CSIRO PUBLISHING
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Impact of Tasmanian blue gum belts and kikuyu-based pasture on sheep production and groundwater recharge in south-western Western Australia

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Abstract. The effect of Tasmanian blue gum (*Eucalyptus globulus*) belts and kikuyu (*Pennisetum clandestinum*) grass on livestock production and groundwater recharge was studied in the high rainfall zone (>600 mm/year) of south-western Western Australia from 1998 to 2001. The objective was to identify optimum combinations of tree belts and pasture for sustainable livestock production and the prevention of secondary salinisation. Treatments were annual pasture, in competition with trees at different orientations (east, west and south), kikuyu pasture in competition with trees at one orientation (west), compared with pasture in the absence of tree competition. Plots had 0, 20 or 36% of their area within 10 m of the tree belt where tree–pasture competition would be expected. Plots (0.48 ha) were stocked with Merino wether hoggets at 12 DSE/ha on annual pastures and 14 DSE/ha on kikuyu pastures. Additional sheep were placed on plots in spring and the annual pasture was destocked in autumn.

Within the growing season, herbage mass was similar across both control treatments as a result of varying stock numbers. However, in summer and autumn the kikuyu control contained between 350 and 4900 kg DM/ha more herbage than the corresponding annual pasture. While both pastures accumulated similar amounts of herbage in 1998 and 2000, kikuyu accumulated more in 1999 (11 900 *v.* 9800 kg DM/ha) as a result of summer rain. Competition from tree belts significantly reduced adjacent annual pasture herbage accumulation (16% average reduction), although there was no difference among the levels of competition. Trees did not significantly affect adjacent kikuyu pasture herbage accumulation.

Both carrying capacity and clean wool production per hectare were significantly higher on kikuyu pasture in 1999 and 2000. Tree competition also significantly reduced the carrying capacity of neighbouring annual and kikuyu pasture by an average of 10%. Clean wool production per hectare was significantly lower on annual pasture in combination with trees (11% reduction on average), but there was less effect of competition on kikuyu pasture.

The kikuyu pasture used 115, 57 and 132 mm more water than the annual pasture in 1999, 2000 and 2001, respectively. The soil water deficit beneath the trees exceeded that below both control pastures by between 297 and 442 mm.

Although the addition of tree belts to annual pasture provided substantial reductions in groundwater recharge, producers would also have to accept losses in livestock production. While kikuyu alone provided significant increases in livestock production and substantial reductions in groundwater recharge, the best compromise was kikuyu in combination with tree belts.

Introduction

The high rainfall zone (HRZ, >600 mm/year) of south-western Western Australia is characterised by a Mediterranean climate, infertile sandy soils and annual pastures that are a combination of legumes, annual grasses and broadleaf weeds. These pastures regenerate from a seed bank at the break of season in autumn–winter, providing high quality green feed for livestock until late spring. In summer and early autumn, livestock rely on dry pasture residues and conserved feed such as hay, silage or grain. The introduction of perennials into these pastures can lengthen the growing season, which will increase carrying capacity and reduce the need for conserved feed.

In addition, perennials can also assist in reducing the incidence of secondary salinisation. Salt originating from the ocean has been deposited into the soil profile by rain and dust over many thousands of years (Allison *et al.* 1990; George *et al.* 1997). This salt, along with the groundwater, is now rising to the soil surface as a consequence of the replacement of the original deep-rooted native vegetation with shallow-rooted crops and pasture (George *et al.* 1997). If current agricultural practices continue, potentially

 10.1071/EA02226 0816-1089/03/070755

6.1 million hectares of land in south-western Western Australia will be affected by secondary salinisation (Ferdowsian *et al.* 1996).

