Yield and water use of temperate pastures in summer dry environments

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Abstract

The water use efficiencies (WUE) of a range of temperate pasture species were calculated from measurements on several different dryland and irrigated pastures in Canterbury. The annual WUE ranged from 6.7 kg DM/ha/mm for a dryland cocksfoot pasture to 40 kg DM/ha/mm for a dryland lucerne crop grown on a Wakanui silt loam soil. The lucerne crop extracted 328 mm of water to at least 2.3 m depth. Its deep root enabled high recovery of rainfall stored in the soil profile. By comparison a perennial ryegrass pasture only extracted 243 mm of water to 1.5 m depth on the same soil type and it had an annual WUE of 18 kg DM/ha/mm. Where practical, species with deep roots should be sown on deep free draining soils to extract all available soil water. On a stony Lismore soil, perennial ryegrass extracted 129 mm of water to a depth of 1.5 m. On a more stony, shallower soil, at the same location, lucerne extracted 131 mm to a depth of 2.3 m. Both pastures had similar annual DM yields and an annual WUE of 16 kg DM/ha/mm. Within the year WUE of the ryegrass pasture ranged from 3 to 22 kg DM/ha/mm. This seasonal variability reflected how soil moisture deficit, soil evaporation and drainage affected pasture growth. During spring, when moisture was non-limiting, clover monocultures and binary mixtures had higher WUEs than pure grass swards due to higher herbage nitrogen (N). Furthermore, a cocksfoot monoculture had an annual WUE of 38 kg DM/ha/mm when fertilised with N but it was only 17 kg DM/ha/mm when unfertilised. These results suggest WUE can be maximised annually and seasonally by growing monocultures of legumes, such as lucerne, adopting grazing management to enhance clover production or strategic application of N fertiliser to maximize growth when soil moisture is available.

Keywords: *Cichorium intybus*, *Dactylis glomerata*, *Lolium perenne*, *Medicago sativa*, *Trifolium ambiguum*, *T. michelianum*, *T. pratense*, *T. repens*, *T. subterraneum*

Introduction

Pasture production in eastern regions of New Zealand is frequently limited by inadequate rainfall, particularly during summer. Therefore it is important to utilise available water as efficiently as possible. On an annual basis water-use efficiency (WUE) can be defined as the ratio of total dry matter (DM) accumulation to total water input to the system. This agronomic approach can be modified to quantify WUE at a range of temporal and spatial levels depending on the scale of interest. For irrigated dairy pastures in Canterbury, Martin *et al*. (2006) benchmarked WUE of ryegrass pastures under non-limiting conditions at 20 kg DM/ha/mm of potential evapotranspiration (PET, Penman 1948). They suggested this was a reasonable value for farmers and Regional Councils to determine how much water is needed to maintain pasture production under various rainfall and irrigation scenarios. This was almost double the annual WUE values they calculated from long term pasture experiments at Winchmore (Rickard 1972; Rickard & McBride 1986) but less than the 30 kg DM/ha/mm of water extracted reported by Brown *et al*. (2005) for lucerne, chicory and red clover. In this paper we examine reasons for the range in WUE values. Emphasis is on understanding the factors that influence WUE on an annual and seasonal basis and identifying management strategies that dryland and irrigated pastoral farmers can adopt to maximise WUE on farm.

Materials and Methods

Data for the analyses of WUE came from nine experiments, as outlined in Table 1, for which DM yields and soil moisture status were monitored intensively. Datasets 1-3 were collected at Lincoln University from pastures and crops grown in a Wakanui silt loam soil of >2.0 m, overlying alluvial gravels. Datasets 4-7 were from experiments on a variable depth Templeton silt loam soil with 0.8-1.5 m of fine materials overlying alluvial gravel. Datasets 8 and 9 were collected at Ashley Dene, Lincoln University's dryland sheep farm. Both datasets were from pastures grown in a Lismore soil but for Dataset 8 there was up to 0.5 m of silty loam over alluvial gravels compared with stones obvious on the surface for Dataset 9.

