profile water storage. Recharge usually increases after clearing and this in turn results in a rise of the watertable. However, monitoring groundwater level fluctuation using piezometers suffers from two complications. Firstly, there is a lag in the response of the groundwater to increased recharge—it may take some years for the increased recharge to reach the watertable. Secondly, a rise in groundwater level results in an increased cross-sectional area of flow and hence an increase in groundwater discharge. The increase in discharge needs to be known and deducted from the groundwater rise if the groundwater level fluctuation is to be used as a measure of increased recharge. Failure to do this results in underestimates of increased recharge resulting from clearing. The recharge estimation reflects the period over which measurements are made and also requires an estimate of the specific yield in order to convert the groundwater rise to an equivalent water depth.

2.4 Water balance

The general water balance equation is:

$$RF = ET + RO + DD + DSM \quad (3)$$

where RF is the net rainfall at the ground surface (corrected for interception losses), ET is evapo-transpiration, RO is runoff, DD is deep drainage (potential recharge) and DSM is the net gain or loss of the soil water store. All units can be written as depth equivalents.

Increasing ET therefore diminishes the contribution of RF apportioned to the remaining three terms. ET comprises surface vapour losses from both the soil (Es) and plants (Ep). Although 'plant wateruse' equates to Ep, there are many studies of agronomic systems which do not distinguish Ep and Es and instead evaluate ET by monitoring DSM and assuming that RO and DD = 0. The basis for this assumption is that RO can be physically prevented around experimental plots and DD is assumed to be a relatively small term compared with RF and ET. Obviously, this approach will overestimate ET if DD occurs. It also depends entirely on the accuracy to which DSM can be measured, and the field variability of the measurements. The recharge estimate is usually annual, over the growing period, and will therefore vary between wet and dry years. In drier regions the errors associated with the technique may exceed the magnitude of the fluxes being measured (Kennett-Smith et al. 1994).

2.5 Measurement of ET

In addition to the water balance method of estimating ET from changes to the soil water store, results are available for several direct methods of measurement. These include: weighing lysimeters (Dunin and Aston 1984); ventilated chambers (Greenwood and Beresford 1979, 1981; Greenwood et al. 1982, 1985; Farrington et al. 1989), heat pulse (Hatton and Vertessy 1990; Jolly et al. 1991; Farrington et al. 1993); energy balance-Bowen ratio method (McIlroy and Dunin 1982; Kalma et al. 1991); and eddy correlation (Moore 1976).

3 Measurements of the water balance and nitrate leaching under native systems

3.1 Introduction

The transpiration from trees varies greatly depending on species, age, soil type, seasonal conditions and depth to watertable (Farrington, 1996). Comparative values can be further confounded by the use of different techniques to measure wateruse.

3.2 Measurements of tree wateruse

Scott (1991) gives the following values of wateruse per stem (heat pulse method): *Eucalyptus* spp. 5–7 L/day; *Banksia* spp. 6–52 L/day; *Pinus* 14–114 L/day; *Tagasaste* 4–19 L/day.

Farrington (1993) gives a range of 31–49 L/day (heat pulse method) for mature *E. wandoo* and *E. salmonphloia* in a mature forest with mean annual rainfall (MAR) of 350 mm near Kellerberrin, WA.

Measurements presented as litres/day are of indicative value only. We need to know the stand density and to have a reliable sample of trees within the stand if heat pulse measures are to be expressed as mm/year and used in water balance estimation. The issue of sampling and data analysis of sap flow measurements has been presented comprehensively by Vertessy et al. (1997). In addition to validating the sap flow method using a cut tree experiment, these authors give two procedures for scaling individual tree sap flow estimates to the stand level based on stem diameter and leaf area index measurements. The first procedure was based on a regression between stem diameter and tree wateruse, developed on a small sample of trees and applied to a stand-level census of stem diameter values. Inputs to the second procedure were tree wateruse and leaf area of a single tree and the leaf area index of the stand. The two procedures yielded similar results, and although the first procedure was more robust, it required more sampling effort than the second procedure.

Perennial shrubs that comprise the ground flora of many native mediterranean native systems are also capable of high transpiration. Greenwood et al. (1985b) found that in the jarrah forest the annual evaporation from ground flora, litter and soil ranged from 360 to 410 mm (about 32–34% of rainfall). Similar findings of high wateruse by ground flora, litter and soil have been reported by Farrington et al. (1989) for the banksia woodland of the Swan coastal plain (mean annual rainfall 670 mm). They found that the contribution to evapotranspiration was 427 mm (64% of MAR). This value rose to 814 mm at a nearby site with a watertable less than 3 m deep (Farrington et al. 1990). Farrington et al. (1992) report that heath and shrub communities in uncleared areas of the Western Australian wheat belt maintain an average daily evaporation rate of about 1.4 mm in winter and spring, rising to over 2 mm/day in summer when unseasonal rain falls.

This ability of native systems to use rainfall which falls outside the growing season of annual crops is a major advantage in terms of reducing deep drainage.

Farrington (1996) gives a table documenting most of the recent estimates of daily and longer term wateruse by eucalypts and other trees in Australia. Summary information relevant to the mediterranean region is given in Table 3.1.

3.3 Responses to episodic events

There are comparatively few data on hydrologic responses to episodic events in the mediterranean climatic zone. However, in higher rainfall zones of Victoria the response of the mountain ash forest (*Eucalyptus regnans* F. Muell.) to bushfire and clear felling is well documented (Langford 1976; Kuczera 1985, 1987; Jayasuriya et al. 1993; Vertessy et al. 1996). These studies show that runoff in regrowth mountain ash forests is significantly less than old growth stands because of differences in forest density and structure.

Based on the measured hydrologic responses of eight large catchments to a bushfire in 1939, Kuczera (1985) developed an idealised runoff curve describing the relationship between mean annual streamflow and mountain ash forest age. The relationship assumes that old-growth forests yield an average of 1195 mm/year and that this subsequently falls to 580 mm/year over the next 27 years after fire or logging. After this, the runoff slowly recovers over about 150 years.

Table 3.1 Wateruse by native vegetation in Mediterranean Australia.

Tree	MAR[a] (mm)	Condition	Wateruse (mm)	Method of estimate	Reference
E. wandoo	1120	Regenerating forest Collie, W.A.	up to 1100	Ventilated chamber	Greenwood et al. (1982)
E. marginata/ E. gomphocephala	830	Mature forest near Perth	497–634	WATBAL	Carbon et al. (1982)
P. pinastar	830	Plantation near Perth			
		(2000 trees/ha)	626–717	WATBAL	Butcher (1977)
		(740 trees/ha)	574–637		
P. pinastar	830	Plantation near Perth (1200 trees/ha)	643–738	WATBAL	Carbon et al. (1982)

[a] MAR is mean annual rainfall.
[b] WATBAL refers to the water balance method.

This work gives an indication of the hydrologic time response of forests subjected to major disturbance under high rainfall conditions. The hydrologic response under mediterranean conditions over this time scale is largely unknown. Over shorter time scales, George et al. (1991) report groundwater responses to episodic large rainfall events with no signs of recession two years later. Reid (1995) also reports episodic groundwater rises in northern Victoria in response to high local recharge and widespread flooding of lower lying areas.

4 Transpiration by trees on land with shallow watertables: a survey of the literature suggests that transpiration is affected by soil texture

E.G. Barrett-Lennard[1], Jane Speijers[1], J. Morris[2] and N. Marcar[3]

Summary

This chapter surveys the literature relating site conditions to wateruse by stands of trees growing above shallow watertables. Analysis of the data suggests that transpiration by stands of trees is affected by E_{pan}, depth of the watertable, planting density and soil texture.

4.1 Introduction

Across the mediterranean agricultural region it is generally accepted that rising watertables have resulted from increased deep drainage after clearing of native vegetation and its replacement with crops and pastures that use less than the incident rainfall.

As far as we are aware, the first suggestion that revegetation of the landscape with trees may reverse the trend of rising watertables is comparatively recent. Greenwood and Beresford (1979) suggested that secondary salinisation (resulting from watertable rise) could be ameliorated using a variety of options including: (a) complete re-afforestation, (b) strategically placed plantations of salt-tolerant ground cover or deep-rooted trees, (c) conventional plantations of commercial softwoods, and (d) more widely spaced plantations to allow agriculture to be combined with forestry (agroforestry).

Intuitively, the arguments of these authors in favour of revegetation appear obvious and uncontestable. However, to implement this agenda in the more arid parts of Australia, two practical challenges must be addressed: (i) revegetation must occur while maintaining and enhancing agriculture (after all, the costs of revegetation will be met primarily from the profits of farming enterprises), and (ii) trees must be planted in such locations that they achieve the greatest salinity abatement benefit for the investment made.

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Until now, the main focus of research in revegetation for salinity abatement has been in improving the targeting of trees to points in the landscape in which more water must be used (eg. Farrington and Salama 1996). As a result of these efforts, there are now several case studies where the planting of trees has been shown to reduce deep drainage and alleviate salinity (eg. Engel 1988; George 1990).

This chapter stems from inquiry in another direction. In particular, we have been concerned with how site conditions affect the ability of trees to use water. Until recently the bulk of the evidence on transpiration by trees has been of questionable integrity, being based either on extrapolation from limited daily observations using ventilated chambers, or on watertable drawdown (reviewed by Raper (1997)).

However, recent technical developments in the ‘heat pulse’ technique (Durham and Hatton 1989) now enable the continuous measurement of transpiration in trees for periods of months or years. This technique therefore provides an increasing body of data which can be used to assess the impact of site conditions on tree wateruse.

4.2 Materials and Methods

Sites

The literature relating to annual transpiration by stands of trees in mediterranean environments is relatively small. Recent reviews by Thorburn (1996) and Raper (1997) list 18 and 11 studies, respectively. In these previous works, the approach has been synthetic or inclusive in nature. In contrast, we have taken an analytical approach and have only adopted data from studies that satisfy critical ‘quality criteria’. Specifically, studies have been adopted where:

1 Transpiration has been measured using the heat pulse technique. Thus, we have not used studies where annual transpiration has been estimated from limited numbers of daily readings of

transpiration using ventilated chambers (Greenwood et al. 1981, 1982, 1985). Neither have we included studies where annual transpiration has been estimated from groundwater monitoring (Hookey et al. 1987; George 1990).

2 Transpiration has been measured for sufficient period to allow a reasonable estimation of annual transpiration.

3 Data are available (or calculable) for pan evaporation, soil texture, and average depth and salinity of the groundwater.

4 Data are applicable to stands of trees, not isolated trees (eg. Greenwood et al. 1981, 1982) or stands with an unmeasured understorey (eg. Dunn and Connor 1993; Farrington et al. 1994).

5 Data from trees grown on waterlogged sites (average watertables less than 1 metre) have not been considered.

On the basis of these criteria, transpiration data have been gathered from seven sites using published sources and our own unpublished data. These investigations are summarised below.

Study 1. Eucalyptus camaldulensis *near Wubin in Western Australia (Marshall et al. 1997; Akilan et al. 1997).* In this study trees were planted on a sandplain seep at a density of about 1100 stems/ha. Water-use measurements were made on two clones at an upslope location and a downslope location. We refer here to the data from the upslope location; the downslope trees are regarded as having been too waterlogged for our purposes. Transpiration measurements were begun when the trees were about 9 years old (May 1991) and continued for one year (April 1992). The trees had mean heights of 15 m and mean trunk diameters of 21 cm (Clone M80) and 18 cm (Clone M66). Depth and salinity of groundwater was measured at three-weekly intervals. Pan evaporation was measured at the Wongan Hills Agricultural Station, about 50 km to the south-east of the site.

Study 2. Eucalyptus camaldulensis *Dehnh. about 160 km east of Brisbane in Queensland (Fraser et al. 1996).* This paper refers to studies at three sites in south-eastern Queensland; however, we focus on ‘Site 2’ where *E. camaldulensis* was planted at a density of 500 stems/ha (G. Fraser, pers. comm., 1998). Transpiration measurements commenced in Spring 1994 (when the trees had an average height of 5.7 m) and continued until Summer 1995 (about 450 days). The site had a clayey texture above the watertable (G. Fraser, pers. comm., 1998).

Study 3. Eucalyptus camaldulensis *Dehnh. near Bakers Hill in Western Australia (Salama et al. 1994).* In this study measurements were made in a 10-year-old plantation growing on a sandy clay lateritic soil. The original plantation had been established at a density of 1111 stems/ha; this was reduced to 580 stems/ha seven years before the start of measurements. The trees in the stand were categorised into three groups (T1, T2 and T3, DBH 18.0, 17.3 and 13.4 cm respectively) on the basis of visual estimates of leaf area. Transpiration measurements were made between October 1990 and March 1992 on one standard tree from each group. The wateruse of the plantation was then estimated based on the relative proportions of T1, T2 and T3 trees in three regions of the plantation (C1, C2 and C3). We focus here on the C1 and C2 regions, for which water-table depth and salinity data are available (C1 – well Y1; C2 – assumed to be the average of wells Y2 and Y3). Pan evaporation at this site was estimated using ESOCLIM, a program that estimates average E_{pan} in Australia based on latitude, longitude and elevation (Ian Foster, pers. comm., 1998).

Study 4. Acacia nilotica *near Tando Jam in Sindh Province, Pakistan (Khanzada et al. 1998).* We refer to two data sets from this study. Site A had a stand of trees established in 1991 at about 800 stems/ha. Transpiration measurements began in March 1994 (when the trees had an average trunk diameter of 10 cm) and continued until February 1995 (when the trees had an average trunk diameter of 12.3 cm). Site B had a stand of trees established in 1991 at 2500 stems/ha. Transpiration measurements commenced in March 1995 (when the trees had a trunk diameter of 9.9 cm) and continued until February 1996 (when the trees had a trunk diameter of 11.5 cm).

Study 5. Eucalyptus camaldulensis *at the Nuclear Institute for Agriculture and Biology Research Station, Pacca Anna, Punjab Province, Pakistan (ACIAR Project 9316, 1996).* In this study, measurements were made on a plantation growing on a sandy loam soil with shallow groundwater of salinity 5 dS/m (J. Morris, pers. comm., 1997). The trees had been planted in 1993 at a density of 2500 stems/ha. Transpiration measurements were made between March 1995 and March 1996 on two plots on which the depth to the watertable differed. Trunk diameters were 3.4 cm (shallow watertable) and 4.1 cm (deeper watertable) at the start of the measurements, and were 5.4 cm (shallow watertable) and 6.2 (deeper watertable) at the end of the measurements.

Study 6. Eucalyptus microtheca *at the Nuclear Institute for Agriculture and Biology Research Station, Lahore, Punjab Province, Pakistan (ACIAR Project 9316, 1996).* We refer to measurements made on a block of trees planted in 1990 at a density of 2000 stems/ha. The groundwater at the site was ca 1.5 m deep and had a salinity of 3 dS/m (J. Morris, pers. comm., 1997). Transpiration was measured between March 1994 and March 1995. Trunk diameters were 7.7 cm at the start of the measurements and 9.1 cm by the end of the measurements.

