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The Water Balance of Pastures in a South Australian Catchment with Sloping Texture-Contrast Soils

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Abstract

The water use of several pasture types was compared in a catchment in the Mount Lofty Ranges, South Australia. The study sites had sloping (less than 14%) texture-contrast soils. The aim was to delineate the water pathways (e.g. evapotranspiration, surface runoff, throughflow) in the catchment and to supply farmers with the best pasture option for minimising deep drainage.

Lucerne (*Medicago sativa* cv. Aquarius) produced more dry matter in summer and used more water than phalaris (*Phalaris aquatica* cv. Sirosa) on the mid- and upper slopes but was similar on the toe-slopes. The clay subsoils on the toe-slope were slightly saline, strongly sodic and sometimes affected by saline groundwaters in winter. After only one year's growth, the lucerne and phalaris pastures used more water than the existing cocksfoot (*Dactylis glomerata*) pasture on all parts of the slope. TOPOG-IRM modelling indicated that on all parts of the slope there was substantial deep drainage under the existing pasture (up to 29% of annual rainfall), with much-reduced deep drainage under phalaris and lucerne.

本文对比了几种牧草的水分利用壮况，以查明流域水分流失渠道(如蒸发蒸腾量，表面径流，壤中流等)，为当地农户找出最佳牧草种类，最大程度减少土壤水分深层渗漏。试验地点在南澳劳伏特山区，地面坡度<14%，土壤剖面质地不均，上层砂土或壤土，下层粘土。对比发现，首蓿在夏季比苡草生产更多的干物质，在坡面的中上部也消耗更多的水分，但在坡面下部两者耗水量接近。坡下部的土壤粘土层有轻微盐化，严重碱化，冬季有时因地下盐

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水位升高而受到影响。在仅仅生长一年以后，在坡地的各个部位，苜蓿和苡草都能比当地原有的鸭茅草利用更多的水分。TOPOG – IRM 模型显示，鸭茅草下的土壤底层水分渗漏严重（可高达年降雨量的 29%），而在苜蓿和苡草下面则大大减少了。

LAND degradation is widespread in the agricultural regions of Australia, affecting vast areas of potentially productive land. Most land degradation (e.g. dryland salinity, waterlogging and erosion) has been caused by the widespread clearance of perennial native vegetation and its replacement with mainly annual crops and pastures (e.g. Saunders and Hobbs 1993). This has led to a drastic change in the hydrology of agricultural landscapes. It is widely acknowledged that recharge under introduced annual crops and pastures is significantly greater than that which occurs under natural vegetation (e.g. Kennett-Smith et al. 1993).

Duplex soils, sands or loams over clays occupy a large percentage of southern Australian agricultural regions (Chittleborough 1992). Their chemical and physical properties vary along a toposequence from crest to flat (Tennant et al. 1992). Duplex soils are particularly susceptible to land degradation when cleared for agriculture. Degradation on duplex soils is exacerbated by the development of rapidly fluctuating perched watertables on slowly permeable subsoil horizons (Cox et al. 1994; Cox and McFarlane 1995). On some sloping duplex soils, significant quantities of water can travel as throughflow on top of the B horizon (Cox and Fleming 1997; Fleming and Cox 1998). This can increase the risk of waterlogging on low slopes. On ‘leaky’ duplex soils, groundwater recharge can mobilise stored salts and bring them into the root zone, particularly in the toe-slopes and flats (Cox et al. 1996; Fitzpatrick et al. 1997). The chemical and physical properties of these duplex soils may change over time (Fitzpatrick et al. 2000).

It is apparent then that catchment water balances need to change so that less deep drainage occurs (Gregory et al. 1992). One option for achieving this may be changed agronomic practices. Lucerne (*Medicago sativa* L.), phalaris (*Phalaris aquatica* L.), and cocksfoot (*Dactylis glomerata* L.) are commercially available pasture species. Previous studies of these pasture species on flat land have shown considerable variation between species in their growth and soil water use (e.g. Whitfield et al. 1992; Crawford and Macfarlane 1995; Lolicato 2000).

The aim of this study was to compare the water balance under lucerne with that under phalaris in three parts of the landscape. In addition, the pastures were compared with the existing (cocksfoot-based) pasture. Although farmers are encouraged to sow perennial pastures as a means of recharge reduction, no study has looked at the differences in their water use on sloping duplex soils.