A brief description of previously unpublished experiments is given while full details of the other experiments are referenced (Table 1). Dataset 2 (H.E. Brown unpublished A) is from a 2-year-old 'Kaituna' lucerne stand established in 2000 and subsequently used for an intensive grazing experiment (Teixeira *et al.* 2007). Dataset 5 (A. Mills unpublished A) is from monocultures of ryegrass and four (white, Caucasian, subterranean, balansa) clovers, and binary mixtures of cocksfoot with

Table 1 Details of the nine data sets used in Figure 1 including source publication, species, soil type, site location, irrigation levels (Dry = dryland, Irr = fully irrigated), number of years measurements were made and number (*n*) of data points contributed to the analyses, and details of measured parameters which include yield (Y), rainfall (R), irrigation applied (I), soil moisture content (SMC), total (T) measurement depth (m) and drainage (D).

Data set	Source	Species/mixture†	Soil	Site	Irr level	Years (*n*)	Parameter measured Y	R	I	SMC	T	D
1	Brown *et al.* (2005)	Luc, Chic, Rc	Wakanui	Lincoln	Dry, Irr	5 (30)	✓	✓	✓	✓	2.3	✓
2	Brown unpublished A	Luc	Wakanui	Lincoln	Dry, Irr	1 (2)	✓	✓	✓	✓	2.3	✓
3	Black (2004)	Wc, Cc, RG	Wakanui	Lincoln	Dry, Irr	2 (9)	✓	✓	✓	✓	2.3	✓
4	Mills (2007)	CF (+ or – N)	Templeton	Lincoln	Dry, Irr	2 (8)	✓	✓	✓	✓	2.3	✓
5	Mills unpublished A	CF/Bal, CF/Sub, CF/Wc, CF/Cc, RG/Wc, RG/Cc, Wc, Cc, Bal, Sub, RG	Templeton	Lincoln	Dry	1 (11)	✓	✓	**N/A**	✓	1.3	✓
6	Mills unpublished B	CF/Bal, CF/Sub, CF/Wc, CF/Cc, RG/Wc	Templeton	Lincoln	Dry	2 (10)	✓	✓	**N/A**	✓	2.3	✓
7	Pollock unpublished	Luc, RG, RG/Wc	Templeton	4km NW Lincoln	Dry	1 (3)	✓	✓	**N/A**	✓	2.3	✗
8	Brown unpublished B	Luc	Lismore very stony loam	Ashley Dene	Dry	2 (2)	✓	✓	**N/A**	✓	2.3	✓
9	Moot unpublished	RG/Wc/Sub	Lismore very stony loam	Ashley Dene	Dry	1 (1)	✓	✓	**N/A**	✓	2.3	✗

Note: †Acronyms for species are lucerne (Luc), Chicory (Chic), perennial ryegrass (RG), cocksfoot (CF), white clover (Wc), red clover (Rc), Caucasian clover (Cc), subterranean clover (Sub), balansa clover (Bal). Species sown as mixtures are separated by /. N/A = not applicable.

each of these clovers and ryegrass with white or Caucasian clover. These binary mixtures were established in 2003 and measurements for this research were taken during the 2004/05 season. These paddocks adjoin those used for the experiment for Dataset 6 (A. Mills unpublished B). This dataset reports results from 2003/04 and 2004/05 from five grass-based pastures used in the 'MaxClover' grazing experiment (Mills *et al.* 2008). Dataset 7 is for the 1993/94 growth season from the open pastures adjacent to an agroforestry experiment described by Yunusa *et al.* (1995). Datasets 8 and 9 are from commercial paddocks of 'Kaituna' lucerne and perennial ryegrass with white and subterranean clover pasture, respectively. Measurements in the ryegrass/clover pasture were taken from August 2002 to November 2003 while in the lucerne they were taken from September 2001 to November 2003. Both datasets were from different paddocks at the Lincoln University dryland farm at Ashley Dene with the lucerne on a more stony (less water retentive) Lismore soil than the pasture.