Study 7. *Blocks of* Eucalyptus camaldulensis *and* Casuarina cunninghamiana *planted at the Girgarre Evaporation Basin in north-central Victoria (ACIAR Project 9316, 1996).* Measurements were made on large blocks of trees planted in 1989 at a density of 625 stems/ha. The soil was a clay loam with a heavy clay B horizon and a watertable at 1–3 m. Transpiration measurements began in July 1994 (when the *E. camaldulensis* and *C. cunninghamiana* had trunk diameters of 10.5 and 10.2 cm, respectively) and continued until August 1996 (when the *E. camaldulensis* and *C. cunninghamiana* had trunk diameters of 12.7 and 14.5 cm, respectively). Pan evaporation at this site was estimated using ESOCLIM as previously described.

Analysis of data

Stepwise multiple regression analysis (Genstat 5, Rothamsted Experimental Station) was used to determine the effects on the transpiration by stands of trees of: planting density (area per tree), soil variables (texture, depth and salinity of groundwater), and climate (E_{pan}).

4.3 Results

Raw data

Table 4.1 shows the raw data available to us after our screening of the literature (12 points from 7 sites). The data set was not ideal for correlational analysis, being small in size, having a limited range in one critical variable (the salinity of the watertable), and having a partial confounding between the soil texture and planting density variables (discussed below).

Effects of E_{pan}

Following a preliminary viewing (Figure 4.1), it appeared reasonable to pool the data into two soil textural groups: clays; and sands and loams. The accumulated analysis of variance (see Figure 1) showed that transpiration on an areal basis was significantly affected by E_{pan} and soil texture group. However, there was no significant difference ($P = 0.191$) in the slopes of the relationships between T and E_{pan} for the two soil textural groups (see Figure 1). Visual inspection of the data suggested that the lack of significance of the interaction may have been due to the small size of the data set. We therefore fitted and tested the significance of separate linear

Table 4.1 Rates of tree wateruse (T) measured using the heat pulse method.

Study	Species	T (mm/year)	E_{pan} (mm/year)	T/E_{pan}	Soil texture	Mean water table depth (m)	Mean water table salinity (dS/m)
1	*E. camaldulensis* – clone M66	1334	2032	0.66	sand	1.16	9.0
	E. camaldulensis – clone M80	1680		0.83			
2	*E. camaldulensis*	≈460	2430	0.189	clay	3.0	6.2
3	*E. camaldulensis*	307	2025	0.152	sandy clay	4.5 (Y1)	6.2 (Y1)
		416		0.205		3.0 (mean of Y2 and Y3)	9.0 (mean of Y2 and Y3)[a]
4 (Site A)	*A. nilotica*	1248	2650	0.471	silty loam	1.3	20
(Site B)	*A. nilotica*	2225		0.84		2	1.5
5 (Site A)	*E. camaldulensis*	1181	1646	0.72	sandy loam	1.5	5
(Site B)		1090		0.66		3	5
6	*E. microtheca*	1048	1618[b]	0.65	loam	1.5	3
7	*E. camaldulensis*	340	1350	0.252	clay	2	17
	C. cunninghamiana	350		0.259			

[a] These values are from Salama (pers. comm., 1997).
[b] R.H. Qureshi (pers. comm., 1997).

regressions for the two textural groups (Figure 4.1). T-tests on the standard errors of the slopes of these lines showed that the slope of the response of the clay group was not significantly different from zero ($P = 0.779$), whereas the slope of the response of the (sand and loam) group was significantly different from zero ($P = 0.034$).

Effects of the depth and salinity of the groundwater

Previous researchers have noted that the transpiration by trees on areas with shallow watertables should be affected by the depth and salinity of the groundwater (Thorburn 1996; Raper 1997). A multiple regression analysis was therefore conducted to test the significance of these factors. In this analysis, account was taken of the effect of E_{pan} on T by treating T/E_{pan} as the dependent variable. We also considered the possibility that the effects might be due to the lower planting densities (larger areas per tree) in the clay group than in the (sands and loams) group.

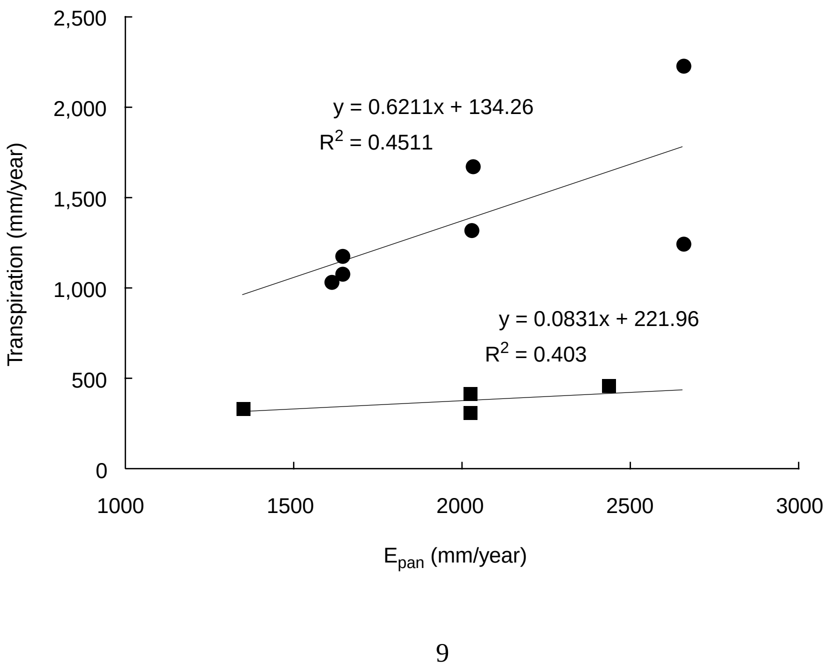
The correlation coefficients for the linear relations between T/E_{pan}, depth of the watertable, salinity of the groundwater and area per tree are shown in Table 4.2. T/E_{pan} was significantly affected by the depth of the watertable ($P < 0.05$) and the planting density ($P < 0.01$). However, there was no significant effect of the salinity of the groundwater; this was presumably because of the narrow range of groundwater salinities in our data set (previously alluded to).

Table 4.2 Correlation coefficients (r) for the interactions between T/E_{pan}, depth of the water table (m), salinity of the groundwater (dS/m), and area per tree (m^2). Superscript letters denote the levels of significance as follows: ns = not significant; * = significant at the 95% level; ** = significant at the 99% level.

Interaction	T/E_{pan}	Depth of water table	Salinity of groundwater	Area per tree
T/E_{pan}	1.000	–	–	–
Depth of water table	-0.635^{*}	1.000	–	–
Salinity of groundwater	-0.414^{ns}	-0.254^{ns}	1.000	–
Area per tree	-0.919^{**}	0.478^{ns}	0.498^{ns}	1.000

Figure 4.1 Effect of soil texture on the relationship between transpiration by stands of trees and E_{pan}. Textures are: sands and loams, ●; clays, ■. The outcomes of the accumulated analysis of variance were as follows:

Dependent variable: transpiration	df	variance ratio	P-value
+ E_{pan} (overall slope)	1	12.69	0.007
+ Soil texture group (different intercepts)	1	33.62	‹0.00 1
+ E_{pan}*Soil texture group	1	2.04	0.191



Effects of soil texture group, area per tree and depth of the groundwater

In the accumulated analysis of variance, the significance of variables depended on the order in which 'soil texture group' was added to the model. When 'soil texture group' appeared after 'depth of watertable' and 'area per tree', there were significant effects from the addition of 'depth of watertable', 'area per tree' and 'soil texture group' (Table 4.3a). In contrast, if 'soil texture group' was added to the model first there were no significant effects of 'area per tree' or 'depth to watertable' (Tables 4.3b and c). This suggests that there was partial confounding between 'soil texture group' and 'area per tree' and 'depth of the watertable'. Nevertheless, there were significant effects of 'soil texture group' that were not caused by variation in either of these other variables.

4.4 Discussion

The analysis presented here suggests that water-use by stands of trees on land with shallow watertables is affected by E_{pan}, depth of the watertable, planting density and soil texture. The responses to E_{pan}, depth of the watertable and planting density are not surprising, having been foreshadowed by previous researchers (eg. Thorburn 1996; Raper 1997). The cause of the soil texture effect cannot be confirmed based on the available data. Nevertheless, it is of interest that in regressions of T versus E_{pan} (Figure 4.1), the slopes for sands and loams appeared to be greater than for clays. The inability of clays to yield greater amounts of water in the face of higher evaporative demand, reflects the fact that for clays there is a greater resistance to the movement of water to the root surface than for sands and loams. The rate of water flow through soil pores is proportional to the fourth power of the diameter of the pores (Russell 1973, p. 429). In general, pore sizes are largest in sands and smallest in clays. Rates of water flow to the root are therefore: sands > loams >> clays.

Until now, tree planting for salinity abatement has been driven primarily by hydrogeological necessity; that is, hydrogeologists have recognised a local cause of salinity, and trees have been planted in such a manner as to address that challenge. However, the

Table 4.3 Effect of changing the order of addition of 'soil texture group' to the outcomes of the accumulated analysis of variance.

Dependent variable: T/E_{pan}	df	Variance ratio	P-value
(a) Variables introduced in order: 'depth of water table', 'area per tree', and 'soil texture group'			
+ Depth of water table	1	34.57	0.004
+ Area per tree	1	42.06	0.003
+ Soil texture group	1	1.95	0.235
+ Salinity of the groundwater	1	1.71	0.261
+ Depth of water table*soil texture group	1	0.03	0.874
+ Salinity of the groundwater*soil texture group	1	1.27	0.323
+ Area per tree*soil texture group	1	0.10	0.766
(b) Variables introduced in order: 'soil texture group', 'area per tree' and 'depth of water table'.			
+ Soil texture group	1	74.31	‹0.00 1
+ Area per tree	1	3.18	0.149
+ Depth of water table	1	1.09	0.355
+ Salinity of the groundwater	1	1.71	0.261
+ Depth of water table*soil texture group	1	0.03	0.874
+ Salinity of the groundwater*soil texture group	1	1.27	0.323
+ Area per tree*soil texture group	1	0.10	0.766
(c) Variables introduced in order: 'soil texture group', 'depth of water table' and 'area per tree'.			
+ Soil texture group	1	74.31	‹0.00 1
+ Depth of water table	1	0.33	0.599
+ Area per tree	1	3.95	0.118
+ Salinity of the groundwater	1	1.71	0.261
+ Depth of water table*soil texture group	1	0.03	0.874
+ Salinity of the groundwater*soil texture group	1	1.27	0.323
+ Area per tree*soil texture group	1	0.10	0.766

data presented in this paper suggest that optimisation of the water-using systems may also require an understanding of the capacity of soils to yield water to tree roots. Farmers will increasingly be faced with multiple hydrogeological challenges. They will need to invest their money in such a way as to get the greatest financial return for their investment in terms of tree growth, water used and land saved from salinity.

More research is needed to confirm the conclusions of this paper and further quantify the relationships between wateruse, soil texture and groundwater. The present analysis has been compromised to some extent by the partial confounding of soil texture with planting density (area per tree). Furthermore, it has not been possible to consider the issues of soil texture in anything but the broadest qualitative terms. Data sets with more balanced combinations of key site parameters (area per tree, depth of watertable, salinity of watertable, soil texture) must be developed to ensure that the confounding of factors is avoided. In addition, there is a need to measure the, probably critical, parameters associated with soil texture that cause the lower rates of transpiration by trees on clays. We have noted above that decreased transpiration on clays may be associated with increased resistance in water flow to roots. Confirmation of this suggestion would require the collecting of data that related tree transpiration to soil hydraulic conductivity, pore size distribution and the presence of macropores.

4.5 Acknowledgments

We are grateful for the cooperation of our Pakistani colleagues in ACIAR Project 9316. Our analysis would have not been possible without access to their unpublished results.

5 Measurements of the water balance and nitrate leaching under agricultural systems

5.1 Deep drainage and nitrate leaching under agricultural systems

A summary of deep drainage measurements obtained from agricultural trial sites is presented in Table 5.1.

The grassland studied by Holmes and Colville (1968) comprised perennial ryegrass (*Lolium perenne,* L.), subterranean clover (*Trifolium subterraneum,* L.), soft brome grass (*Bromus mollis,* L.), heron’s bill (*Erodium botrys*), barley grass (*Hordeum leporinum*), capeweed (*Cryptostemma calendula*, (L.), Druce) and Yorkshire fog (*Holcus lanatus,* L.).

Water balance for the Dunin et al., (1996) study gave growing season rainfall of 404 mm; ET of 370 mm and DD of 100 mm (25% of rainfall). This indicates that water stored in the profile before the growing season was used to meet the ET requirement.

This study also examined nitrate leaching using porous ceramic suction cup samplers. Results showed that for a fertiliser input of 17 kg/N/ha, the leaching loss (>0.9 m depth) was 5 kg NO_3–N/ha and the crop uptake was 55 kg N/ha.

The deep drainage value obtained for the 1993 season was regarded as a rare occurrence and resulted primarily from the initially high soil water store. Nevertheless, nitrate leaching was not great because the fertiliser bulge remained within the root zone at <0.9 m depth.

The study of Anderson et al. (1998) gives rainfall over the period of deep drainage as 419 mm in 1995 (11 May to 15 August) and 278 mm in 1996 (2 July to 15 September). As a percentage of rainfall over the period of leaching, deep drainage losses amount to 51% and 41%, respectively.

The report of White (1997) gives the composition of the permanent pasture as a mixture of Phalaris (*Phalaris aquatica*), cocksfoot (*Dactylis glomerta*), subterranean clover (*Trifolium subterraneum*) and volunteer species including annual ryegrass (*Lolium rigidum*) and broadleaf weeds. The annual pasture contained annual ryegrass, subterranean clover, *Vulpia* spp. and broadleaf weeds. It is important to note that for shorter measurement periods in 1994 (4 May–31 December, 205 mm rain) and 1997 (1 January–19 August, 267 mm rain), there was no deep drainage and hence, no nitrate leaching. It is also important to note that the site had a substantial component of lateral subsurface flow. Models that do not include this lateral subsurface flow (62–70 mm in 1995 and 14–23 mm in 1996) will over-estimate deep drainage.

The measured deep drainage under the pasture systems reported by Ridley et al. (1996) and White (1997) is much lower than the estimates of 228 and 314 mm for perennial and annual winter-active pastures at Bendigo (MAR 605 mm), as reported by Clifton and Johnston (1997). Their estimates were obtained using the WAVES one-dimensional simulation model and they also concluded that lateral flow of water was very low at rainfalls up to 800–900 mm. These simulation results are inconsistent with the experimental data reported by White (1997), where lateral flows (surface and subsurface) were comparable to, or exceeded, the deep drainage flux.

White (1997) also reports on nitrate losses in deep drainage. Suction cup samples were used as a measure of the flux concentration in the water moving through the soil. In order to calculate the nitrate losses below the effective root zone (>180 cm), the mean nitrate concentrations sampled in suction cups at 120 cm were used in conjunction with the deep drainage fluxes. Results for 1995 and 1996 are presented in Table 5.2.

Results reported from other Victorian studies using ^{15}N applied as ammonium sulfate suggest that leaching of fertiliser-derived nitrate does not occur in red-brown earths (Smith et al. 1989). Fillery and McInnes (1992) reported a similar finding for the East Beverley site in WA. Under a deep sand at Moora in WA, Anderson et al. (1998) report the losses given in Table 5.3.