Materials and Methods

Site location, climate and soils

The experimental site was located in the Keynes catchment in the Mount Lofty Ranges, South Australia. The climate is Mediterranean and the mean annual rainfall is 544 mm, more than 75% falling between April and October. The catchment soils are typical of many in the > 500 mm rainfall region of the Mount Lofty Ranges (Fritsch and Fitzpatrick 1994; Cox et al. 1996). Slopes average 14%. The Overview provides background information about the area and Figure 5 of the Overview shows its location.

Pits were excavated along five toposequences in the catchment and soils were classified according to both Soil Survey Staff (1996) and Isbell (1996) criteria. Chemical properties of the soil horizons were measured on selected samples using standard techniques (Rayment and Higginson 1992). Saturated hydraulic conductivities (K_s) of the A, E and B soil horizons were measured at 12 sites in each of the upper, mid- and toe-slopes of the catchment, using a disc permeameter (Perroux and White 1988). At the same locations, intact cores (0.047 m diameter and 0.05 m height) were collected for measurement of soil water characteristics[1] and bulk density.

Experimental design

There were three pasture types: lucerne-based, phalaris-based, and the existing pasture comprising cocksfoot, subterranean clover (*Trifolium subterraneum* L.) and annual grasses and weeds. Each plot was approximately 0.2 ha. Lucerne (*Medicago sativa* cv. Aquarius) and phalaris (*Phalaris aquatica* cv. Sirosa) plots were sown in the first year of the trial (1996) and replicated at each of the three levels of the landscape (that is, there were two plots of each crop at each of the upper, mid-, and toe-slopes). The existing pasture surrounded the lucerne and phalaris plots; detailed measurements were collected from one plot location at each landscape level. Physical barriers prevented run-on; overland flow and throughflow were measured using v-notch weirs and tipping buckets installed in drains (Cox and McFarlane 1995). Further details are in Cox and Pitman (2001).

Measurement of soil water stored in the profile

Soil water storage was monitored regularly (2–3 times a week in summer, weekly in winter), from 1996 to 1997 using a neutron moisture meter (NMM) (CPN Corporation, California, USA). Readings were taken at 0.1, 0.2, 0.35, 0.5, 0.7, 0.9, 1.1, 1.4 and 1.7 m. The neutron probe was calibrated from measuring the water content of soil cores (623 cm^3) collected at various periods of the year. Cores were dried at 105°C for 24 hours; gravimetric soil water content was then calculated and linear regressions ($r^2 > 0.8$) established for each soil horizon. Probe readings were taken at the same time as core sampling for each access tube. The bulk density of each sample (and of samples from the soil pits) was calculated from the known core volumes; their respective volumetric water contents were then derived.

Plant production and root distribution

On four occasions, pasture was harvested for the calculation of pasture dry matter availability. About 18 months after lucerne and phalaris establishment, 10 soil cores were taken from each of the three existing pasture plots and from one lucerne and one phalaris plot at each of the three toposequence positions. One core from each site (taken from approximately 1 m downslope of the NMM access tube) was sectioned to correspond with the neutron probe reading depth, sealed in a plastic bag and used for additional NMM calibration. A second core was placed on a core tray, which was sealed and labelled for detailed profile description. The remaining eight cores were cut into 0.2 m sections and placed in plastic bags that were sealed, labelled, and stored for root washing. All samples were stored at < 4°C prior to analysis.

Roots were washed using the hydropneumatic elutriation method described by Smucker et al. (1982); this method reportedly recovers 15–25% more root dry weight than careful handwashing techniques (Mackie-Dawson and Atkinson 1991). The technique requires two sieve sizes (0.5 mm and 1.0 mm) to retain the roots. Further soil pits were excavated to allow analysis of root growth and distribution, including a qualitative description of root growth and penetration down the profile.

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[1] Needed for the water balance modelling but not discussed in this paper.

Morphological measurements of length, area and root length density (RLD) were determined from scanned samples in the WinRHIZO™ package (Regent Instruments Inc., Quebec, Canada), using the method of Tennant (1975).

Hydrological modelling

Rainfall, solar radiation, wind speed, temperature and humidity were recorded hourly at an automatic weather station located in the catchment. TOPOG-IRM (a hydrological modelling package based on terrain analysis) (Dawes and Hatton 1993) simulations were run using the climatic, soil and vegetation data until soil water changes, overland flow and throughflow were correctly predicted. Actual evapotranspiration was derived from Penman–Monteith type equations (Monteith 1981) within TOPOG-IRM (Dawes and Hatton 1993). Deep drainage was determined by difference using the water balance equation for texture-contrast soils (Gregory et al. 1992).