Unless otherwise stated annual data are DM yield and water used for the period 1 July to 30 June. Annual WUE was calculated from measurements of total DM yield/ha (Y) and total water used (Equation 1):

Equation 1 $WUE = Y/(R+I+\Delta SWC-D)$

Rainfall (R) records were either monitored on-site or were obtained from the Broadfields meteorological station which is 2 km N of Lincoln University. The amount of water applied as irrigation (I) was measured using flow meters or rain gauges depending on the application method. At all sites, the changes in soil moisture content (ΔSWC) were monitored using time domain reflectometry (TDR, 0-0.2 m) and neutron probe (Troxler 4300). Measurements were made at 0.1 or 0.2 m increments to a depth of 1.3-2.3 m, depending on species sown and soil depth (Table 1), at approximately 10-14 day intervals during active growth. In all datasets, except 7 and 9, water use (Equation 1) was interpolated to daily values in relation to PET. The soil water balance could then be solved daily and drainage (D) taken as precipitation (R+I) in excess of field capacity on any given day.

For Datasets 7 and 9, drainage was not removed from the total water used for dry matter production. However, the timing of drainage events was estimated. Specifically, when a rainfall event was greater than 90% of the current soil moisture deficit then drainage was deemed to have occurred.

Results and Discussion

Annual DM yields and the associated water used for all the datasets are summarised in Fig 1. The DM yields ranged from 5.0 t/ha/yr for a dryland pasture in Dataset 4 to a maximum of 28.0 t/ha/yr for irrigated 'Kaituna' lucerne grown on a deep Wakanui silt loam soil in 1997/98 (Dataset 1). The water used to produce the DM ranged from 400 mm/ha/yr for dryland lucerne (Dataset 2) to a maximum of 1012 mm for irrigated white clover (Dataset 3). These resulted in annual WUE values from 6.7 to 40.0 kg DM/ha/mm of water. This large range in annual WUE can be ascribed to differences in soil water holding capacity, the plant water extraction and the efficiency of water utilisation in dry matter production. The upper bound in Figure 1 represents a theoretical maximum for WUE as defined by the net photosynthesis of a pasture relative to the amount of water the pasture transpired (Brown 2004). In practice, this can only be achieved when no soil evaporation or drainage occurs. Several of the datasets show an annual WUE approaching this level.

The water available for use by pastures depends on the timing and amount of rainfall and irrigation events, and the ability of the soil to store water. For irrigated pastures, management of the balance between water supply and demand can be used to increase WUE and this was discussed by Martin *et al*. (2006).

In dryland conditions, the combination of available water capacity of the soil and the depth of extraction by roots contribute to annual WUE. This can be illustrated for perennial ryegrass and lucerne using Datasets 2, 3, 8 and 9 (Fig. 2). The dryland lucerne (Dataset 2) grown on a deep Wakanui silt loam soil (high water storage capacity) had an annual WUE of 40 kg DM/ha/mm. This resulted from the extraction of 328 mm of water to a depth of at least 2.3 m. Therefore the total water use included a substantial component of winter rainfall that was stored in the soil profile. When grown on a very stony Lismore soil (low water storage capacity), lucerne still extracted water to at least 2.3 m, but only 131 mm of stored soil water was extracted (Dataset 8). As a result, the annual WUE was 16 kg DM/ha/mm. The performance of the ryegrass/clover pasture on a less stony Lismore was similar to lucerne with total water extraction of 129 mm (Dataset 9). In both pastures, the annual WUE was 16 kg DM/ha/mm, but the ryegrass pasture only extracted soil moisture to a depth of 1.5 m. Ryegrass on the Wakanui soil (Dataset 3) extracted 243 mm, also to a depth of 1.5 m (Fig. 2) and consequently its annual WUE of 18 kg DM/ha/mm was lower than for the lucerne. These results indicate that, where practical, deep rooting species should be sown on deep soils to fully exploit the full water

Figure 1 Total annual dry matter yield (t DM/ha/yr) and annual water use (mm) from the nine datasets. See Table 1 for treatment details. Lines represent (a) the theoretical maximum water use efficiency of 44 kg DM/ha/mm, (b) a benchmark WUE of 20 kg DM/ha/mm proposed by Martin *et al*. (2006), and (c) 6.7 kg DM/ha/mm for a dryland cocksfoot monoculture (Mills 2007).