Table 5.1 Deep drainage measurements from agricultural systems.

Region	Rain (mm)	DD (mm)	Crop	Location & method of measurement	Reference
SW NSW	323 (MAR)	27	Fallow	Balranald WATBAL	Murphy (1993)
		13	Fallow–Wheat		
		2–3	Vetch–Wheat		
		0–2	Vetch–Medic		
		0	Lucerne		
		2	Medic–Medic–Wheat		
		1	Vetch–Vetch–Wheat		
S.Aust.	700 (MAR)	120	Grassland	Mt Gambier WATBAL	Holmes and Colville (1968)
NSW	404 (MAR 505)	100	Wheat	Wagga WATBAL	Dunin et al. (1996)
NE VIC	693 (MAR 597)	66	Phalaris	Rutherglen WATBAL	Ridley et al. (1997)
		69	Cocksfoot		
		80	Annual ryegrass		
		89	Fallow		
SW NSW	697	45	Annual pasture, no lime	Book Book WATBAL	White (1997)
		62	Annual pasture, lime		
		44	Perennial pasture, no lime		
		24	Perennial pasture, lime		
	666 (MAR 650)	62	Annual pasture, no lime		
		70	Annual pasture, lime		
		52	Perennial pasture, no lime		
		22	Perennial pasture, lime		
WA	380	7	Lupin	E. Beverley WATBAL	Gregory et al. (1992)
		6	Wheat		
WA	703	214	Wheat/lupin	Moora WATBAL	Anderson et al. (1998)
	438	114	Wheat/lupin		

Table 5.2 Nitrate losses in deep drainage below annual and perennial pasture at the Book Book trial site.

Year	Rainfall	Annual pasture		Perennial pasture	
		no lime	lime	no lime	lime
	(mm)	(kg N/ha)		(kg N/ha)	
1995	697	3	12	3	3
1996	666	4	10	5	2

Anderson et al. (1998) report that summer rainfall in the lead-up to the 1996 season resulted in greater mineralisation under pasture, causing the increase in N losses by leaching in 1996, even though the amount of deep drainage diminished from 214 mm in 1995 to 114 mm in 1996 (Table 5.1)

Farrington (1996) points out that wateruse by annual agricultural plants across southern Australia depends primarily on the distribution of rainfall during the growing season. If the growing season commences early, crop growth is enhanced and if rainfall is below average later in the growing season wateruse is reduced. Growing season evapotranspiration losses (mm) for three sites in Western Australia are summarised in Table 5.4 (Nulsen and Baxter 1982; Farrington et al. 1992, 1993).

Table 5.3 Nitrate losses in deep drainage below agricultural systems at Moora, W.A. (deep sand).

Year	Rainfall (mm)	Wheat/lupin kg N/ha	Wheat/pasture kg N/ha	Lupin/wheat kg N/ha	Pasture/pasture kg N/ha	Pasture/wheat kg N/ha
1995	703	59	34	35	17	–
1996	438	40	43	23	28	21

Table 5.4 Evapotranspiration losses for three Western Australian sites under wheat, barley, lupin and annual pasture.

Location	Wheat	Barley	Lupin	Annual pasture
Kondut	115	153	83	37
Cunderdin	118	175	194	96
North Kellerberrin	192	–	247	179

The results were obtained using the ventilated chamber method and showed that the evapotranspiration by the cereals and the lupins was consistently higher than that of the annual dominant pasture, subterranean clover. Growing season effects could be seen in the data. If the season started early then lupin evaporation was higher than cereals, but if the season started later then cereals used more water than lupins.

The ventilated chamber method has been criticised because micrometeorological conditions imposed at the crop surface may enhance evaporative losses from the chamber. However, in a comparative study between the ventilated chamber and the energy balance Bowen ratio method using a lupin crop, Dunin et al. (1989) reported average values over six days of measurement as 2.8 mm/day for the energy balance method and 2.9 mm/day for the ventilated chamber.

Kennett-Smith et al. (1994) consider the principal controls on potential recharge (deep drainage) to be soil type (increases in clay content decrease recharge), rainfall (increasing rainfall increases recharge) and vegetation characteristics (longer growing season and/or deeper roots decrease recharge). They provided a comprehensive review of deep drainage estimates for the south-western Murray Basin under cropping and pasture systems. Reported measurements were obtained using the chloride displacement front method (Walker et al. 1991) or the water balance method. Measured deep drainage rates ranged from <1 mm/year to 70 mm/year, with sites covering a mean annual rainfall from 255 to 580 mm/year. Before clearing, the recharge rate was generally considered to be less than 1 mm/year, although Allison et al. (1990) put the figure at less than 0.2 mm/year and O'Connell et al. (1997) report values of 0.06–0.14 mm/year at a range of uncleared sites.

Kennett-Smith et al. (1994) report that throughout most of the Murray Mallee study region there was little or no macro-structural development. Average clay content of the top 2 m of the soil profile was therefore used as an indication of soil texture as this provided the best relationship with deep drainage estimates. In the 300–400 mm/year mean annual rainfall region there was a clear trend of decreasing recharge with increasing clay content for the crop–fallow–pasture rotation systems. Outside this rainfall zone the relationships between estimated deep drainage and clay content are not as clear. There is however, a general trend for deep drainage to be less than 10 mm/year when the clay content is greater than 25% and can exceed 30 mm/year when the clay content is less than 10%. The range of observations for the cropping and pasture systems for different clay contents and mean annual rainfall zones is summarised in Table 5.6.

The above data show that there is little recharge under semi-arid pastures. The term 'cropping' applies to rotation systems that usually comprise cereal (predominantly wheat) and sheep or beef cattle grazing. Land is often left fallow between May–June in the belief that this improves soil moisture storage.

O'Connell et al. (1990) have estimated that deep drainage below land which has been cropped and fallowed is from 5–7 mm/year greater than under continuous cropping. Within a particular clay class

Table 5.5 Summary of deep drainage estimates for the SE Murray Basin (recalculated from Kennett-Smith et al. (1994))

Land use		Cropping			Pasture	Pasture	
MAR (mm/yr)		270–430			250–300	300–600	
Clay % 0–2 m		‹1 0	10–20	›20	0–50	‹25	›25
Deep drainage (mm/yr)	(mean)	23	11.4	6.2	2..0	36.5	4.5
	(s.d.)	13	10.0	4.6	2.6	–	3.3
	range	3–40	1–39	0–23	0–8	13–60	1–12
	((n)	10	34	25	8	2 8	3
	(geometric mean)	18	8	5	0.7	28	3

under cropping the data are clearly log-normally distributed and geometric means provide an appropriate indication of the effect of clay content on deep drainage. Potential annual evapotranspiration ranged from 1700–2100 mm/year for the cropping sites and 1500–2200 mm/year for the pasture sites. Importantly, the data reflect typical field conditions rather than optimal cropping conditions often associated with agricultural trial sites.

Table 5.6 Summary of deep drainage estimates for Western Australia (R. George, pers. comm.)

Region Location	Soil	Rain (mm)	Veg'n type	Method	Deep drainage agric. (mm)	Deep drainage native (mm)	Reference
Swan coastal plain							
Gnangara	sand	830	banksia	Tritium		174	Thorpe (1989)
Gnangara	sand	775	banksia	WATBAL		85	Allen (1981)
Gnangara	sand	775	banksia	Cl		120	Sharma and Craig (1989)
	sand	775	pines 25 years	Cl	4		Sharma and Craig (1989)
	sand	775	pines 8 yrs	Cl	245		Sharma and Craig (1989)
Gnangara	sand	785	banksia	W & Cl		46	Farrington and Bartle (1989)
Gnangara	sand	775	banksia	Cl		333	Carbon et al. (1982)
Gnangara	sand	775	banksia	Cl		224	Sharma et al. (1983a)
Gnangara	sand	775	old pines	Cl	85		Sharma et al. (1983b)
Gnangara	sand	775	banksia	Cl		15	Sharma et al. (1983b)
Gnangara	sand	775	banksia	Oxy Deut		120	Sharma and Hughes (1985)
South West forests							
Ernies	saprolite	800	Jarrah 8251	Cl		3.5	Johnston (1985a)
			Jarrah	mass Cl		1.4	Johnston (1985a)
Salmons	saprolite	1250	Jarrah 1351	Cl		4.4	Johnston (1985a)
			Jarrah	mass Cl		25	Johnston (1985a)
Salmons	saprolite	1250	Jarrah	Cl		10	Loh & Stokes (1982)
Salmons	saprolite	1250	Jarrah	Cl		50	Johnston (1987)
Brunswick	saprolite	1120	100% forest			70	Peck et al. (1973)
	saprolite	1120	30% cleared		500		Peck et al. (1973)
Wights	saprolite	1150	100% cleared	Sy	80		Loh and Stokes (1982)
Woolbelt plus							
Brockman	saprolite	910	100% forest	WATBAL		8	Peck et al. (1973)
	saprolite	910	40% cleared		73		
Wooroloo	saprolite	880	100% forest	WATBAL		3.9	Peck et al. (1973)
	saprolite	880	30% cleared		61		
Dale	saprolite	490	100% forest	WATBAL		0.8	Peck et al. (1973)
	saprolite	490	60% cleared		24		
Hotham	saprolite	730	100% forest	WATBAL		1.9	
	saprolite	730	50% cleared		26		
Williams	saprolite	500	100% forest	WATBAL		1.1	Peck et al. (1973)
	saprolite	500	70% cleared		37		
East Collie	saprolite	820	100% forest	WATBAL		1.7	Peck et al. (1973)
	saprolite	820	40% cleared		60		
Lemons	saprolite	750	50% cleared	Sy	32		Loh and Stokes (1982)
Bingham Rv	saprolite	725	cleared	Sy	48		Loh and Stokes (1982)
Batalling	saprolite	650	cleared	Sy	40		Loh and Stokes (1982)
Bakers Hill	saprolite	590	annuals	Sy	24		Loh and Stokes (1982)
Esperance	saprolite	500	annuals	WATBAL	35		R. George (unpublished data)
Bedford H	saprolite	600	annuals	WATBAL	36		R. George (unpublished data)

Sy denotes specific yield (ie. groundwater rise method).

Recently, R. George (pers. comm.) has comprehensively analysed deep drainage data for the literature pertaining to the Western Australian mediterranean region. Theses data ares summarised in Table 5.6.

Using the data in Table 5.37, R. George (pers. comm.) has established relationships between deep drainage (recharge) and annual rainfall (Figure 5.1).

The data show clearly that the difference in deep drainage between agricultural and native systems is dependent on the rainfall, with a difference of about 3 orders of magnitude at 400 mm rainfall and 1 order of magnitude at 1200 mm.

5.2 Old versus new cultivars of wheat

Siddique et al. (1990) and Tennant et al. (1991) report the use of water by old and new varieties of wheat at Merredin in WA. The old variety 'Purple Straw' had the highest total wateruse, at 206 mm and the lowest yield (1.16 t/ha) of the varieties tested. The modern varieties had total wateruses between 185 and 196 mm and yields ranging from 1.62 to 2.12 t/ha. The modern varieties also appear to use slightly more water after flowering (39 to 46 mm) than the old variety (34 mm). The results indicate that improvements in grain yield have not necessarily been accompanied by an increase in total wateruse. Siddique et al. (1990) also observed that new varieties have significantly less dry matter invested in the root system than the old varieties.

5.3 Introduced perennial species

Nearly 40 years ago, Holmes (1960) reported on soil-water deficits under mallee heath and lucerne on deep sands in South Australia (mean annual rainfall of 510 mm). In both cases, there appeared to be insignificant drainage to the watertable at 7 m and the soil water deficits created under both systems were quite similar over a two-year period. The results showed that lucerne dried out the soil profile as effectively as the existing mallee vegetation.

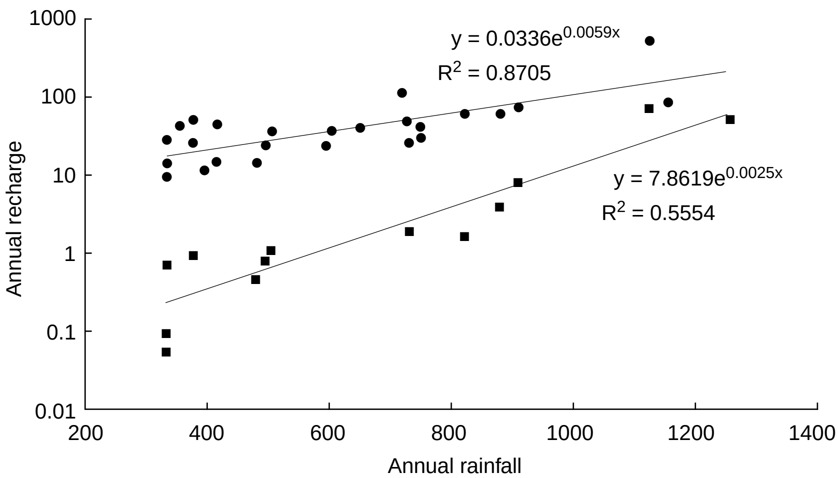
For the 900 mm rainfall zone of SW Australia, Carbon et al. (1982) reported that perennial summer active pastures of lucerne, African lovegrass and *Hyparrhenia hirta* gave similar deep drainage to native forests.

At Balranald in NSW (MAR 323 mm), Murphy (1993) found no deep drainage under lucerne (Table 5.1), compared with 13 mm under a wheat–fallow rotation.

A Western Australian south coast study by Nulsen and Baxter (1987) reported that lucerne had an excess of transpiration over rainfall of 50 mm over 1 year and a recent report by Latta and Blacklow (1997) showed that the soil profile was drier to 150 cm under lucerne than under either annual medic or sub-clover.

One of the difficulties in assessing the performance of perennial crops is to determine if the trial details adequately mimic the performance of the production system as a whole. If the perennial species is to be grazed or harvested, then leaf area will be severely

Figure 5.1 Summary of Western Australian data relating deep drainage (recharge) to rainfall under agricultural and native systems (R. George, pers. comm.).



depleted and this usually coincides with a time of high transpiration demand. In drought years, the system can also be prone to overgrazing by stock or feral species.

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Appendix — Annotated selected references

Agricultural systems

Gregory, P.J. Tennant, D., Hamblin, A.P. and Eastham, J.

Components of the water balance on duplex soils in W.A.

Australian Journal of Experimental Agriculture, 1992, 32, 845–55

* Crop growth and yield is often proportional to the quantity of water used by the crop
* Available water that is not used results in a loss of yield with respect to potential yield
* Unused water can lead to land degradation for example perched water tables on duplex soils
* Wateruse is calculated from:

  (S2 – S1) + P

  and equated to: E + T

This relationship is poor on duplex soils

* Shallow rooting reduces the available water therefore topsoil requires regular replenishing by rainfall
* Most of the increases in yield were associated with increased wateruse in the post anthesis period and reduced evaporation.

Lewis, G.J. and Thurling, N.