Results

Soil types

From crest to flat, the soils were a sequence of Typic Palexeralfs to Aquic Palexeralfs to Natraqualfs; elsewhere the sequence was red and brown Chromosols to brown Sodosols to brown Dermosols. On the mid- and upper slopes, the topsoils were acidic (pH 6.2–6.7), nonsaline ($EC_{1:5}$ 0.01–0.06 dS/m)[2] and nonsodic (ESP < 5%).[3] The subsoils on the mid- and upper slopes had variable pH (6.5–7.6), were nonsaline ($EC_{1:5}$ 0.021–0.045 dS/m) and were usually nonsodic (ESP < 6%) except at depth (ESP was 10% at 1 m). On the toe-slopes, the topsoils were also acidic (pH 5.8–6.9) and nonsaline (0.015–0.045 dS/m) but were sometimes sodic (ESP 3–15%). The subsoils on the toe-slopes also had variable pH (6.6–7.8) and were often slightly saline ($EC_{1:5}$ <0.2 dS/m) and strongly sodic (< 21%).

Bulk density of the topsoil (0–0.4 m) was similar (1.5–1.7 g/cm^3) and not significantly different ($P < 0.05$) at all positions on the slope (Table 1). Bulk density of the subsoil was significantly ($P < 0.05$) higher on the toe-slope (< 2.0 g/cm^3 at 0.9 m) and lower on the upper slope (< 1.9 g/cm^3 at 1.50 m) than elsewhere. The change in the bulk density of the subsoil with depth was similar on the upper and middle slope but different on the toe-slope.

Table 2 shows the average K_s values. In general, K_s on the toe-slope was significantly ($P < 0.05$) lower than on the mid- and upper slopes in the A and B horizons (average 0.9 and 0.05 m/day, respectively) but was significantly ($P < 0.05$) higher in the E horizon (average 0.18 m/day).

Table 1. Bulk density of soil in a toposequence.

Depth interval (cm)	Mean bulk density (g/cm^3)[a]		
	Upper slope	Mid-slope	Toe-slope
0–20	1.503 (1.417–1.589)	1.570 (1.395–1.735)	1.490 (1.439–1.677)
20–40	1.738 (1.705–1.793)	1.717 (1.434–1.892)	1.627 (1.491–1.765)
40–60	1.659 (1.405–1.838)	1.796 (1.712–1.948)	1.823 (1.689–2.020)
60–80	1.631 (1.312–1.824)	1.741 (1.657–1.868)	1.973 (1.755–2.242)
80–100	1.665 (1.439–1.887)	1.825 (1.769–1.983)	2.030 (1.802–2.508)
100–120	1.820 (1.659–1.920)	1.925 (1.810–2.008)	2.012 (1.775–2.248)
120–140	1.856 (1.683–1.946)	1.818 (1.813–1.823)	1.976 (1.764–2.134)
140–160	1.894 (1.720–2.014)	1.892 (1.881–1.904)	1.843 (1.698–1.984)

[a] Figures in brackets indicate the range

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[2] $EC_{1:5}$ is the electrical conductivity; dS/m = deciSiemens per metre.

[3] ESP is exchangeable sodium percentage.

Rainfall

The annual rainfall was 14% below average in the first year of the trial (when the lucerne and phalaris were sown), close to the average in the second year of the trial and 26% below average in the final year (Table 3). The rainfall from April to October followed a similar pattern, with a 12% reduction in the first year, a slight increase (3%) in the second year and a substantial (40%) decrease in the final year.

Soil water

Figure 1 shows the change in soil water content (SWC) over two years below three pasture types on the upper slope of the catchment (the darker the shading, the higher the SWC). The SWC of the A horizon (approximately 0–0.35 m) followed a similar pattern under all treatments, responding rapidly to rainfall events. The type of overlying pasture did not significantly affect SWC over time ($P < 0.05$) (Fig. 2). During each winter, a perched watertable developed to some degree on all treatments within the clay subsoil (at approximately 0.5–0.6 m depth).

Table 2. Average measured saturated hydraulic conductivity (*Ks*) used in the modelling of deep drainage (m/day).

Horizon	Toe-slope	Mid-slope	Upper slope
A	0.93	1.97	2.06
E	0.18	0.14	0.11
B	0.05	0.08	0.07

In the soil profile below 0.35 m, changes in SWC were more gradual, and less influenced by the weather conditions. Under cocksfoot-based pasture, SWC at 0.35–1.7 m increased over the period of study at all slope positions (Table 4), based on end water content minus the initial water content (the amount of water used by the plant or drained). Under phalaris, SWC decreased at all slope positions, with the greatest water uptake in the upper slope position, followed by the mid- and toe-slopes. Under lucerne too, SWC decreased most in the upper slope region, followed by the mid- and toe-slopes. This trend was confirmed by solving the water balance to 1.8 m depth (Table 5). Lucerne on the mid- and upper slope and phalaris on the upper slope dried the soil profile over a two-year period. Over the same period, the SWC increased in all landscape positions under the cocksfoot. Thus, the greatest deep drainage occurred under cocksfoot; there was substantially less deep drainage under phalaris, and there was an uptake of soil water from below 1.8 m by the lucerne in the upper and mid-slope positions. In the toe-slope position, deep drainage was similar under lucerne and phalaris (Table 5).