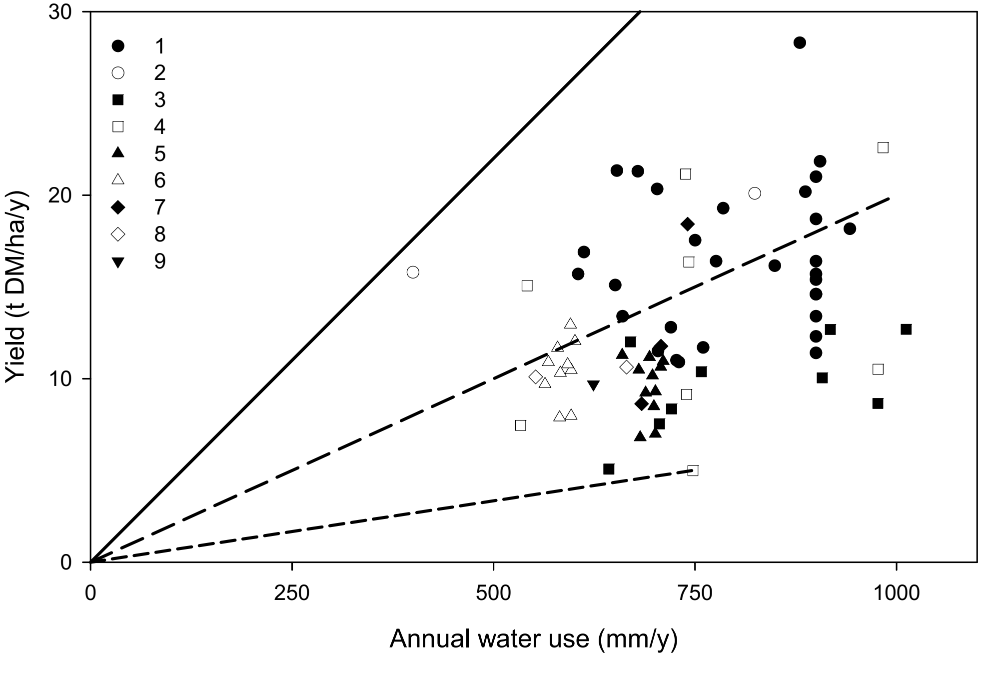


Figure 2 Water extraction (mm) from each 0.1 m soil layer from 0-2.3 m depth for lucerne (circles) and grass based pasture (triangles) on a deep Wakanui silt loam (solid symbols) or a Lismore (A) very stony loam and Lismore (B) stony loam (open symbols) measured in Datasets 2, 3, 8 and 9. See Table 1 for treatment details.