Growth, development, and yield of three oilseed *Brassica* species in a water limited environment

Australian Journal of Experimental Agriculture 1994 34 93–103

* Later flowering species had higher yields as they developed more extensive root systems capable of extracting more water from depth later in the season. (*B. campestris* cp. *B. napus*) (author suggestion)
* Cultivar 81794 (*B. juncea*) showed earlier onset of stem elongation and first open flower (FOF) therefore a greater proportion of seasonal rain fell during reproductive Development than cultivars of *B. napus*. Thus yields were higher for 81794. ie greater seed yield as it used a higher proportion of seasonal evapotranspiration.
* Wateruse after FOF (WUpf) of 81794 was 20% higher than ‘Westbrook’ which had a post anthesis development phase of similar duration.
* Experiments with wheat have also shown that increased wateruse after FOF was the major factor associated with improved yield. (Anderson 1991)
* The higher WUEdm for 81794 was largely due to lower soil evaporation.
* Suggest improving yields by prevention of soil evaporation, or, extracting a higher proportion of water held in the profile. Also increase HI by increasing the % water used post anthesis.
* The higher WUf (before FOF) was associated with a higher DMI rather than improved partitioning to developing seed.

Hamblin, A., Tennant, D. and Perry, M.W.

Management of soil water for wheat production in Western Australia.

Soil Use and Management, 1987, 3(2), 63–69

* WA:
  average yield = 1.05 t/ha
  annual increase = 10 kg/ha/yr
* Rest of Australia:
  average yield = 1.6 t/ha
  annual increase = 15 kg/ha/yr.
* Cite data (no reference) to claim a linear relationship exists between transpiration and grain yield.
* Times of water deficit giving major effects on yield are:

– stem elongation
– flowering
– grain filling

* Wheat takes 95–110 days to flower and is mature 40–60 days later.
* Grain yields decrease if sowing is delayed.
* Crops are grown primarily on the current season rainfall.
* Duplex soils can become water logged in winter.
* Structural stability of the surface frequently influences the evaporative losses by prolonging the constant rate stage.
* Strategies for management:
  – single light cultivation
  – stubble retention
  – gypsum

Other: improve the rate of canopy and root development so that the crop shades the soil and extracts more moisture (by having higher nitrogen, using a legume rotation).

Dracup, M., Belford, R.K. and Gregory, P.J.

Constraints to root growth of wheat and lupin crops in duplex soils.

Australian Journal of Experimental Agriculture, 1992, 32, 947–61

* 60% cropping region of WA is on duplex soils, mainly in the medium rainfall zone with a mediterranean climate.
* Comprises light textured topsoil over heavier textured subsoil. Topsoil generally has a low water holding capacity.
* Crops on these soils show considerable spatial variability and tend to yield below their potential. Restricted growth may be a result of poor root growth which leads to inadequate water and nutrient supply.
* Unpublished data of Belford, Tennant and Dracup indicates that 40% of the variation in wheat yield on a yellow duplex soil near Beverley could be explained by linear relationships between maximum depth of roots and the water extracted from the B Horizon. Table 1. Root growth and depth of water extraction in duplex soils in W.A. shows data 1969–1991 (mainly unpublished) 27 sites.
* Constraints to root growth:
  1. mechanical impedance: compaction by agricultural traffic restricts water and gas movement and prevents root growth, hardening by cementing agents. Measured by penetrometer resistance and /or bulk density. Root elongation usually ceases at 0.8–5 MPa penetrometer resistance (Greacen et al. 1969) and 1.4–1.8 Mg/m^3 bulk density (Vepraskas 1988), but can get good growth in B horizons of high resistance, probably due to preferred pathways, differences in macro structure. Manage with gypsum and deep tillage, mixing B with A.
  2. water logging: concentration of rainfall over 2–3 months means soils are prone to waterlogging, duplex soils more so. SEW30 index = accumulated height of water table above 30 cm for each day. O_2 depletion varies with depth and duration of waterlogging.
  3. salinity
  4. acidity
  5. alkalinity
  6. disease

  1 and 2 are considered to be the dominant constraints.
* If A horizon less than 50 cm roots penetrate 5–8 mm/day (average over season to anthesis) and rarely go deeper than 1 m.
* Depth of rooting is highly variable on duplex soils.
* Root systems are shallower and smaller on duplex than on deep yellow soils.
* Crops with higher root density at depth have higher yields (Gregory et al. 1992)
* High root to plant mass ratio indicates hostility of the duplex soils (Hamblin et al. 1990). The root to plant mass ratio decreased by 40% when the soil was loosened.

Belford, R.K., Dracup, M. and Tennant, D.

Limitations to growth and yield of cereal and lupin crops on duplex soils

Australian Journal of Experimental Agriculture, 1992, 3,2 929–45

* Duplex soils renowned for variable crop performance. Variation is discussed.
* Aims are to reduce variability and increase yields, review effects of water logging and water stress.

* Depth of sand over clay: deep sands have less water storage and more leaching of nutrients. Hamblin (1988) found yield of cereals decreased as depth of sand over clay increased from 60–200 cm. But if less than this then subsoil impermeability can exert a large influence.
* Factors influencing the variability were found to be operating throughout the season, affecting vegetative growth, reproductive development and grain filling.
* Highest yields were from southern area of trial with a thinner sand layer, little water logging, water extraction from the clay was greater.
* Grain yield was negatively correlated with water table height, and well correlated with water extracted from the clay more so than from the entire profile.
* O_2 concentrations can fall rapidly in waterlogged duplex soils.
* Chlorosis in older leaves associated with low N, from denitrification, leaching and slow N uptake by roots from anaerobic soil.
* Studies at this site have shown larger losses of N from waterlogged areas compared to well-drained areas.
* SEW30 index (Sieben 1964b) used to calculate the intensity of the water logging.
* Water logging usually accounted for less than a third of the variation in crop yields.
* Increased incidence of take-all disease on cereal crops has been widely reported on water-logged soils.
* Danger of salinity associated with water-logging.
* Wheat has higher density fibrous roots than lupins, therefore is better placed to explore planes of weakness and preferred pathways.
* Nutrition on duplex soils is discussed.
* Soil physical conditions: hardsetting or crusting.
* Hardsetting associated with clays with low shrink swell characteristics.
* Sand-clay interface described as a possible site for restriction to plant growth.
* Clay of the B horizon is often dispersive and poorly structured, high bulk density and strength and low porosity, therefore is hostile to root growth.
* Amelioration by ripping (physical) and gypsum (chemical).
* Crops grown on ripped areas showed faster early root penetration and slightly higher root densities at depth, and extracted more water at depth after flowering.
* Duplex soils impose a combination of stresses.

Anderson, W.K., French, R.J. and Seymour, M.

Yield responses of wheat and other crops to agronomic practices on duplex soils compared with other soils in W.A.

Australian Journal of Experimental Agriculture, 1992, 32, 963–70

* Responses to: sowing time
  – cultivar
  – N fertiliser
  – seed rate
  – soil type
* Examined yield improvements
* High input treatment gave 51% higher yield on other soils, and 42% on duplex soils compared to the low input treatment
* Responses to earlier seeding and extra seed were greater on duplex soils.
* Grain yield of wheat from the highest yielding treatments plotted against wateruse.

Shultz, J.E.

Soil water changes under fallow–crop treatments in relation to soil type rainfall and yield of wheat.

Australian Journal of Experimental Agriculture and Animal Husbandry, 1971, 11, 236–242

* Fallowing used as a means of increasing stored water in the soil.
* Amount stored rarely exceeds 30% of the rainfall.
* Experimental sites near Adelaide.
* Water content profiles were recorded every 2–3 weeks
* Daily meteorological observations available.
* Soil water changes shown and changes in profile water contents.
* Give maximum amounts of water stored
* Recharge of soil water after beginning of winter rains was more efficient in grassland than fallow on some soils. (Others show no apparent difference, but none where fallow was more efficient.)

* Fallowed soils gave higher yields, which may be due to increased nitrogen availability.
* Fallow crops used more water but used it more efficiently than grassland crops.
* Fallow conserves stored water in early spring, when the grassland would be using this water for growth.

Anderson, W.K.

Increasing grain yield and water use of wheat in a rainfed Mediterranean type environment.

Australian Journal of Agricultural Research, 1992, 43, 1–17

* Treatments: time of sowing
  cultivar
  nitrogen fertiliser
  seeding rate
* Measured: grain yield
  yield components
  biomass
  grain quality
  wateruse
  soil chemical variables
  weather variables
* Aim for the crop to use all the rainfall available to it.
* Early sowing accepted as a means of increasing yield (Anderson and Smith 1990)
* Nitrogen fertilisers widely used.
* Semi-dwarf varieties accepted now as higher yielding
* Factors other than water supply which limit production include, cultivar, sowing time, weeds and nutrition.
* These factors act by decreasing wateruse, water-use efficiency or harvest index.
* The component of wateruse that is transpiration is proportional to biomass production (Briggs and Shantz 1914; deWit 1958; Hanks et al. 1969) any factor that increases transpiration will increase biomass and grain yield.
* Evaporation from the soil is quite variable.
* Optimal pre to post anthesis wateruse ratio suggested to be 2:1 or greater (Passioura 1983)
* Aim of these experiments was to determine if agronomic treatments could bring yields to the limits imposed by seasonal wateruse.
* Yield increases that were observed were mainly due to time of sowing and seeding rate.
* Seasonal wateruse was influenced by sowing time, N fertiliser, seed rate, and cultivar.
* The change from low input to high input hardly affected seasonal wateruse but wateruse efficiency was increased from 9.2 to 12.4 kg /ha/mm.
* Experiment does not consider runoff or drainage below 1 m ie. considered these to be 0.
* Wateruse post anthesis always greater for the earlier sowings.
* For increased yields it was suggested that farmers must select the appropriate cultivar in combination with most effective agronomic practices changing one or the other alone will not increase yields as much.
* Increases in yield were due to increased wateruse in the post anthesis period rather than pre anthesis or total wateruse. This is assumed to be due to advancement of anthesis from earlier sowings.
* Losses by evaporation reduced by improved agronomic practices.

van den Boogard, R., Veneklaas, E.J., Peacock, J.M., Lambers, H.

Yield and water use of wheat (*Triticum aestivum*) in a Mediterranean environment: cultivar differences and sowing density effects.

Plant and Soil, 1996, 181, 251–262

* When water is limiting grain yield depends on the amount of water taken up and transpired by the crop and the amount of biomass produced per unit water uptake.
* Improve grain yield by increasing the amount of water transpired, and increasing the biomass production per unit transpired water, or by increasing the harvest index.
* Reduce soil evaporation.
* Early ground cover by the crop will reduce incident radiation and therefore reduce evaporation from the soil surface.
* Ratio of photosynthetic rate and transpiration rate has a major influence on plant wateruse efficiency (Condon et al. 1990; Farquhar and Richards 1984; Veneklaas and Peacock 1994 Knight et al. 1994).
* Harvest index strongly influenced by the pattern of wateruse through the season, ie it is higher when a larger proportion of total available water is used after anthesis.
* Soil moisture measured with a neutron probe.
* Assumed runoff and drainage to be negligible.

* Evapotranspiration = difference between precipitation and the change in total moisture content in the profile.
* Grain yield was associated with above ground biomass.
* WUE expressed as ratio of above ground biomass or grain yield and cumulative evapotranspiration over the growing period.
* Aimed to determine if higher cumulative evapotranspiration was associated with extraction of water to a greater depth, or extraction of water from the surface to lower soil moisture contents, by investigating the amount of water above wilting point at various depths at the end of the season.
* A higher cumulative ET was associated with extraction of water to depth of 45–90 cm
* Estimate soil evaporation from relationship between above ground biomass and cumulative ET.
* In plot of biomass versus cumET, q of water evapotranspired at the beginning of the season that is not associated with biomass production can be found from the intercept with the x-axis by extrapolation of the linear relationship.
* During early growth higher sowing densities showed a smaller proportion of the water used to be evaporation from the soil surface, and a larger part was transpired. Differences between densities reduced during the season.
* At the higher sowing densities water appeared to be the limiting factor later in the season. Optimum sowing density depends on the timing of post anthesis water deficits which varies with environments.
* Avoid faster earlier growth as it leads to earlier water depletion.

Chootummatat, V., Turner, D.W., and Cripps J.E.L.

Water use of plum trees (*Prunus slicina*) trained to four canopy arrangements.

Scientia Horticulturae, 1990, 43, 255–271

* Water stress lowers net productivity and fruit production.
* Method of training expected to influence wateruse.
* Measured wateruse of the trees before and after fruit harvest.
* Soil moisture measured with a neutron probe, 110 cm and 50 cm from the trunk to 90 cm
* Class A pan evaporation, minimum and maximum temperatures and rainfall were measured at site. R.H. from Perth Bureau of meteorology 30 km west.
* Net radiation above and beneath the canopy using spot net radiometer.
* Water loss calculated using,

  $AET = (P + I) - (D + R) - DS$

  AET = evapotranspiration
  P = precipitation
  I = irrigation
  D = drainage
  R = surface runoff
  DS = change in water stored in the soil
  all in mm/day
* Drainage flux was calculated from Ksat, soil suction (h) with depth (z)
* Water withdrawal by roots calculated from v/v water contents at depth using equations from Rose and Stern (1967).
* Wateruse per unit energy intercepted calculated based on wateruse per total radiant energy intercepted.
* Vertical losses considered to be 0, amounts moving laterally were less than 1 mm/day
* Drying patterns under the training systems shown as hand drawn contour lines with depth.
* If water supply adequate the roots extracted moisture from the top 30 cm. As soil became drier roots tended to absorb more water from deeper in the profile
* Tatura has a larger number of fruiting sites present therefore greater yield and hence greater wateruse efficiency

Gregory, P.J., Tennant, D., and Belford, R.K.

Root and shoot growth, and water and light use efficiency of Barley and wheat crops grown on a shallow duplex soil in a Mediterranean-type environment.

Australian Journal of Agricultural Research, 1992, 43, 555–573

* Comparison of barley and wheat
* Mean wheat yield of the WA wheatbelt 1974–1984 was only 1.05 t/ha, mean for rest of Australia was 1.6 t/ha

* Little known about the wateruse of crops on WA duplex soils, thought that clay layer is restrictive to root growth and therefore limit the crops ability to extract water.
* Differences in early growth and the timing of wateruse between the barley and wheat may lead to differences in grain yield.
* Aims:
  1. measure seasonal pattern of root and shoot growth of both species on duplex soil.
  2. measure the interception of photosynthetically active radiation (PAR) and calculate the efficiency of conversion of PAR to dry matter.
  3. measure wateruse by the crops and estimate the dry matter production per unit of water used.
  4. to estimate transpiration and dry matter production per unit of transpiration for comparison with values estimated in other environments.
* Location: East Beverley
* Plants sampled weekly
* Roots sampled four times between sowing and anthesis at 4 weekly intervals
* Ground cover estimated on 9 occasions.
* Light interception (i) measured on 6 occasions above and below canopies.
* Proportion of ground surface shaded by the crop (f) and the proportion of PAR intercepted by the crop (i) related the Green area index (g) by:

  $f = 1 - \exp^{-KfG}$

  and $i = 1 - \exp^{-KiG}$

  Kf and Ki are attenuation coefficients

  Combine above to give: $i = 1 - (1 - f)^{Ki/Kf}$
* Soil moisture (v/v) measured with neutron probe, fortnightly at 10 cm intervals between 0 and 70 cm and at 20 cm intervals from 70 cm to 170 cm.
* Used Ec = Ef(1 – i) to separate evaporation and transpiration. (Cooper et al. 1983)

  Ec = evaporation from cropped soil

  Ef = evaporation from fallow soil

  i = proportion of incident radiation intercepted by the crop (from third equation above)
* Table 1 shows monthly meteorological data for E Beverley 1988
* Barley roots penetrated to 80 cm, wheat only to 60 cm
* Wateruse calculated from the measured changes in soil water storage and rainfall. Assumed no drainage from the profile (no change in water content through season at depth of 150 cm)
* Table 6 shows total wateruse (ET) and wateruse before and after anthesis.
* Table 7 shows depletion of soil water storage in selected soil layers for the season and the post anthesis period.
* Pre-anthesis wateruse was mostly from rainfall, soil water storage at 40–80 cm was depleted predominantly in the post anthesis period.
* Accretion of water occurred in the 80–160 cm layer early in the season followed by depletion after anthesis (? but said no change in water content at 150 cm through season?? Should 80 – 160 cm layer actually be 80–140 cm ???).
* ET in all crops was similar but dry matter production differed. WUE for shoots reflected dry matter production. Figure 7 represents rate of water depletion from 40–80 cm during grain filling.