Dry matter production and root analysis

Lucerne-based pasture was significantly ($P < 0.05$) more productive than the phalaris-based or cocksfoot-based pasture in the upper and mid-slope positions. It was also more productive on the toe-slopes but not to the same degree. Toposequence position in this regard was highly significant ($P < 0.01$). Table 6 shows the summer

Table 3. Monthly rainfall at Keyneton township and seasonal rainfall for the Keynes catchment (mm).

	J	F	M	A	M	J	J	A	S	O	N	D	Total	Apr–Oct total
Average[a]	18	23	20	35	62	64	80	76	63	49	29	25	544	429
1996	48	15	13	37	37	67	121	9	48	58	9	5	467	377
1997	47	8	30	10	10	132	84	80	73	53	15	7	549	442
1998	10	61	2	7	56	24	12	85	73	0	35	39	404	257

[a] 78-year average data from Bureau of Meteorology

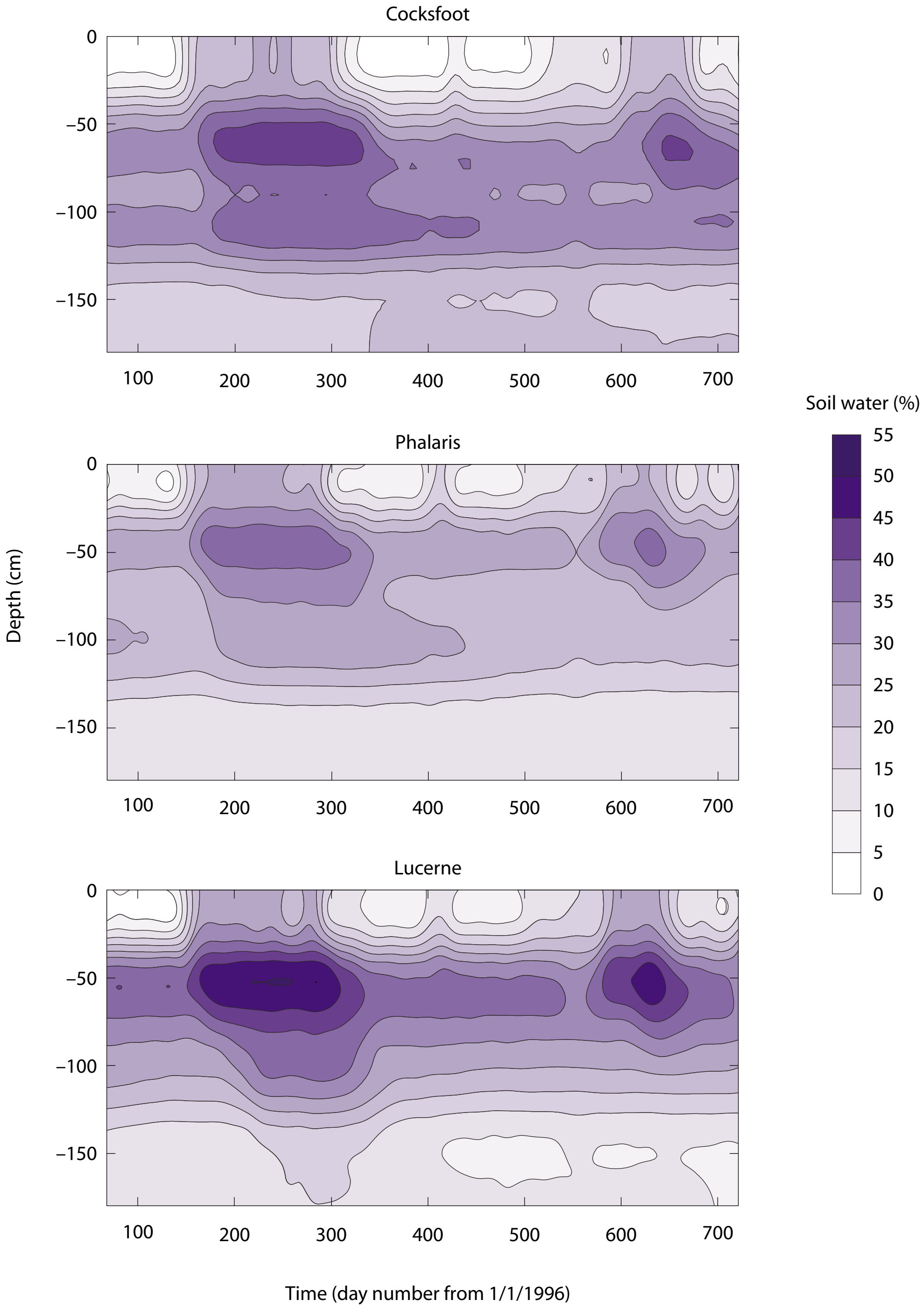

Figure 1. An example of soil water content (volume %) over a two-year period, under three pasture treatments on the upper slope, showing the development of perched watertables within the B horizon (average 35–75 cm).

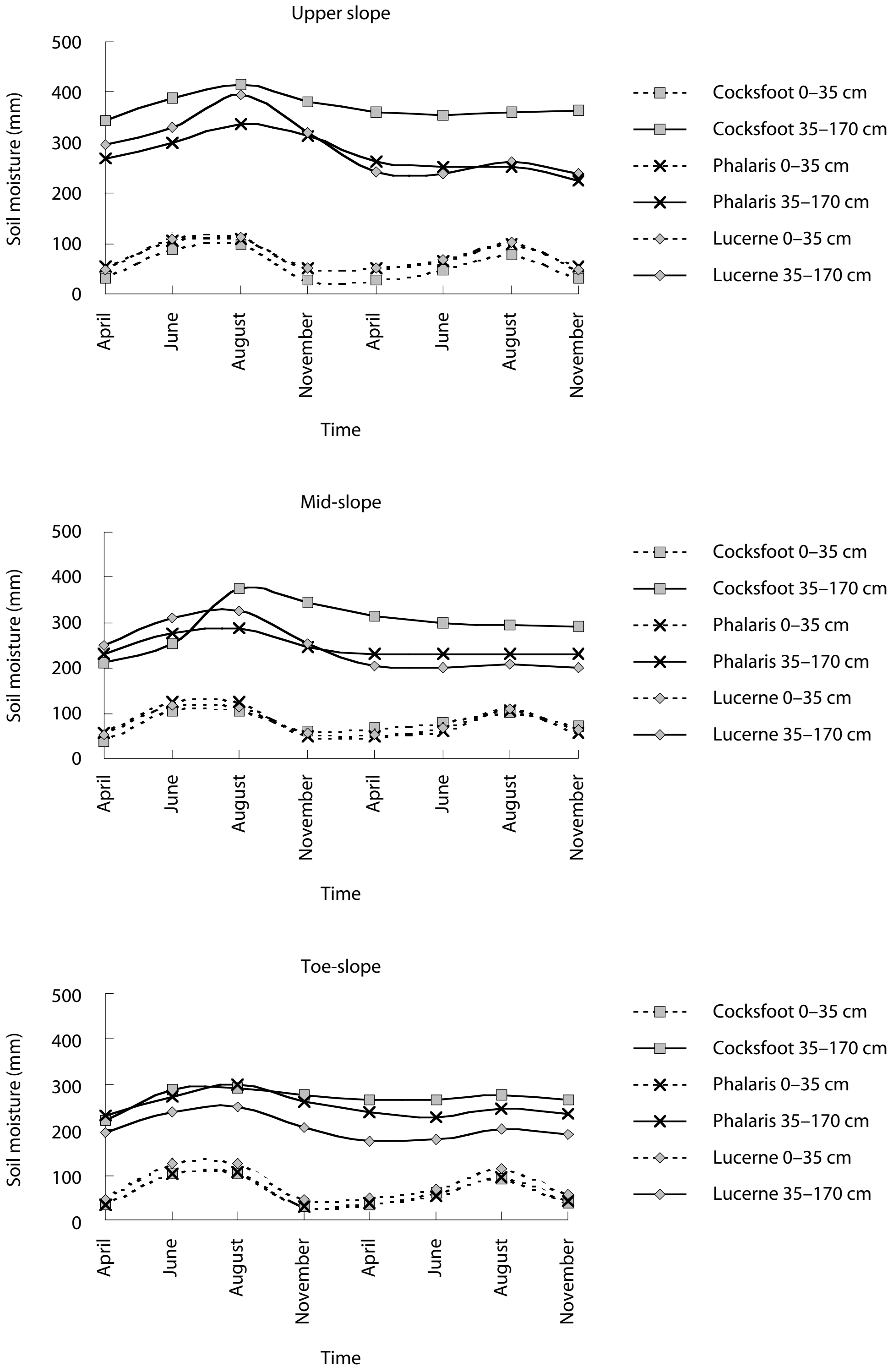

Figure 2. Average monthly soil water content (mm), from April 1997 to December 1998, under pasture.

growth advantage of the lucerne compared with the cocksfoot and phalaris-based pastures (the lucerne production in April 1997 was much higher than the other two pastures on all slope positions).