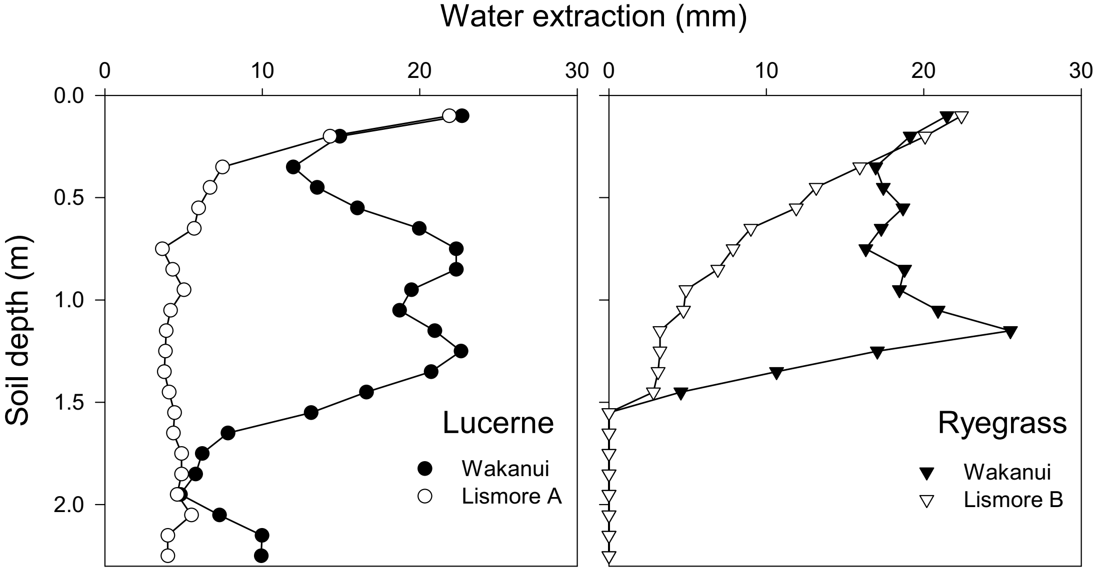


Figure 3 Accumulated DM yield (t DM/ha) and water use (mm) over 1 year of a dryland perennial ryegrass pasture at Ashley Dene, Canterbury (Dataset 9, Table 1). Dark grey bars represent rainfall, light grey lines differentiate periods with different WUE where (a) had a WUE of 22 kg DM/ha/mm (17/9/2002-23/1/2003), (b) was 3 kg DM/ha/mm (23/1-29/4/2003), (c) was 18 kg DM/ha/mm (29/4-12/6/2003) and (d) was 9 kg DM/ha/mm (13/6-16/9/2003).

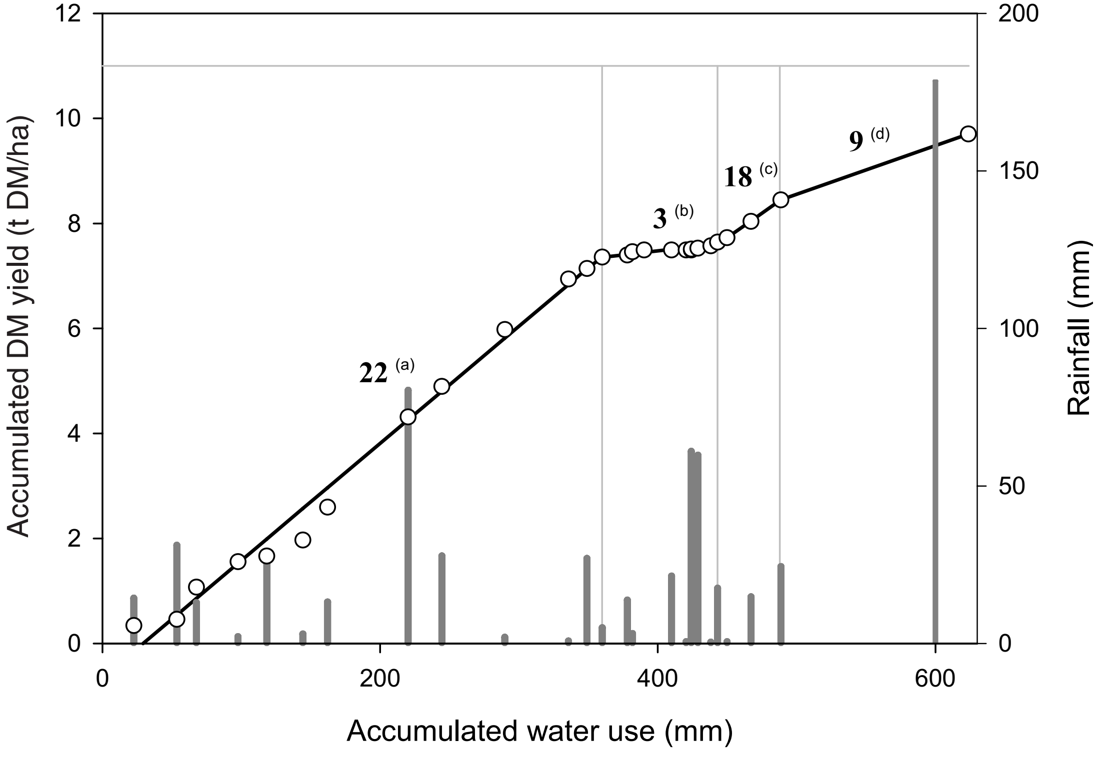
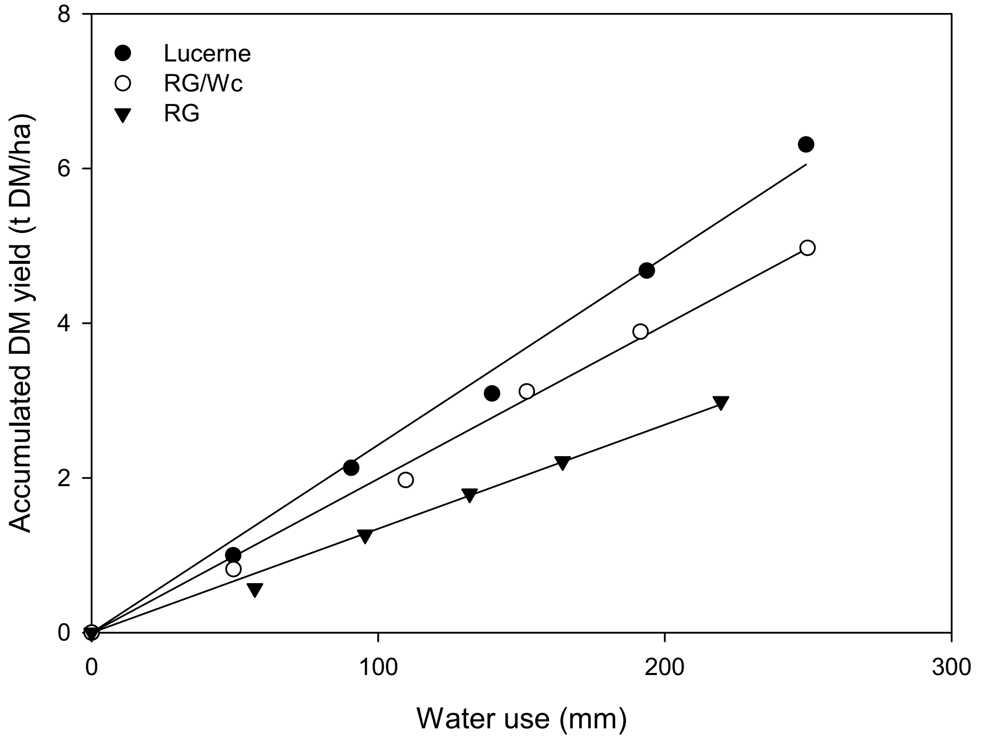