One method for reducing the threat of salinity is to incorporate deep-rooted perennial plants into agricultural systems that mimic the original native vegetation (Hatton and Nulsen 1999). Previously studied solutions include lucerne (*Medicago sativa* L., Angus *et al.* 2001; McCallum *et al.* 2001; Ridley *et al.* 2001; Ward *et al.* 2001, 2002) and phalaris (*Phalaris aquatica* L., Scott and Sudmeyer 1993; Ridley *et al.* 1997; Dolling 2001). While lucerne has demonstrated an ability to use more water and reduce groundwater recharge (Angus *et al.* 2001; McCallum *et al.* 2001; Ridley *et al.* 2001; Ward *et al.* 2001), both species have limited application in the HRZ of south-western Western Australia because they are poorly suited to the acid soils that are common in the region. Kikuyu (*Pennisetum clandestinum* Hochst. Ex Chiov.) is a tropical perennial grass that is both productive (Sanford *et al.* 1997) and persistent in this region on acid soils, although it is confined to areas that do not experience sustained winter frosts (Mears 1970). Kikuyu also possesses a deep root system (Ferdowsian and Greenham 1992) and green leaves through summer and autumn, which enable it to fill the 'autumn feed gap' (Sanford *et al.* 1997) and use more water (McDowall *et al.* 2003).

Unfortunately, perennial pastures alone may not be able to reduce drainage sufficiently in the HRZ (Webb 1993; Heislers and Reid 1996; Bond *et al.* 1997; Ridley *et al.* 1997; Walker *et al.* 1999). To restore the hydrological balance may require the introduction of trees into farming systems (Bond *et al.* 1997; Walker *et al.* 1999). In the HRZ of south-western Western Australia, Tasmanian blue gums (*Eucalyptus globulus* Labill.) are grown for woodchips, with plantations currently occupying more than 130000 hectares. Blue gums integrated with pasture in an alley farming system provide an opportunity to reduce groundwater recharge to acceptable limits, while continuing livestock production and supplementing farm income (Eastham *et al.* 1994; Lefroy and Scott 1994). However, if trees are planted over a large area of the landscape to control groundwater recharge, there will be a corresponding increase in the tree–pasture interface and resource competition (Stirzaker *et al.* 1999, 2002; Lefroy *et al.* 2001; Knight *et al.* 2002).

The aims of this study were to: (i) determine whether the inclusion of kikuyu grass with subterranean clover (*Trifolium subterraneum* L.) can provide useful increases in livestock production and reductions in groundwater recharge compared with a traditional annual pasture; (ii) quantify the competition effects between Tasmanian blue gum belts and annual and perennial pastures; and (iii) determine the impact of a blue gum alley-farming system on sheep production and groundwater recharge in the HRZ of south-western Western Australia.

Materials and methods

Site details

The study was conducted near Albany (35°54′S, 117°49′E), Western Australia, between 1998 and 2001. The soil type was a petroferric brown sodosol (Isbell 1996). The watertable was located 20 m below the surface and was fresh (10 mS/m). Annual pasture treatments were established on a long-term subterranean clover-based pasture and the perennial pasture (kikuyu grass) treatments located on a neighbouring paddock sown by the farmer in 1995. At the start of the experiment in April 1998, the annual pasture consisted of subterranean clover (48%), erodium [*Erodium botrys* (Cav.) Bertiol.; 38%], dock (*Rumex pulcher* L.; 6%), capeweed [*Arctotheca calendula* (L.); 5%], and winter grass (*Poa annua* L.; 3%), together with small amounts of annual ryegrass (*Lolium rigidum* Gaudin), barley grass (*Hordeum leporinum* Link), brome grass (*Bromus diandrus* Roth), chickweed (*Cerastium glomeratum* Thuill), crassula (*Crassula decumben* Thunb.), flatweed (*Hypochoeris glabra* L.), serradella (*Ornithopus* spp.), silver grass (*Vulpia myuros* L.C.C.Gmel.) and sorrel (*Acetocella vulgaris* Fourr). The perennial pasture consisted of kikuyu (cv. Whittet; 83%), subterranean clover (11%), chickweed (4%) and small amounts of annual ryegrass, barley grass, capeweed, erodium and winter grass. The Tasmanian blue gum belts adjoining the annual pasture treatments were planted north–south (Fig. 1) in 1993 and those alongside the kikuyu pasture in 1992, following ripping of the cemented laterite to a depth of about 1 m. Trees were planted at a density of 1250 stems/ha, in 11 rows, 4 m apart, trees 2 m apart in the rows. The trees had an average diameter at breast height (DBH) of 0.15 m, height of 13.4 m and wood volume of 98 m^3/ha in 1998 and average DBH of 0.17 m, height of 14.7 m and wood volume of 136 m^3/ha in 2000. For further information on soil characteristics and climate measurements refer to Andrew and Lodge (2003).