For all three pasture treatments, examination of roots in soil pits confirmed that most roots were in the top 0.3 m of the soil profile (Table 7); this is consistent with other studies (Evans 1978; Gregory 1998). Visual inspections revealed a dense mat of roots in the top 0.1 m under all treatments, but surface samples (0–0.1 m) were not analysed because it would have taken too long to prepare samples of such a large amount of extraneous organic material.

Table 4. Average change (initial–final) soil water content (mm), 35–170 cm soil depth, over a two-year period (1996 to 1997).

Pasture	Upper slope	Mid-slope	Toe-slope
Cocksfoot	14.9	81.8	48.9
Phalaris	58.0	11.2	1.8
Lucerne	74.8	57.8	10.5

Figure 3 shows mean data (from eight cores per treatment per slope position) for the scanned root samples. The cocksfoot samples were taken from the pre-existing pasture; the other samples were taken about 18 months after pasture establishment. Cores were taken to the maximum depth possible given soil conditions and the limitations of the drilling rig; most samples were no deeper than 1.4 m. As indicated in Figure 3, most of the cocksfoot and phalaris root material below approximately 0.9 m was dead.

Discussion

Soil water, deep drainage and water use

The soil water content of the A horizon was similar under all pasture types. In the autumn/winter of the first year of the trial, a perched watertable developed within the B horizon under all pastures and at all slope positions. By the autumn of the second year, the lucerne, and to a slightly lesser degree the phalaris, had begun to dry the profile below 0.35 m; this, combined with below average rainfall, reduced the development and duration of perching. Under the cocksfoot, the soil profile below 0.35 m had remained at a higher SWC; perching developed earlier and lasted longer than for the other two pasture treatments.

Table 5. Average water balance for different pasture/slope treatments (mm), 0–180 cm soil depth.

	Cocksfoot			Phalaris			Lucerne		
	Upper slope	Mid-slope	Toe-slope	Upper slope	Mid-slope	Toe-slope	Upper slope	Mid-slope	Toe-slope
Rainfall[a]	897	897	897	897	897	897	897	897	897
Evapotranspiration[b]	752	755	826	806	785	872	878	877	870
Surface runoff[a]	2	2	18	1	2	40	1	43	1
Throughflow[a]	8	18	74	8	44	14	13	13	29
Change in water storage[c]	–59	–141	–102	19	–32	–50	44	26	–49
Deep drainage[d]	194	263	81	63	98	21	–39	–62	46

[a] Actual measurements
[b] Actual evapotranspiration from TOPOG-IRM
[c] Initial–final soil water content
[d] Deep drainage is by difference in the water balance equation

Predicted deep drainage losses under cocksfoot were substantial over the two-year period, particularly in the upper and mid-slope positions. There was less drainage at the toe-slope position, because 73.5 mm of infiltration was removed via throughflow. Generally, throughflow increased downslope due to the increase in bulk density, and consequent lower porosities, of the sodic B horizon.

Deep drainage under the cocksfoot pastures ranged from 9% to 29% of annual rainfall over the two years. Under the phalaris treatments, deep drainage ranged from 21 to 98 mm, or 2–11% of the total rainfall for the period.

Phalaris persisted longer into summer than cocksfoot, broke dormancy earlier, had

Table 6. Mean dry matter production (kg/ha) of lucerne, phalaris and cocksfoot-based pastures, at three toposequence positions, over four time periods.

Slope	August 1996	October 1996	April 1997	October 1997	Total
Lucerne sites					
Upper	1211.6	2851.5	2393.9	2860.3	9317.3
Mid	1123.9	2954.2	1518.9	2461.1	8058.1
Toe	796.5	1871.2	1229.4	1796.7	5693.8
Phalaris sites					
Upper	1033.5	2732.4	936.1	2440.5	7142.5
Mid	902.2	2623.6	888.9	1491.4	5906.1
Toe	938.2	2618.4	905.0	1764.8	6226.4
Cocksfoot sites					
Upper	941.4	2904.6	552.1	1796.1	6194.2
Mid	902.8	2295.0	599.2	1667.1	5464.1
Toe	997.4	2098.6	767.9	1637.7	5501.6

Table 7. Root length densities at discrete depth intervals for the three pasture species tested.