French, R.J. and Shultz, J.E.

Water use efficiency of wheat in a Mediterranean-type Environment. 1. The relation between yield, water use and climate.

Australian Journal of Agricultural Research, 1984, 35, 743–764

* Southern Australia, where most of the water used by wheat comes from the rainfall occurring during April to October.
* Total wateruse in this paper refers to evapotranspiration.
* Measurements at 61 field locations 1964–75
* 75% of the rain falls in the growing season.
* Soil types: Dr, Db, Gr, Gn, Gc, Ug. (Northcote 1979)
* Table 1 contains site climate data and yields, for each year (does not contain soil type!!!!) Plots of grain yield or dry matter yield versus wateruse are derived from this data.
* Close relation between yield per mm wateruse and the yield per mm of growing season rainfall.
* Key factors contributing to yield are: early sowing, long interval in which daily evaporation from sowing to anthesis is low, high water supply

particularly before anthesis, and a high harvest index.

* In this environment rainfall only exceeded wateruse in the interval from sowing to the end of tillering, therefore from tillering to maturity the crops rely on the water stored in the subsoil.
* 72% of wateruse occurs by anthesis, 40% or greater used from end of tillering to anthesis, which is when most of the dry matter is produced.
* Greater efficiency occurs when pan evaporation rates are low, and ratio actual WU to potential WU is high.
* Two components of ET, evaporation and transpiration difficult to separate in the field.
* Additional water losses can occur due to runoff or deep drainage but the sites were selected to minimise these effects.
* Hanks (1969) shown that q of water lost by evaporation can be obtained from the intercept on the wateruse axis of the linear relation between yield and wateruse, values beyond this intercept represent amount of water transpired by the crop. Similar technique cited earlier:
* *In plot of biomass versus cumET, q of water evapotranspired at the beginning of the season that is not associated with biomass production can be found from the intercept with the x-axis by extrapolation of the linear relationship.* (Van de Boogard et al. 1989)
* Both authors find similar results (110 mm and 119 mm), which is about a third of the total wateruse.
* Daily evaporation determined by: $Y = mW/E_p$ (de Wit, 1958)
  Y = dry matter yield
  W = wateruse (mm)
  Ep = average pan evaporation from sowing to maturity
  m = a constant dependent on the proportion of rainfall lost by evaporation and the soil type.
  m = 65(1 – (loss by evaporation/total wateruse)(
* deWit formula used as an index of potential yield for wheat.
* Table 6 gives actual and potential yields in SA.
* For each weeks delay in sowing grain yield was reduced by 200–250 kg /ha
* Early sowing gives more tillers and more grains per unit area, longer interval from sowing to anthesis, lower average daily pan evaporation rate from sowing to maturity.
* Evidence that a SA wheat crop needs 475 mm wateruse for maximum yield (French 1978)
* If above water is not supplied in rainfall it must be supplied by that stored in the soil.
* Found that if rainfall was less than 260 mm relation is:
  $Y = -1110 + 12.7X_1 + 10.4X_1$ ($r^2 = 0.63$)
  Y = grain yield
  X_1 = change in water stored
  X_1 = rainfall
* A reduction of 1 mm wateruse before anthesis can reduce grain yields by up to 30 kg /ha, since the main determinant of yield in this environment was found to be the amount of water used before anthesis.
* No discussion of soil type at each site

French, R.J. and Shultz, J.E.

Water use efficiency of wheat in a Mediterranean-type Environment. 2. Some limitations to efficiency.

Australian Journal of Agricultural Research, 1984, 35, 765–775

* Evaluates reasons why crops from previous paper did not achieve potential yields.
* Uses same data as previous paper and introduces data sets from other experiments.
* Climate determines potential yield management skills of farmer determine actual yield.
* Figure 2 relates rainfall to grain yield, also showing individual responses to: application of nitrogen, phosphorus, copper, control of eelworm and multi-factor research, delayed time of sowing, effects of weeds, and water-logging.
* Time to achieve LAI of 3, if delayed can reduce the time the crop has for maximum growth rate, ie. limits conversion of radiant energy into dry matter.
* Nutrient deficient plant uses water at about the same rate as a well-balanced plant (Leggett 1959)
* Figure 3 relates nitrogen content of plant tops with wateruse. Gives value of 0.65 kg/ha nitrogen and 0.07 kg/ha phosphorous required for each mm water transpired to achieve maximum yield. Thus to produce 1t grain with the maximum efficient use of water transpired, a crop has to take up 32.5 kg N and 3.5 kg P.
* Presence of weeds reduces WUE.

* Also yields reduced due to root rot, “take all” and cereal cyst nematodes. Effects of these reduced by rotations with legume crops.
* Water logging occurred at 2 sites: Saddleworth 1971 and Northfield 1971. Figure 2 shows yield reduction due to waterlogging (line G).
* Harvest index was higher in crops which were sown early and had completed anthesis before moisture stress was evident. Those crops with higher HI were the higher yielding crops.
* Suggest using silicon content as an indication of transpiration (Hutton and Norrish 1974 , and, Shultz and French 1976).
* Suggest future research should be aimed at measuring more accurately the evaporation from the soil surface. Potential yield can then be defined from the amount of water available for transpiration.
* Again no description of soil types at each site. Therefore soil type not considered as a significant factor limiting yield.

Passioura, J.B.

Physiology of grain yield in wheat growing on stored water

Australian Journal of Plant Physiology, 1976, 3, 559–565

* Aim: to see to what extent the pre-anthesis growth of the plant could be sacrificed before the grain yield became limited by the number of grains more so than post anthesis drought.
* Pot trial
* Figure 1 shows relation between grain yield and water used after anthesis. Total available water supply was 1850 g.
* Yield increased from 1 g to 4 g per plant by forcing the plants to save water for post-anthesis growth.
* When plants used less than 1200 g water before anthesis the grain yield was reduced. May be due to a lower transpiration rate that did not increase after anthesis, or by reacting to the late water supply by producing more tillers, which produced little grain.
* Table 1 shows WU before anthesis and grain number.
* Non-linear grain yield to WU after anthesis implies that there is an increase in WUE at anthesis, or that much of the grain was formed from reserves.
* Further experiment to determine the above shows that most of the grain yield of moisture stressed plants comes from a redistribution of reserves (Figures 2 and 3)
* Conclusion: grain yield of crops grown with limited water supply can be increased by forcing the plants to save water for their post-anthesis growth. This saved water allows the plant to increase its photosynthesis after anthesis, and gives the plant extra time to translocate reserves to the grain.

Passioura, J.B.

Grain yield, harvest index and water use of wheat.

Journal of the Australian Institute of Agricultural Science, 1977, 43, 117–120

* View yield as a combination of three factors:
  1. amount of usable water
  2. efficiency of wateruse
  3. harvest index
* Increasing any one of the above should increase yield.
* Usable water depends on rainfall, amount stored in the soil, losses to weeds, evaporation from the soil and the effective depth of the soil from which the roots can extract water.
* Promoting rapid development of leaf area to reduce evaporation from the soil can lead to an early depletion of moisture, which can be detrimental to harvest index.
* Claims that roots penetrate as far as the wetting front in some areas, therefore little improvement can be made there. However in other areas root growth is restricted so that at maturity a large proportion of available soil moisture remains at depth in the soil.
* The rate of local recharge of ground water would provide an upper limit to the sustained advantage that deeper rooted plants would have over shallower rooted ones. If local recharge is large breeding for deeper roots could increase the supply of usable water.
* WUE is difficult to manipulate. There is variation between cultivars.
* Grain yield depends on the water used after anthesis. Therefore HI depends on the proportion of the total water supply that is used after anthesis.
* Figure 1 shows yields of individual plants as a function of water supply, with some given total water supply at sowing and others given one third at sowing and remainder metered out over the

growing period. Those with total water supplied at sowing consistently showed much lower grain yields.

* Figure 2 shows HI against % water used after anthesis, for the same experiment as above.
* Improve HI by influencing the time of anthesis, but also have to consider frost damage at anthesis.
* If it were possible to slow the rate at which roots extract water from the subsoil, the amount of water remaining in the soil at anthesis would increase, subsequently there should be an increase in yield.
* If the plant is utilising subsoil moisture (the topsoil must be dry) it is using the seminal roots. Water has to be transported through the dry topsoil to the shoots, hence there is greater resistance to flow. Increasing the resistance of the seminal roots should result in a reduced rate of early extraction of subsoil moisture (Passioura 1972, 1974).

  The above manipulation should not alter the crops response to a 'good' year since under higher rainfall the topsoil should remain moist and the plant would be extracting water via the nodal roots, not the seminal roots.
* In the field, encouraging deep rooting may result in an early depletion of extra water before anthesis. OR, restricting early growth of a cultivar that performs well when water supply is large may result in increased HI but the total water used may be reduced so as to reduce yield.
* Avoid these interactions by concentrating on improving the factor that seems to most sensitively limit yield in a given environment.

Burch, G.J., Smith, R.C.G. and Mason, W.K.

Agronomic and physiological response of soybean and sorghum crops to water deficits 2. Crop evaporation, soil water depletion and root distribution.

Australian Journal of Plant Physiology, 1975, 5, 169–177

* NSW semi-arid environment.
* Summer sown crops
* Sorghum did not deplete maximum water store by more than 100 mm.
* Rainfed crops of soybeans depleted the soil water store by 130 and 170 mm (2 different cultivars). This equated to a 35% reduction in yield when compared to irrigated crops.
* Post-flowering WUE of rainfed crops of soybeans was one third that of sorghum.
* Root distribution of soybean cultivar Ruse, indicated that it was unable to extract water below 80 cm at bean-fill. Cultivar Bragg, maintained a deep root system to 120 cm, but matured 2 weeks later than Ruse.
* Figure 4 shows soil moisture content to 140 cm under each crop
* In determining wateruse losses from the surface (runoff) and drainage were not considered.
* A water balance model was developed to predict weekly changes in soil water store.

Hsiao, T.C. and Avevedo, E.

Plant responses to water deficits, water-use efficiency, and drought resistance.

Agricultural Meteorology, 1974, 14, 59–84

* California
* More detailed physiological aspects of plant-water relations.
* Mainly discuss responses to water stress at a cellular level.
* Transpiration related to $C0_2$ assimilation.
* Discussion of C3, C4 and CAM species.
* Implications for yield

Greenwood, E.A.N., Turner, N.C., Schulze, E.D., Watson, G.D. and Venn, N.R.

Groundwater management through increased water use by lupin crops.

Journal of Hydrology, 1992, 134, 1–11

* WA, near Beverley. Shallow duplex soil.
* Mediterranean climates and proximity to ocean means that cyclic salts tend to be stored in the soil.
* Agricultural vegetation uses less water than pre-agricultural forests.
* Increasing leaf area should increase crop wateruse. Planting at higher density or sowing earlier will increase early leaf area development before low temperatures slow growth.
* Evaporation from crop and soil surface measured with horizontal flow ventilated chambers
* Air temperature, solar radiation, and air flow also measured
* Transpiration measured using heat balance technique of Fichtner and Shulze (1990) this technique is explained.

* Soil moisture measured gravimetrically every 5 cm to 20 cm then every 10 cm from 20 to 60 cm.
* Early sowing and higher densities led to and increase in total evaporation during the late winter due to an increased leaf area index prior to flowering. Crops with highest leaf area were first to deplete soil water leading to rapid leaf loss during late flowering and early grain filling.
* Total wateruse and grain yield could not be measured due to disease occurring mid to late grain filling.
* Shepherd et al. 1987 and Turner and Nicolas 1987, have shown that in Mediterranean climates early growth, and greater early wateruse leads to higher yields, not lower yields.

Armstrong, E.L., Pate, J.S. and Tennant, D.

the field pea crop in south Western Australia–patterns of water use and root growth in genotypes of contrasting morphology and growth habit.

Australian Journal of Plant Physiology, 1994, 21, 517–532

* Understanding yield variability based on variations in the effectiveness with which roots can extract soil water, and the ability of foliage to produce biomass per unit of absorbed water.
* WUE here refers to total dry matter production per unit of evaporation under field conditions, or gravimetrically recorded loss of water from potted plants in a glasshouse.
* Plants of high WUE show smaller isotopic discrimination against $^{13}CO_2$ during CO_2 fixation than plants with lower WUE. (Farquhar and Richards, 1984, Farquhar et al. 1989, and, Hall et al. 1990). Conclusion is that more efficient genotypes should show lower values of (^{13}C in their dry matter.
* Water economy assessment based on neutron probe readings and regressions of cumulative yield against cumulative evapotranspiration
* Field site: Wongon Hills
* Nine harvests of each genotype during season.
* Eight soil moisture measurements, (at 10 cm then every 20 cm to 3 m) Table 1 shows dates for these and above harvests.
* Total seasonal wateruse, Et, estimated from sowing to 122 days. From 0–39 DAS Et assumed to equal moisture loss from bare soil using:

  E = Eox1/t
  E = moisture loss from bare soil
  E_0 = Class A pan evaporation
  t = number days since last rain.
  From 39–122 Et estimated by:

  Et = DS + P

  DS = change in water stored in the profile.
  P = Precipitation recorded for period.
* Total seasonal wateruse taken to be the sum of Et values for all sampling periods of the growth cycle.
* Pea roots recorded to a depth of 240 cm, measured using root coring data from last four harvests. This data was compared to trends of soil moisture depletion with depth.
* No surface runoff but deep drainage not discounted
* WUE determined by division of crop biomass production with accumulated Et. Alternatively, slope of regression of cumulative total biomass against cumulative Et through out the season. Second method only used up to 106 DAS due to unknown magnitude of biomass loss.
* WUE was determined in the glass house for each genotype under conditions of adequate water supply. (pots maintained at field capacity) Moisture loss determined by weight required to return to field capacity.
* Figure 1 shows rainfall (A), mean, max, and min temperature (B), and stored water (C) for the duration of the season.
* Table 2 shows relationship between biomass production, Et and WUE for each genotype.
* Figure 2A shows Et against DAS (cumulative crop wateruse) and 2B shows daily evapotranspiration rate for field crops.
* Figure 3 compares cumulative plant wateruse and daily transpiration rate of pot trials.
* Figure 4 shows plots of soil water depletion, expressed as mm decrease in stored moisture per 20 cm depth zone. Differences indicate variations in effective rooting depth.
* Difference between maximum water recharge in rooting profile and minimum final moisture content of the same profile at the end of the season suggested that a total of 90 mm of soil water had been available and utilised by the pea crop.
* Even though roots found at 140 cm, water at this depth was not fully utilised. Roots could not achieve densities adequate for full extraction.
* Table 3 compares soil wateruse and WUE of field peas with other crops. High and inefficient

wateruse expected from early sowings. Generally accepted that high water supply results in less economical biomass production from each unit of water they consume. This report does not support this. Conclusion is that water losses, deep drainage, and inefficiencies in water usage at this site are particularly large.