Table 2 Spring (Sept-Nov) WUE (kg DM/ha/mm) of 'Wana' cocksfoot (CF) fertilised with 300 kg N/ha (CF+N) or 0 kg N/ha (CF-N) from Dataset 4 and from 11 monocultures and pasture mixes over the same period from Dataset 5. See Table 1 for treatment details. SEM is the standard error of the mean of the linear regression, forced through the origin, fitted to the relationship between accumulated DM (kg/ha) yield and water use (mm). R^2 is the coefficient of determination.

Dataset	Pasture	WUE	SEM	R^2
4	CF+N	38	1.0	0.97
4	CF-N	17	0.6	0.96
5	Bal	40	1.6	0.96
5	Sub	32	1.4	0.97
5	Wc	33	1.0	0.98
5	Cc	30	1.0	0.97
5	RG	15	0.6	0.95
5	CF/Bal	34	0.9	0.98
5	CF/Sub	37	1.3	0.98
5	CF/Wc	30	0.7	0.99
5	RG/Wc	30	1.2	0.96
5	CF/Cc	23	0.7	0.97
5	RG/Cc	23	0.6	0.98

Figure 4 Spring dry matter yield (t/ha) and water use (mm) for lucerne (WUE = 24 kg DM/ha/mm), perennial ryegrass/white clover (RG/Wc, WUE = 20 kg DM/ha/mm) and perennial ryegrass (RG, WUE = 13 kg DM/ha/mm) pastures from Dataset 7 at Lincoln, Canterbury between 29/9-9/12/1993. See Table 1 for treatment details.



holding capacity of the soil.