	Root length density (cm/cm^3)		
Depth interval (cm)	Cocksfoot	Phalaris	Lucerne
10–30	3.7	6.0	6.5
30–50	0.9	1.8	1.9
50–70	0.5	0.8	0.7
70–90	0.2	0.4	0.5
90–110	0.2[a]	0.3[a]	0.3
110–130	0.1[a]	0.2[a]	0.3

[a] The bulk of root material in the cocksfoot and phalaris samples below 90 cm was dead

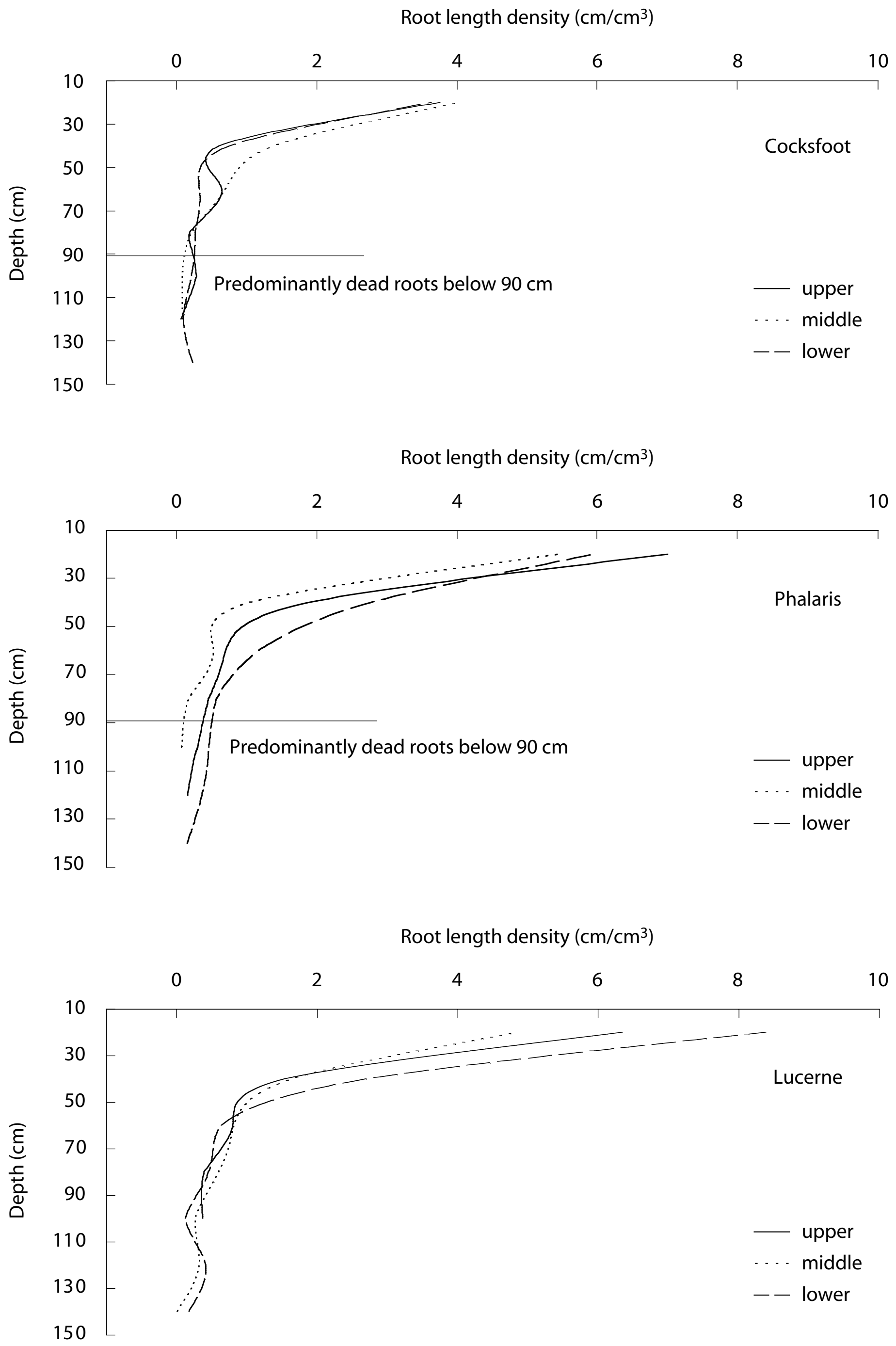

Figure 3. Root length density emphasising toposequence effects for cocksfoot, phalaris and lucerne.

proportionally more groundcover, and produced between 0.5 and 1.0 tonnes/ha more dry matter at each slope position. This additional growth resulted in increased evapotranspiration. These factors, and the substantially smaller increases in SWC under phalaris than under cocksfoot, suggest that farmers should be encouraged to sow phalaris rather than cocksfoot.