Greacen, E.L. and Hignett, C.T.

A water balance model and supply index for wheat in South Australia

CSIRO Division of Soils Technical Paper No. 27, 1976

* Model developed to simulate the soil water regime under wheat.
* Cornish (1950) showed that 50% of the variation in wheat yield can be attributed to rainfall parameters and a time trend.
* Emphasis is given to growth and water uptake capacity of the root system.
* Model developed from data of three wheat crops and tested on seven other sites. Indices of the water supply factor derived from the model were related to yield on 30 plots from the National Soil Fertility Project in South Australia
* Inputs:
  – daily rainfall
  – potential evaporation
  – maximum water holding capacity of each soil layer.
  – initial water content of each soil layer
* Simulates a two-layer soil, ie. An A horizon (0–30 cm) and a B horizon (30–150 cm) the top 10 cm are considered under a separate account, giving a water balance for the cultivated layer. This allows consideration of evaporation from a shallow saturated layer even though the water content of the entire A horizon is low.
* Model superimposes the root growth of the crop as a function of time and cumulative evaporation. Daily water requirements of the crop are taken from the root zone. Potential evaporation is modified by a factor depending on the crops stage of development, is limited by the absorbing capacity of the root system, and available water content. This factor and the depth and density of the roots were calculated at 7–day intervals
* Two root systems: seminal (growing vertically downwards) and nodal (growing approx. 60° to the vertical for 5–30 cm then vertically) (Passioura 1972). Nodal root development begins at tillering, which can be confined to the surface 40 cm of soil under normal conditions and may not develop at all in a dry season.
* Root distribution pattern results in a two-layered system corresponding roughly to the soil layers. Near anthesis (maximum root development) the A horizon is densely populated with both nodal and seminal roots and the B horizon is only sparsely populated by seminal roots only.
* Site descriptions:
  1. Roseworthy 1968.
     Sandy red-brown earth
     0–12 cm loam A over coarsely structured medium clay B
     calcareous at 30 cm.
  2. Tepko 1970.
     brown solonised soil
     0–30 cm sandy clay loam over sandy clay.
     Fine limestone to surface.
  3. Reeves Plain 1971
     sandy red-brown earth
     0–18 cm sandy loam A over red-brown clay
     calcareous at 46 cm.
* Soil samples taken for root length measurement to coincide with stages of development.
* Soil moisture content changes measured with a neutron probe except Roseworthy where hand augured samples were used. Further data collected from 7 other sites but not root length.
* Two processes simulated for root development: elongation, and, increasing density.
* Figure 1 shows rate of radicle extension against penetrometer resistance.
* Figure 2 Shows depth of root zone with time.
* Evaporation measured at intensive sites with class A pan evaporimeter. At other sites estimated from maximum temperature and vapour pressure data.

  $Epan = 2.44 + 0.21\ \Delta e$, $r = 0.85$

  De = saturated vapour pressure for water – vapour pressure of the air.
* Model has several options for simulating water storage capacity. Simplest is overflow system, with a lower limit of wilting point and an upper limit of field capacity. For intensive sites the upper limit was taken as the wettest measured profile adjusted for evaporation and drainage losses since last significant rain.
* Claim is made that for open, light soils with a hydraulic conductivity that varies with water content and where rainfall events are discrete, a concept of a constant field capacity level for upper

limit of water storage capacity is satisfactory. For medium to heavy soils where the conductivity – content function allows prolonged significant drainage, the upper limit depends on the rainfall characteristics and the hydraulic properties.(Gardner 1968)

* Second option uses a simplified K(q) function which determines water loss by drainage from B layer on the assumption of unit hydraulic gradient at the lower boundary.
* Figure 5 includes data from Salter and Williams 1965 for English soils, and data from the South Australian, intensive site, soils. Water holding capacity against wilting point. I assume the X-axis is actually moisture content at wilting point for the range of soils. Values are on a gravimetric basis.
* For simulation of the soil water regimes there are two periods considered, that of fallow and that of crop. If soil moisture content at seeding is not known the fallow model allows computation of a value.
* Drying of initially wet soil occurs in three stages (Philip 1957)

  1. rate of evap from soil, Es, determined by potential evaporation
  2. Es depends largely on water content and soil hydraulic properties
  3. dry surface layer acts as an effective mulch.

  Figure 6 shows cumulative evaporation from a red-brown earth under various surface conditions. Initial constant rate phase was only approx. 1 day

* Loss from crop also based on potential E from a free water surface, modified to give potential evapotranspiration Et depending on developmental stage of the crop.

  Et = fEpan

  f = the crop factor = 1.22N/(3.55 + N) if Epan < 450 mm
  N = number of weeks from seeding.
  If Epan > 450 mm f = 0.5

* Maximum uptake rate from the soil, Em, assumed to depend on the root length and the fractional available water content, qf, of the layer.
* Figure 7 is rate of uptake by subsoil roots against available water content. Assumption of a linear relationship between Em and qf
* Figure 10 is a plot of available soil water, predicted and actual, with time in weeks, for the first 25 weeks. Figure 11 the same for each site, but for the latter part of the season.
* Errors in prediction explained by seasonal or site peculiarity not covered in the model.
* Water stress index of Nix and Fitzpatrick (1969), is the quantity of water stored at peak anthesis divided by the mean weekly potential evaporation rate during the critical period, indicating the number of weeks that the water supply would last at the potential evaporation rate of the critical period. This does not fit SA environment. Prediction of peak anthesis was difficult, and at this stage available stored water content is rapidly changing.
* French and Shultz (unpublished) propose an optimum amount of water for each stage of growth.
* Due to difficulties in predicting stages of growth, a single index for total water used by the crop from seeding to the end of week 48 was found to be satisfactory. This is shown in figure 13, ie, yield versus cumulative wateruse. SEa was found to account for 77% of the variability. Total rainfall or total rainfall + stored water for the season account for 50% of the yield variability.

Kennett-Smith, A., Cook, P.G. and Walker, G.R.

Factors affecting groundwater recharge following clearing in the south western Murray Basin.

Journal of Hydrology, 1994, 154, 85–105

* In SA removal of native vegetation has resulted in raised water tables and associated with this is an increase in land and stream salinity(Peck 1978)
* In other areas the ground water has been depleted (Brown et al. 1983)
* There is a need to understand groundwater recharge.
* Two approaches for obtaining areal estimates of recharge. 1. Using remote methods such as geophysics or satellite imagery. 2. Investigate how more easily measured factors affect recharge, and vary within a given region.
* Influences appear to be:

  Soil type – decreased recharge with increased clay content.

  Rainfall – increasing recharge with increasing rainfall

  Vegetation characteristics – decreased recharge with longer grower season and deeper roots.

* This paper deals with this second approach and attempts to quantify the affects of the above factors on recharge. To understand this the results

from a simple water balance model are presented and compared to field data.

* Study sites are within the Murray–Darling Basin, comprising NW Victoria, Eastern SA and southwestern NSW.
* Much of this region was covered with Eucalyptus mallee woodland, and has since been cleared.
* Mean annual rainfall varies from 250–500 mm. Rainfall is slightly winter dominant in the north, increasing in winter dominance to the south.
* Soil types are described on a broad scale
* Table 1 is a description of the 18 study sites. Figure 1 is a site location map.
* At most sites it is assumed that deep drainage will become recharge.
* Water balance model used was based on WATBAL, which is a simple 'bucket' approach, where it is assumed that water moving below the zone of ET (Z_{ET}) becomes deep drainage.
* Z_{ET} is represented by maximum soil moisture storage MAXST.
* MAXST determined by $St_{aff} - ST_{wp}$ using average clay content over the depth of Z_{ET}
* It is assumed that recharge occurs when MAXST is exceeded.
* ZET assumed to be 2 m under crops and 2–4 m under pasture. BUT, if it is assumed that there is an exponential decrease in the effect of evapotranspiration with depth, then ZET can be estimated by a step function. This gives an effective ZET of 0.5 m under crops and 0.5–1m under pasture.
* Model adds daily rainfall and removes actual ET (AET) from soil moisture storage. AET determined by assuming that potential evapotranspiration (PET) is 80% of pan evaporation. Ratio of AET to PET varies with soil moisture storage, 0 at wilting point to 1 at field capacity.
* If no vegetation evaporation assumed to occur in the top 1m only.
* No macro-structural development through most of the study site, therefore average clay content in the top 2 m of the soil profile was used as an indication of soil texture. This gave best relationship with potential recharge. Figures 3 and 4 show potential recharge versus % clay content. Indicates a trend of decreasing recharge with increasing clay content.
* In areas where clay content is greater than 25% the recharge rate is generally less than 10 mm/yr. Between 30–50% clay the trend of decreasing recharge is not observed, suggested that this may be due to the properties of the clays, such as cracking. At such clay contents it appears that mineralogy will have an effect on the permeability of the soil. Soil structure will clearly have an effect on permeability and hence recharge as there is an opportunity for rapid percolation between peds, along cracks, root channels or worm channels. For this preferential flow to occur it is suggested that conditions near saturation are required.
* Found that recharge is related to three variables: clay content, rainfall and evaporation, however clay content was the most strongly correlated. It was difficult to separated the effects of evaporation from that of rainfall as evaporation increases as rainfall decreases.
* In general model results are consistent with field data.
* If impermeable layers exist there may be resultant lateral flow and recharge elsewhere, however on a regional basis there would be no difference in the total recharge. If there is no lateral drainage then the hydraulic properties of the impeding layer will determine the drainage flux and hence the recharge rate.
* Considering mean annual rainfall threshold as indicators of potential recharge could be misleading as recharge is dependent on the frequency and magnitude of discrete rainfall events.

Yunusa, I.A.M., Sedgley, R.H., Belford, R.K. and Tennant, D.

Dynamics of water use in a Mediterranean environment. 1. Soil evaporation little affected by presence of plant canopy.

Agricultural Water Management, 1993, 24, 205–224

* Extent to which groundcover determines Esc (soil evaporation from cropped surfaces) evaluated using microlysimeters, under two levels of canopy cover.
* Site: Merredin. Mean annual rainfall of 310 mm. This site is compared to a site in Syria: Aleppo. Figure 1 is a comparison of the two climatic conditions. Figure 2 shows weather data for the growing season.
* Soil: Coarse textured Colgar loamy sand(CLS), and fine textured Merredin sandy loam (MSL).

CLS has 40 – 50 cm grey sand, bulk density of 1.7, over a sandy clay layer. MSL is fine brown to reddish with surface bulk density 1.6.

* Soil moisture content measured with neutron probe every 10 cm in the first 50 cm then 20 cm increments to 1.5 m.
* Drainage and runoff not observed during the study period, but may have occurred on CLS at 6 DAS, before recordings commenced. Wateruse between sowing and 21 DAS was estimated using model of Ritchie (1972).
* Maximum extractable moisture was considered as the difference between the moisture content of the wettest profile and that of the driest profile.
* Moisture storage was similar on cropped and fallow crops until 70 DAS on CLS and 84 DAS on MSL, after this cropped plots became drier.
* Cumulative bare soil evaporation was similar for both soils. ET was similar until 70 DAS when GAI was below 0.5. In this time Et was similar to Es. 84 DAS ET was higher on MSL, this difference grew. Wateruse by the crop post anthesis was marginally higher on MSL. Total ET at the end of the season was 29% higher on MSL, this difference reflected in leaf and dry matter production. GWUE higher on MSL. Figure 3 shows crop wateruse characteristics.
* Microlysimeters were weighted daily between 9 and 10 am from 27 to 134 DAS (2 weeks before harvest). Daily moisture loss determined from change in weights divided by cross sectional area. A change of 1000 mg equates to a water loss of 0.23 mm.
* Set of microlysimeters with 28 1 cm holes drilled were installed in July for later use. The holes were to allow root growth so that the moisture content within the lysimeter was similar to that of the outside soil. When they were used the bases were sealed and the holes covered with plastic film.
* An allowance had to be made for rainfall when determining Esc from microlysimeters. Formula given for estimation of Esc,n.
* Faster leaf development on MSL therefore less radiation transmitted to soil surface. DM accumulation similar on both soils up to 60 DAS then greater on MSL until harvest. Pattern of DM accumulation on both soils was consistent with radiation interception.
* 0.99 correlation coefficient for Es determined by water balance method and by microlysimeters indicates their accuracy.
* Figure 5 shows daily rates of soil evaporation.
* Crop on MSL transpired 62% more water than on CLS. Transpiration efficiency of total biological yield was similar on both soils, however TE of grain yield was higher for the crop on MSL.
* It is concluded that under the dry conditions, canopy cover did not suppress evaporation from the soil surface. Less than 55% of radiation was intercepted by the crops. This is below the proposed threshold of 90% (Ritchie and Burnett 1971). Even when dense canopies are produce their effectiveness is reduced by windy conditions.
* Promoting early growth can lead to early depletion of soil moisture and hence early drying off. Also reduced yield due to depleted soil moisture at grain filling.
* On CLS an greater proportion of ET was via Esc.
* Conclusion that regional differences in weather and soil conditions can dictate different strategies to improve wateruse efficiency.

Karimi, M.M. and Siddique, K.H.M.

Rainfall distribution and grain yield of spring wheat in Western Australia.

Western Australian Department of Agriculture, Division of Plant Industries Technical Report No. 29, 19##{?}

* Yield data obtained from WA Dept. of Ag Crop Variety trials, from 8 WADA research stations.
* Figure 2 shows WA rainfall isohyets, and the locations of the research stations.
* Table 1 gives lat. and long. For each site and a brief description of soil type, with Northcote 1979 classifications.
* Monthly rainfall data with missing records filled with long term average values.
* Table 2 gives the number of years of trials at each site and the average grain yield at each site.
* No attempt made to separate the effects of soil types.
* Four grain yield–rainfall models are discussed.
* Table 3 gives percentage of trials with each sowing date.
* Table 4 shows average monthly, yearly and growing season rainfall for each site.
* Grain yield and annual rainfall were correlated at all sites bar Newdegate and Esperance. Annual rainfall accounted for 45% of grain yield variation at Merredin, and 40% of yield variation at Salmon

Gums. At Esperance and Newdegate, annual rainfall accounted for very little of the yield variation.

* Forward stepwise regression was used to determine the periods of rainfall most closely associated with yield.
* Table 6 shows coefficients of determination using periodic and monthly models.

Tennant, D.

Effects of deep tillage on root growth and water use of wheat and lupins.