Experimental layout and treatments

Treatments and plots are shown in Figure 1 and Table 1. All plots were 0.48 ha in size. There was insufficient tree–pasture interface at the site to replicate all treatments, and details of replication are shown in Table 1. Previous work by Albertson *et al.* (2000) showed that competition between Tasmanian blue gums (up to age of 10 years) and annual pasture for water and nutrients was primarily confined to a zone 10 m from the tree–pasture interface. Treatments in the present study were designed to allow for this, with 0, 20 and 36% of plot area within this competition zone. Plots in competition with trees were placed along the tree belts, either side of the annual pasture facing east, west and south, and on the west-facing belt in the kikuyu pasture (Fig. 1). Control plots were placed in the centre of each respective pasture 110–160 m from the tree belts, depending on location in the annual pasture, and 210 m in the kikuyu pasture.

Pasture management

Both annual- and perennial-based pastures were topdressed with 140 kg superphosphate/ha [(9.1% phosphorus (P), 11.5% sulfur (S)] in autumn each year and sprayed for red-legged earth mite on the 11 May, 24 June and 14 October 1998 using dimethoate (400 g a.i./L) at 100 mL/ha. Pastures were sprayed again on the 13 October 1999 and 11 October 2000 using omethoate (290 g a.i./L) at 100 mL/ha.

In winter 1998, erodium and capeweed began to dominate the annual pasture treatment. To prevent a massive seed set, plots were 'spray-grazed' on 31 August with MCPA amine (500 g/L) at 1 L/ha. Extra sheep were placed on all treatments, except for the south-facing plot, resulting in stocking rates of 19–63 sheep/ha, from 2 to 17 September, depending on the herbage mass.

Between 13 and 20 May 1999, all treatments were sown to subterranean clover (cv. Trikkala, cv. Karridale and cv. Esperance mixed at 40, 40 and 20%, respectively) because of the low clover seed bank in the kikuyu pasture (29 kg/ha). Plots 6, 7, 8, 13, 14, 15, 16, 17,