Modelling showed that under lucerne deep drainage occurred only on the toe-slope. At this point on the toposequence, 46 mm (5% of the total rainfall) passed below the 1.8 m profile boundary; groundwaters were shallow, so it probably contributed to recharge. In both the upper and mid-slope positions, soil water (44 and 26 mm respectively) was depleted from below 1.8 m by the lucerne. Numerous other studies, at smaller scale, support the ability of lucerne to extend its roots to a considerable depth, extract soil water from deep within the profile and reduce deep drainage. This study demonstrated that lucerne significantly reduces deep drainage on duplex soils at a small subcatchment scale, particularly at the upper and mid-slope positions. The main advantage of lucerne over the other pasture species tested appears to be the ability to extend roots into the subsoil and extract soil water stored deep in the profile, which would otherwise contribute to deep drainage. Lolicato (2000) reached a similar conclusion in his comparison of lucerne with cocksfoot, phalaris and birdsfoot trefoil (*Lotus corniculatus*). At the toe-slope position, where there was poor drainage and increased salinity, lucerne and phalaris both performed similarly, allowing deep drainage of 27–29 mm, in comparison to 63 mm at that position under cocksfoot.

Dry matter production and root analysis

Lucerne produced more dry matter over two years than the phalaris or cocksfoot in the upper and mid-slope positions. This was largely due to the summer dominant growth of lucerne. Phalaris and cocksfoot generally showed similar dry matter production, although phalaris production was slightly higher than that of cocksfoot over summer. Lucerne production was consistently lower than phalaris and cocksfoot on the toe-slopes where soils were slightly saline.

The decline in root material below 0.3 m in the catchment was quite marked for all species. Ridley and Simpson (1994) reported a study on a duplex red soil with a similar A/B horizon at approximately 0.3 m; they found a more gradual decline, with substantial root length density (RLD) to 0.5 m (approximately two-thirds of that in the 0.1–0.3 m interval). The Keynes catchment data suggested that a restrictive A/B horizon may encourage root proliferation in the surface soil.

Visual inspection of soil pits indicated distinct differences in rooting depth between species: cocksfoot roots were observed to 1.2 m, phalaris to approximately 1.5 m and lucerne to more than 2.0 m. The cocksfoot had been established for many years, so had probably established a maximum rooting depth for that environment. Soil pits dug some 18 months after the establishment of the lucerne and phalaris pastures showed that root extension to 2.0 m had already occurred. Subsequent pits did not indicate that phalaris was increasing its penetration to any extent. The lucerne root system could not be excavated to the full extent as its taproots followed cracks into the underlying sandstone. Both the phalaris and the lucerne roots had taken advantage of macropores, cracks and other faults to extend into lower depths. There was little evidence of roots elsewhere in the soil matrix at depth.

Figure 3 shows root length for each toposequence. The relatively low RLD of cocksfoot in the 0.1–0.3 m range is obvious. In the 0.3–0.7 m section of the soil profile, cocksfoot RLD is 0.25–0.5 cm/cm^3, whereas phalaris and lucerne are closer to 0.5–1.0 cm/cm^3. Phalaris and lucerne have more roots in the 0.1–0.3 m region; phalaris appears to show differences related to toposequence position, with a higher RLD below 0.3 m, in both the upper and toe-slope positions. This is consistent with pasture growth trends for phalaris, with lower pasture cuts on the mid-slope. Lucerne RLD seems consistent below 0.5 m, at all toposequence positions; its main advantage over the other two pastures is that substantial live roots extend down the profile. At depth, many of these roots were still less than 1 mm in diameter compared to the fine, hair-like roots of both cocksfoot and phalaris. Decreases in SWC under the three pasture types are consistent with the densities and morphology of their root systems.

Conclusions

The results of this study show that both lucerne and phalaris will produce a higher amount of dry matter and use more water resulting in less deep drainage than the cocksfoot-based pastures that farmers are currently sowing. Lucerne is the best choice on mid- and upper slopes; phalaris is best for low slopes, where soil salinity and sodicity reduce the performance of lucerne.

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