WA Department of Agriculture, Division of Plant Research. Technical Report No. 3, 19##{?}

* Higher yields from wheat on soils after cultivation to 35 cm. Generally due to disruption of dense soil layers leading to better root penetration rate and improved final depth of rooting.
* Trial site: Wongan Hills. Soil is a deep loamy sand with a ferruginous gravel at varying depths.
* Soil moisture measured fortnightly with neutron probe.
* Soil strength with bush recording penetrometer.
* Depth of rooting and root density determined from 7.5 cm diameter cores over the crown of single plants.
* Data from penetrometer show the presence of a dense soil layer between 10 and 35 cm depth. Deep tillage removed traces of the pan. Figure 1 presents these data.
* Rates of root penetration were significantly faster following disruption of the dense soil layer by deep tillage. Figure 2 shows effects of deep tillage on root penetration. Figures 3a and 3b show root distribution with time.
* Cumulative water loss to 4 m is summarised in Table 2. For both species water loss was less under conventional tillage. Claims that wheat under deep tillage used 24 mm more water than under conventional tillage. Does not explain distinction between water loss and wateruse. No description of how E or ET values were determined.
* Figure 4 shows water depletion over 2 growth intervals.
* Depths of maximum water extraction were 30–50 cm deeper following deep tillage.
* Table 3 presents DT effects on yield, yield components and wateruse efficiencies. But this WUE is based on total water lost from the profile, not the quantity of water transpired. No account is made for evaporation from the soil surface or water loss through deep drainage.
* If 24 mm more water was taken up it was expected that there would be significant yield increases since 1 mm extra water used should lead to 10 kg /ha yield increase (Tennant 1981). However no yield benefit was realised in this trial.
* A soil type contribution is implied. Also claims that in a wet season of 1983 high soil moisture contents interacted favourably with soil strength resulting in more rapid root penetration through the dense layer.
* Yield responses to DT are less significant under high rainfall.

Wright, G.C. and Smith, C.G.

Differences between two grain sorghum genotypes in adaptation to drought stress. 2. Root water uptake and water use.

Australian Journal of Agricultural Research, 1983, 34, 615–626

* Reports relationship between rooting density and water extraction and growth and grain yield.
* Site: Narrabri Agricultural Research station, northern NSW. Irrigated system versus rainfed.
* Soil moisture measured gravimetrically and by neutron probe.
* Rainfed crop depended heavily on its ability to extract stored soil moisture as the total rainfall for the season was 151 mm, and total pan evaporation was 1000 mm.
* Soil water depletion through time presented in Figure 1. Patterns of soil water extraction with depth shown in Figures 2 and 3.
* Table 1 outlines total seasonal wateruse.
* Results show varietal difference in wateruse.
* Genotypes that restrict wateruse before anthesis may be useful in water limiting environments. Passioura (1972) and Blum (1972) have shown that limiting pre-anthesis water usage has resulted in greater WUE under rainfed conditions.

Doyle, A.D. and Fisher, R.A.

Dry matter accumulation and water use relationships in wheat crops.

Australian Journal of Agricultural Research, 1979, 30, 815–29

* Site: Tamworth, NSW, 1973, 1974, and 1975. Soil was a red-brown earth, Dr2.12 (Northcote 1965)
* In SE Australia, where water supply is limiting at the end of the crop cycle there is a point of optimal pre-anthesis growth so that stored water is available post-anthesis to achieve maximum yields. An optimum date for flowering has also been recognised.
* Relationship of evapotranspiration and dry matter accumulation is elucidated.
* Soil moisture determined gravimetrically.
* Sowing, anthesis and maturity dates, as well as available soil water content at key times, are summarised in Table 1.
* Table 2 summarises climatic conditions during crop growth.
* Plant densities, days to 400 g/m^2 dry matter (DM), and DM at anthesis and maturity as affected by sowing density, sowing date and season are summarised in Table 3.
* Dry matter production related to evapotranspiration is illustrated in Figure 2.
* Effect of year, sowing date, and sowing density on available soil water are summarised in Table 4.
* In 1974 and 75 increased sowing densities lead to increased early crop evapotranspiration, indicated by soil moisture at anthesis. Later sowing tended to increase soil moisture at anthesis and reduce moisture at maturity.

Hamblin, A.P., Tennant, D. and Cochrane, H.

Tillage and the growth of a wheat crop in a loamy sand.

Australian Journal of Agricultural Research, 1982, 33, 887–897

* In WA sandy soils collapse under winter rainfall, reducing their porosity. Paper addresses effects of cultivation practices on surface soil structures. 1977 commencement.
* Site: Wongan Hills. Soil is a deep yellow sand. Rainfall 345 mm (mean annual)
* Tillage treatments:
    1. disc plough (DP) > single pass with scarifier and combine drill seeding.
    2. direct drilling with unmodified combine seeder (CDD) after herbicide
    3. direct drilled with triple disc drill (TDD)
* Soil moisture measured with neutron probe.
* At this site direct drilled crops have grown more slowly throughout the growing season. This is illustrated in Figure 1 (data from 1980)
* Table 1 is a summary of mean annual rainfalls, grain yields and plant numbers for 5 years of trials.
* Figure 2 shows growth rate over time from sowing. The DP curve is declined progressively with time while others fluctuated. The fluctuations are suggested to occur as a result of recovery from nitrogen and/or water stress (Halse et al. 1969). It is suggested that the DP crop did not suffer from fluctuations in nitrogen and/or moisture stress. This crop also started with a higher growth rate, suggested that this crop started with more available nitrogen. There was no significant difference in mineralised nitrogen between the treatments. Suggestion is then made that physical conditions at the start of the season were more favourable for the DP treatment ie ploughed seed bed.
* Figure 3 shows cumulative wateruse with time. DP treatment had higher daily rate of wateruse. Difference was greatest between 60 and 80 days.
* Figure 4 shows the difference between wettest and driest water contents for each soil layer. More subsoil moisture was used by the DP treatment. Figure 5 shows date of sampling at which each soil layer achieved maximum moisture content. This indicates the DP treatment had a more rapid movement of water through the profile. In a wet year, the DP treatment may allow deep drainage past the root zone. Direct drilling of sandy soils may be useful in controlling secondary salinisation. (? But rooting depths were greater under DP and it used more water).
* Disc ploughing has resulted in high grain yields due to lower soil strength, more rapid wetting up of the soil and deeper early penetration of roots. This conclusion is for loamy sands, and does not apply to a general comparison of tillage systems on other soil types.

French, R.J.

The effect of fallowing on the yield of wheat. 2. The effect on grain yield.

Australian Journal of Agricultural Research, 1978, 29, 669–684

(Part 1 discusses effect of fallowing on soil moisture storage and nitrogen supply)

* Sites: 5 in SA wheat belt. 5 seasons, cultivar Gabo throughout. Sown in May–June and Harvested in December.
* Coarse textured and fine textured soils. Sites chosen so that runoff and deep drainage assumed negligible.
* Moisture contents taken at: 0–15 cm, 15–30 cm, 30–60 cm, 60–90 cm and 90–120 cm
* Field capacity and wilting point moisture contents also determined.
* Wateruse determined as difference in soil
* Data from all sites and seasons pooled.
* Wateruse has major effect on yield (x = wateruse)

  Dry matter (kg/ha):
  $Y = -3273 + 43.9x - 0.0449x^2$
  < 65% of variation accounted for by WU

  Grain (kg/ha):
  $Y = -1013 + 14.5x - 0.016x^2$
  < 62%

  Harvest index:
  $Y = 0.475 - 0.99 * 10^{-3}x + 0.14 * 10^{-5}x^2$
  < 18%
* Also separate linear regressions of grain yield on wateruse given.
* Significance of water is greater in dry seasons and in coarse soils with lower water holding capacity.
* Yield regressions for rainfall in the growing season (x = April–October rainfall):

  Dry matter(kg /ha):
  $Y = -3689 + 49.9x - 0.0555x^2$
  <63% of variation accounted for by season rainfall

  Grain (kg/ha):
  $Y = -877 + 14.4x - 0.0166x^2$
  <56%

  Harvest index:
  $Y = 0.506 - 1.1 * 10^{-3}x + 0.16 * 10^{-5}x^2$
  <22%

* Figure 1 shows relationship between WU and yield.

* In dry growing season 72% of the variability was accounted for by moisture content at sowing, with each additional mm available soil water and total soil water yielding 9.1 kg/ha and 5.9 kg/ha respectively (A dry season is approx 200 mm rainfall.) In the moist seasons this value drops to 25%, with each mm of available soil water yielding 3.7 kg/ha. Author is considering additional water to be that above 76 mm, which has been shown to be the threshold below which no grain forms.
* Yield-nitrate relationship for dry sites (less than 230 mm WU), was insignificant, but for sites with more than 230 mm WU the quadratic regressions are given as: (x = nitrate nitrogen kg/ha 60 cm, at sowing)

  Dry matter (kg /ha):
  $Y = 3803 + 47.6x - 0.1242x^2$
  <18% of variation accounted for by nitrate nitrogen

  Grain (kg/ha):
  $Y = 1170 + 14.2x - 0.033x^2$
  <29%
* Dry matter and grain yield for all sites and seasons is summarised in Table 1.
* Dry matter and grain yield are 37% and 31% higher, respectively, following fallow, with no effect of fallow on harvest index. These increases are at the expense of two extra cultivations and a loss of 7 months grazing.
* Yield regression based on additional water supply due to fallow was determined.

  $Y_f = 23.7 + 15.0x - 0.069x^2$
  59% yield variation accounted for by extra stored moisture
  Y_f = additional yield due to fallow (kg/ha)
  x = additional water at sowing due to fallow (mm)
* Significant increases in yield occurred in 8 out of 10 experiments on coarse soils, but only 3 of these showed significant increases in stored soil moisture at sowing. Claim is made that yield response is due to other factors.
* On the fine soils increases in yield occurred due to fallow in 10 of 14 experiments and 9 of these showed significant increases in stored soil moisture at sowing.
* On the coarse soils there was a negative correlation of yield with total fallow rain (July to sowing). Suggestion is that this is due to leaching of nitrates.
* The opposite was true on the finer soils. No response to fallow when the growing season rainfall exceeded 520 mm.

- Table 5 summarises WU and WUE by all crops at each site. On fallow, 14 out of 24 crops used significantly more water. WUE on fallow greater than on non-fallow: 6.1 kg/ha/mm compared to 5.1 kg/ha/mm.
- 70% of the total water loss from the 120 cm profile was from the top 60 cm. 18–25% was the highest proportion of water loss from the 90–120 cm layer, and this occurred on the fallow only.
- All crops extracted water to contents below that at 15 atm. Suggestion that consideration of water content above that at 15 atm is inaccurate when determining total available water.
- On fine textured soils, nitrogen application allowed for greater wateruse, little response to nitrogen on coarse soils. Suggestion that the water is held at lower tensions in coarse soils therefore plants were able to extract water, however on the fine soils the applied nitrogen allowed the plants to extract water that is held at higher tensions.
- Conclusion drawn that for fallow to be of use the soil must be fine textured with more than 20% clay in the subsoil, 15–30 cm layer. This soil should store 125 mm water to a depth of 120 cm. BUT fallow should occur at a time when subsoil moisture can be recharged ie. a period of significant rainfall.

Hamblin, A., Tennant, D. and Perry, M.W.

The cost of stress: dry matter partitioning changes with seasonal supply of water and nitrogen to dryland wheat

Plant and Soil, 1990, 122, 47–58

- Aim has been to maximise assimilates into grain of cereal crops. Now considering root system. Shultz 1974, estimates 30% of the dry matter of dryland wheat crops is contained within the roots, which is greater than the estimates of Lupton et al. (1978) and Welbank (1974), for temperate cereal crops. Suggested that higher stresses result in greater proportion of dry matter partitioned to roots.
- Site: Merredin Research Station. Average rainfall of 310 mm. Anthesis occurs at 100–105 DAS coinciding with increased temperatures, increased vapour pressure deficits and decreased rainfall. Soil was a deep phase of Colgar series. Yellow loamy sand with 18% clay to 60–70 cm over mottled lateritic sandy clay (35% clay). This soil readily deformed by traffic when moist, therefore a traffic pan had developed across the whole site. Becomes cemented and massive on drying.
- Portable weather station used to obtain: solar radiation; air temperatures; class A pan evaporation and; relative humidity. Root mass, length and density estimated from 5 cm core samples taken directly over plant. Soil moisture measured to 180 cm with neutron probe. Penetrometer measurements made at seeding to 55 cm, with 3.5 cm increments (30^{o} included angle cone).
- Figure 1 shows DM accumulation and LA for 1984 and 85. Grain yields given in Table 2.
- Treatments:
  nitrogen application (+ or–)
  Loosened subsoil (to 35 cm)
  Rotations: W/W and L/W
- Figure 2 shows stored soil water between 10 cm and 190 cm (averaged) for the 18-month period of the study. The limit to available soil water was taken as the driest soil water profile at the end of both harvests.
- Effect of the traffic pan was more pronounced in the drier season.
- Root mass to total biomass ratios plotted against DAS in Figure 5. These ratios decline in the wetter year.
- Unfavourable soil conditions reduced shoot growth and increased the proportion of dry matter partitioned to the roots.
- Mechanical impedance is less understood, however growth trends indicate restricted supply of moisture and nitrogen. There is a reduction in root elongation but a proliferation of lateral root growth.

Hamblin, A. and Tennant, D.

Root length density and water uptake in cereals and grain legumes: How well are they correlated?

Australian Journal of Agricultural Research, 1987, 38, 513–27

- Root length per unit volume of soil (Lv) of root length per unit area of ground surface (La) have in some studies been correlated with water uptake, while in others there has been no correlation.
- This paper deals with differences in root distributions and densities with different species, and whether the differences have any effect on water uptake.
- Sites: Wongan Hills and Merredin. Experiment was conducted on three different soil types at Merredin.

* Soils: Wongan Hills loamy sand; Norpa acid loamy sand; deep phase of Colgar series (70 cm loamy sand over degraded mottled laterite profile of sandy clay), and; Merredin series sodic red-brown earth (sandy loam over a red clay loam). The Colgar soil had a hard indurated gravely clay at 120 cm.
* Details of climate and soil properties is given.
* Two cereals and two legumes at each site.
* Soil moisture monitored by neutron meter.
* Water flow was assumed to be one dimensional and positive incremental differences with time attributed to rainfall and deep drainage, and negative incremental difference attributed to root uptake and redistribution. Maximum depths of water uptake were compared to depths from which roots were extracted.
* Water uptake by roots and upward flux due to evaporation accounted for nearly all the rainfall in the less permeable sites, but deep drainage is inferred from changes in the water content distribution and known rooting depth on the loamy sand soils.
* Water retention curves determined from undisturbed samples wetted to near saturation on suction tables, desorption curves determined by the filter paper method (Hamblin 1981). Field values for soil water potential constructed by interpolation from these curves.
* Water loss determined by:

  WL = (S1 + P) – S2
  S = soil water storage at sowing (1) and harvest (2)
  P = precipitation
* Water loss computed separately for the period after each crop canopy had a leaf area greater than $1m^2/m^2$. It is assumed that soil evaporation would be a small proportion of wateruse during this time.
* Lupins had the lowest La values at each site.
* Water loss over period given in Table 2.
* Average water loss was greater for wheat and lupins than for barley and peas. The sparse root growth of lupins suggests that this water loss may be due to evaporation from the soil.
* Differences in root depth occurred as a direct response to differences in total wetted depth of the soil at each site.
* No species reduced soil water contents to –1.5 MPa below 1m in the Merredin soil. The Colgar soil was depleted to –1.5 MPa throughout the profile to 20 cm below the maximum depth from which roots were extracted.
* Some available soil moisture was not extracted from the basal third of the Wongan and Norpa profiles by maturity.
* Suggestion is made that the incomplete extraction at Wongan may be due to the high axial resistance caused by deep roots in the presence of too low a potential gradient.
* Change in water content with depth for each species at each site is shown in Figure 3. Rainfall distributions shown in Figure 4.
* On the three Merredin soils water uptake varied more with soil type than with species or root density distribution.
* Conclusions:
  – strong evidence for genotypic variation in root morphology of the four species.
  – cereal species showed consistently greater root length
  – water loss over the season varied between species, higher correlation with maximum rooting depth than with total root density
  – most rapid water uptake occurred in soil layers with higher water potentials

Yunusa, I.A.M., Sedgley, R.H. and Tennant, D.