Inability to utilise available moisture is most likely to occur in summer. Analysis of the seasonal pattern of the ryegrass/clover pasture at Ashley Dene (Dataset 9) highlighted the range of factors that affect WUE (Fig. 3). The WUE was ~22 kg DM/ha/mm with 360 mm used between 17/9/2002 and 23/1/2003. The seasonal WUE then decreased to just 3 kg DM/ha/mm through the driest months of February to April of 2003. During this period, 70 mm of rain fell but the pasture had dried off and the water was lost with little pasture recovery. This ineffective rainfall is a common occurrence in summer dry environments with water lost due to high soil evaporation. The combination of warm soil and low herbage cover causes rapid soil evaporation of the first 10-20 mm of any rainfall event (Jamieson *et al.* 1995). In practice, it is likely that summer rainfall is ineffective for a dried off pasture when the rainfall event is less than the calculated weekly evapotranspiration. In early April, 120 mm of rain restored soil moisture to near field capacity but it took another 3 weeks before the pasture regained full ground cover and WUE increased. For the May-June period, WUE was lower than in spring at 18 kg DM/ha/mm. After this, temperature began to limit pasture growth, and some of the 178 mm of winter rainfall was lost as drainage due to the low water holding capacity of the soil. Together this reduced the WUE to 9 kg DM/ha/mm.

WUE also differs among species. This can be demonstrated by a comparison of results from several datasets, particularly during the spring period (Sept-Nov) when the seasonal WUE of all species is highest due to the most favourable atmospheric conditions (Sinclair *et al*. 1984) and readily available soil moisture. Table 2 shows the range of WUE values calculated for spring from Datasets 4 and 5. In most cases the clover monocultures had a higher WUE (30-40 kg DM/ha/mm) than their respective binary mixes (23-37 kg DM/ha/mm) and the ryegrass monocultures had the lowest WUE of 15 kg DM/ha/mm. Similar results were obtained from Dataset 7 in which the spring WUE of a pure perennial ryegrass sward was 13 kg DM/ha/mm whereas the value for the perennial ryegrass pasture with white clover was 20 kg DM/ha/mm (Fig. 4). In the same experiment the highest WUE was for lucerne at 24 kg DM/ha/mm.

The higher WUE observed for legumes compared with grasses is likely to be caused by their higher herbage N content. This maximises photosynthetic efficiency per unit leaf area (Peri *et al.* 2002) and ensures higher rates of photosynthesis are obtained per unit of water used leading to higher dry matter production. In spring, the N fertilised cocksfoot monoculture in Dataset 4 had a WUE of 38 kg DM/ha/mm compared with 17 kg DM/ha/mm for the unfertilised pastures (Table 2). The N content of green herbage (averaged over three regrowth periods) was 4.2% (+N) and 2.9% (-N) or equivalent to 247 kg N/ha to produce 6.0 t DM/ha compared with 72 kg N/ha to produce 2.7 t DM/ha (Mills 2007). The difference highlights that N availability has a major influence on seasonal WUE. It is likely that the increased WUE ascribed to modern dairy farms (Martin *et al*. 2006) indirectly reflects their greater recent use of fertiliser N. Equally, pasture management that encourages clover content and thus N transfer within pastures is also likely to have a higher WUE.

Conclusions

The range of results summarised in this paper highlight several important principles for maximising WUE on farms. In dryland systems, high WUE in spring can be achieved through the use of legume monocultures, such as lucerne, or grazing management that encourages annual and perennial clover production in grass based pastures. The use of fertiliser N on grass dominant pastures will also increase their WUE if economically feasible. Importantly, matching deep tap rooted species, like lucerne, to deep soils will also maximise extraction of rainfall stored in the soil profile giving greater annual pasture production and WUE. In irrigated situations, management that allows soils to be close to their drained upper limit or field capacity going into winter are likely to experience consequent drainage losses.

ACKNOWLEDGEMENTS

Financial assistance for PhD scholarships was provided for H.E. Brown by FoRST Bright Futures and for A. Mills by Meat & Wool NZ, AGMARDT, the Cocksfoot Growers Association and Sinclair Cummings Trust.

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