Dynamics of water use under annual legume pastures in a semi-arid Mediterranean environment.

Agricultural Water Management, 1992, 22, 291–306

* Annual regeneration of pasture from seed bank in the soil is critical. Favourable moisture conditions for growth required for at least five weeks after flowering (Cornish 1985).
* In this environment 30–40% of seasonal ET is lost through Esc (soil evaporation under canopy), during early winter. (Cooper et al. 1983; Keatinge and Cooper 1983; Siddique et al. 1990)
* Keatinge and Cooper (1983) claim that ET and E from bare fallow soil are similar early in the season, dry matter produce in this time is from ‘free water’ therefore they suggest rapid canopy closure to use water that would otherwise be lost. But, if recharge is inadequate this can lead to premature depletion of stored water.
* On fine textured soils Rickert et al. (1987) showed that the high native N resulted in rapid early growth and high ET in spring wheat, however, in a

coarse textured soil with low native N and leaching of moisture deeper in the root zone resulted in slower canopy closure and slower moisture depletion, followed by a better water supply during grain filling.

* Attempts have been made to limit ET on heavy textured soils (heavy or coarse) before anthesis, by maintaining a fixed number of culms per unit area of land (surgical technique). This gave a 19% yield increase over 2 years for spring wheat,(Islam and Sedgley 1985). Now trying to breed for limited number of culms.
* Water saving concept evaluated in this study for annual pasture legume on a range of soil types.
* Site: Merredin. Table 1 gives monthly rainfall, pan evaporation and temperature for 1987, 89 and long term averages.
* Weighing lysimeters on adjacent soil types: Colgar loamy sand (CLS) and Merredin sandy loam (MSL) light and heavy respectively. CLS is coarse textured, acidic, has good internal drainage and has a subsurface bulk density of 1.7. Forms a hard-pan at depth over a sandy clay loam. MSL has a thin surface layer of fine textured sandy loam over clay loam to clay, poor internal drainage, neutral to alkaline reaction and a density of 1.6. (Rickert et al. 1987)
* Time to flowering recorded as number of days after sowing.
* Soil moisture storage (S) monitored fortnightly with a neutron probe, at 10 cm intervals to 150 cm , starting at 20 cm.
* Fraction of available water (FAW) in rooting depth calculated by:

  FAW = (Sn – Sd)/ (Sw – Sd)

  Sn = moisture storage in rooting profile at any time
  Sd = water stored in the driest profile during the season
  Sw = water stored in the wettest profile during the season.

  The driest profile was obtained one week after final sampling on 130 DAS
* ET was determined from two hydraulic weighing lysimeters, 2.27 m^2 in cross section and 1.2 m deep on CLS and 1.1m on MSL.
* Two components of ET assumed to be independent and additive (Denmead 1973) Therefore can use:

  T = ET – Esc

Esc estimated using method of Cooper et al. (1983):

  Esc = Es(1 – f)

  Es = bare soil evaporation rate
  f = fraction of incoming radiation intercepted by the crop canopy.

  Es estimated using the model of Ritchie (1972).

* 1989 studied considered pasture revegetation on MSL: three treatments—control, mown and grazed.
* Fraction ground cover (FGC) and dry matter (DM) assessed starting at 64 DAR, continuing at three-weekly intervals.
* Soil moisture monitored at three-weekly intervals from 43 DAR until last sampling date at 148 DAR.

  ET = P – (S – RO – D mm
* Drainage was negligible on this soil but runoff may have occurred, therefore ET was estimated between 43 and 64 DAR since runoff was impossible to quantify. Taken to be potential evapotranspiration using Penman-Monteith equation (Monteith 1965).
* ET for period between regeneration and 43 DAR obtained from 3 existing access tubes, from previous season.
* FGC and DM developed more rapidly and reached higher levels on MSL than on CLS
* ∑ET similar on both soils to 70 DAS, then MSL began to use more water than CLS, to a maximum difference of 10 mm at 98 DAS, the difference reduced to 2 mm by the end of the season. Seasonal ET of both soils averaged 134.7 mm at final sampling at 125 DAS.
* ET consistently higher on CLS late in the season.
* ∑ET/∑Etpot was higher for CLS (102–109) DAS indicating greater moisture availability on CLS.
* FAW depleted initially to a greater extent on MSL, however recharge and later depletion was similar on both soils. ∑ET/∑Etpot higher on MSL to 100 DAS, then CSL gave higher values.
* In first 20 DAS Esc was only component of ET. After this T rose from 0.1 mm/day to 1.5 mm/d by 75 DAS on MSL and 1.2 mm/d at 90 DAS on CLS.
* Greater difference between the soils for T than for Esc.
* WUE higher on MSL than on CLS but transpiration efficiency was similar on both soils.

* In the regeneration experiment the control showed faster moisture depletion. By 128 DAR the FAW of the control was less than half that in the grazed. However at the end of the season FAW did not differ significantly between treatments.
* No significant difference in WUE between control and mowed.
* More vigorous growth on MSL promoted early wateruse and early depletion of stored water later in the season. Data also supports modifying wateruse by controlling canopy development.
* Water relations for seed production were probably better on CLS. Details of plant response to the low pH of this soil has not been documented but it is thought that Serena medic was unable to exploit soil moisture on this soil due to poor adaptability to this soil characteristic.
* Conclusion is that there is scope for development of water saving strategy on MSL but not on CLS, due to the poor water holding capacity of CLS. On the pasture exp. The saved water did not result in significantly higher post anthesis DM production. May have had beneficial effect on seed set and seed size.

Pook, E.W. and Costin, A.B.

Root distribution and soil moisture studies in some perennial ryegrass and phalaris pastures on the southern tablelands, south eastern Australia.

Field Station Record, CSIRO Division of Plant Industry, 1971, 10, 59–72

* Persistence of perennial pasture species depends on their ability of deep roots to extract moisture from the subsoil.
* Phalaris found to be deeper rooting than perennial ryegrass, explaining why phalaris persists to a greater extent through drought
* Sites: Wollogorang near Goulburn, and Ginninderra near Canberra.
* Roots sampled to 30 cm by coring and by auger to greater depth. Roots of each species separated by hand, roots from other species were removed.
* Soil moisture content was determined gravimetrically. Wilting point and field capacity were determined by pressure plate and porous plant apparatus, respectively.
* No allowance for runoff, and there was no limit to the total soil moisture stored in the subsoil. Topsoil store had a maximum capacity of 90 mm. ET losses calculated at rates of:

  0.75 Ew from topsoil until 25 mm remained
  0.6 Ew from topsoil until exhausted
  0.7 Ew from subsoil store when primary store was empty
  Ew = free-water evaporation.
* Patterns of root distribution shown.
* Ungrazed pasture showed lower moisture content at depth, and was less than wilting point.
* Water budget estimated indicate that substantial build up of moisture store is unlikely as removal of water during the warmer months is rapid. Costin (unpublished data) has shown that under deep rooted species on heavy-textured soils the hydrologic cycle is effectively closed.
* Conclusion is that on medium-heavy textured soils deep rooting species such as phalaris would be expected to utilise nearly all the available moisture stored in the subsoil after occasional wet years.

Yunusa, I.A.M., Sedgley, R.H. and Siddique, K.M.H.

Influence of mulching on the pattern of growth and water use by spring wheat and moisture storage on a fine textured soil.

Plant and Soil, 1994, 160, 119–130

* Objectives: to evaluate use of surface mulching as a method to modify patterns of growth and wateruse so as to increase available soil moisture during grain filling. And the evaluate the residual effects on moisture storage during the following summer fallow.
* Site: Merredin on a fine textured soil: duplex, with 10 cm reddish brown sandy clay to clay loam over yellow sandy clay. pH increases fro 6.1 at the surface to 7.8 below 50 cm.
* Soil moisture measured with a neutron probe, monitored at fortnightly intervals from 20 cm with readings in 10 cm increments. Moisture content in top 20 cm determined gravimetrically.

  $ET = P - (\Delta S + RO + D)$

  Runoff and drainage rare on this soil. Es determined with a weighing lysimeter.
* Mulching reduced leaf area per plant by reducing the number of culms (22%) therefore green area index was reduced.
* The mulched crops used 15 mm less water than the control before anthesis (ET reduced by 11%, made up of 8.5% reduction in transpiration and 16.7% reduction in Esc–> 8 and 7 mm, respectively), mulched crop was unable to

increase ET during grain filling. This was due to reduced soil temperature for the duration of the season under mulch.

* Mulching did not have significant effects on total above ground dry matter or grain yield but it did increase wateruse efficiency for grain yield by 18%. Mulched crop produced fewer but heavier grains.
* Mulched treatments had more available moisture at the start of the next season. But mulching during the summer fallow period had little effect. The increase in available water is attributed to moisture saved by mulching in the previous growing season.
* Transpiration was determined using data for fraction of intercepted radiation and available soil moisture.

Native systems

Carbon, B.A., Roberts, F.J., Farrington, P. and Beresford, J.D.

Deep drainage and water use of forest s and pastures grown on deep sands in a Mediterranean environment

Journal of Hydrology, 1982, 55, 53–64

* In WA replacing native forests with winter growing annual pastures has increased the deep drainage since pastures transpire less water than native trees.
* Annual pastures have a shallow root zone, and senesce during summer.
* Considers Swan Coastal Plain, deep uniform coarse sands. Permanent water table at 15 –20 m.
* Soil moisture measured with neutron probe
* Rainfall measured with standard rain gauge.
* Soil-moisture characteristics determined to allow calculation of deep drainage, using the redistribution sub-routine of the computer model for water balance in coarse textured soils (Carbon and Galbraith 1975). Drainage calculated assuming Darcian flow using a one-day computer time step.

  (flux) = $K(d\Psi/dZ)$

  K = hydraulic conductivity
  Ψ = soil water potential
  Z = soil depth

  Evapotranspiration solved by:

  $E = R - \Delta S - U$

  R = rain
  ΔS = increase in stored soil water
  U = deep drainage.

  Percentage of annual water balance occurring as deep drainage was calculated by:

  $100U/(U + E)$

* Figure 1, A and B shows change in soil water potential and soil hydraulic conductivity respectively, with water content in the Spearwood sand.
* Figure 2 shows soil water profile beneath native forest at site 1
* Figure 3, pine forest at site 1
* Figure 4, *Bromus mollis–T. subterraneum* pasture
* Figure 5 , *Eragrostis curvula–T. subterraneum* pasture
* More stored water beneath annual pastures than perennial
* More stored water in the 6 m below native forest than pine forest.
* Soil moisture below native forest depleted through the summer to 3 m, only that below 3m remained available. This was replenished to original level the following winter.
* Average of 34% of the annual water balance of the native forest was calculated to pass through the soil as deep drainage.
* Below pine forest there was less available moisture at the beginning of summer.
* Pine forests transpired more water. Native forests have a more gradual consumption of water, therefore more soil water is available during the summer drought.
* Replacing native forests with perennial pastures would have little effect on deep drainage, however annual pastures would lead to significant increases.

Nusen, R.A., Bligh, K.J., Baxter, L.N., Solin, E.J. and Imrie, D.H.

The fate of rainfall in a mallee and heath vegetated catchment in southern Western Australia.

Australian Journal of Ecology, 1986,11, 361–371

* Shrub eucalypt once covered much of the areas now used for cereal cropping.
* Removal has led to increases in deep drainage beyond the root zone and consequently salinisation has occurred.

- * Vegetation affects the redistribution of rainfall below the surface. Stemflow allows for greater water storage at depth. Alison and Hughes (1983) speculate that the water was transported to depth via channels occupied by living roots. Removal of the mallee may make these channels inoperative.
- * Aim of this study was to describe the hydrology of a naturally vegetated catchment.
- * Soil types Dy 3.43 and Dy 3.42 (Northcote 1974)
- * Brown loamy sand or sandy gravel over pale brown to light yellowish brown mottled sandy clay. A horizon varies from 5–30 cm mottled zone extends to silicified hardpan of cemented silty sandy clay at 3 to 5 m.
- * Runoff measured with a stainless steel, parabolic, 30°, v-notch, knife edge weir.
- * Overland flow measured on 4×4 m^2 plots with a 1.2 mm stainless steel ring driven into the soil with 25 cm above ground. Overland flow collected in 62-litre drums.
- * Rainfall measured with a 0.2 mm tipping bucket pulviograph near the weir, as well as three standard rain gauges.
- * Soil moisture by neutron probes installed to 5 m.
- * Saturated hydraulic conductivity at four sites using 30 cm diameter infiltration cylinders (Talsma 1969).
- * Samples taken for gravimetric moisture content at 50 cm radial intervals beginning from the base of the tree, at depths 0–10 cm and 10–20 cm
- * Water flow pathways were assessed using rhodamine-B powder dye powder sprinkled on the soil surface around and over the crown of two trees.
- * Dye solution was ponded to a depth of 10 cm in 4 m^2 infiltrometer rings at three sites.
- * Borehole drilling showed that there was no groundwater accumulation under the catchment, therefore no drainage below the root zone.
- * Observed an increase of soil moisture at depth in the hardpan.
- * Figures 2 and 3 are moisture profiles under mallee and heath, respectively.
- * Saturated hydraulic conductivity was very low therefore unlikely that recharge occurred at depth, hence very little transfer of water into the 3.5 –5 m region of the profile under heath.
- * Under mallee there was some storage increase at depths greater than 5 m.
- * Dye appeared to be uniformly distributed in the A horizon but only penetration observed into B horizon was associated with pathways around living roots. No evidence of dye movement through interpedal cracks, voided root channels or channels occupied by dead roots, occlusion is suggested. The dye used is cationic, thus strongly adsorbed on the clay exchange sites.
- * Radial moisture contents suggest that stemflow enters the soil at the base of the mallee trees. The water flows down the soil–root interface where it is stored at depth for use during summer.
- * The net effect observed was that the canopy and stems redistribute about 8% of the rain falling on the catchment. Small changes in gross hydrology can have significant consequences, eg. clearing of land and development for agriculture in southern WA has resulted in an additional 4–10% of mean annual rainfall percolating below the root zone to recharge the ground waters (George 1978; Peck and Hurle 1973). After 15–20 years this causes secondary salinity in lower landscape areas.
- * Clearing may change the mode of entry of water into the deep profile from preferred pathways to a uniform flow system (authors claim this requires further investigation).