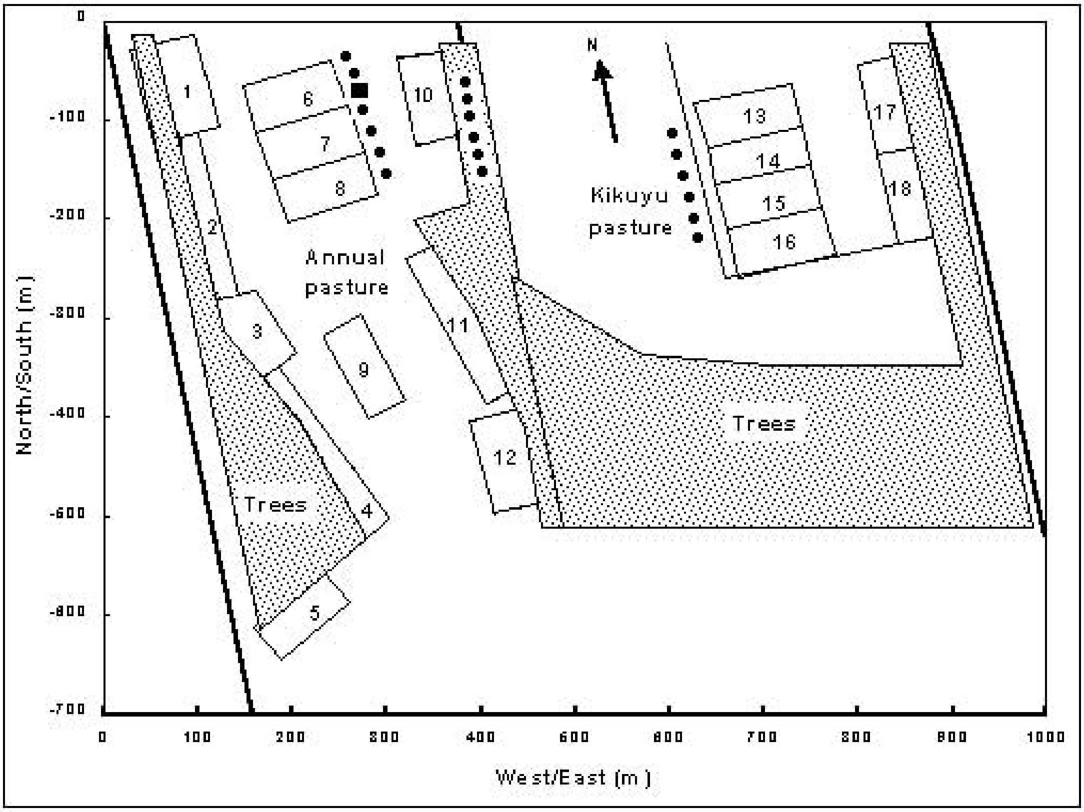

Figure 1. Layout of tree–pasture experiment at Albany, Western Australia. Plots, weather station (■) and neutron moisture meter access tubes (●) are indicated. See Table 1 for key to plot numbers.

18 were sown at 200 kg/ha and plots 1, 2, 3, 4, 5, 9, 10, 11, 12 at 100 kg/ha (refer to Table 1 for treatment), based on the size of the original clover seed bank.

The aim of grazing management was to prevent the annual and kikuyu treatments exceeding herbage masses of 3000 kg DM/ha and 4000 kg DM/ha, respectively, by adjusting stocking rate in winter and spring. The intention was to minimise differences in leaf area that could result in differences in herbage accumulation rates independent of tree competition.

Livestock management

The first draft of Merino wether hoggets was introduced to the experiment in April 1998. Sheep grazing the annual pasture were finally removed in January 2001 and those grazing kikuyu pasture in October 2001. New drafts were introduced in early summer 1998–99 and 1999–2000 from hoggets purchased by the host farmer. The base stocking rates for sheep grazing annual and kikuyu pastures were 12 and 14 sheep/ha, respectively. Additional sheep were placed on plots in an attempt to prevent herbage mass exceeding 3000–4000 kg DM/ha. Stock were removed from the annual pasture treatments in

Table 1. Details of treatments, plots and sampling at the experimental site, Albany, Western Australia

See Figure 1 for location of plots

Treatment	Pasture base	Orientation (facing)	Treatment code	Plot no.	Number of sampling units per plot
Control, no competition	Annual	—	ANO	6, 7, 8, 9	4
with trees	Kikuyu	—	KNO	13, 15[A]	4
20% of pasture in	Annual	West	A20W	10, 12	16
competition with tree belt	Kikuyu	West	K20W	17, 18	16
	Annual	East	A20E	1, 3	16
	Annual	South	A20S	5	16
36% of pasture in competition	Annual	West	A36W	11	12
with tree belt	Annual	East	A36E	2, 4	12

[A]Includes 14, 16 in 1998.

summer–autumn when dry herbage mass reached 800–1000 kg DM/ha, to prevent soil erosion. Sheep were removed from plots for shearing in October each year and returned 3 days later.

Internal parasites were a problem in the experiment, which became apparent by the end of 1998. Following identification and control of worms in the 1998 draft, slow-release Ivomectin capsules were used in the 1999 draft. Hoggets did not respond and were found to be carrying Ivomectin-resistant worms. Subsequently, regular sampling for worm burdens and varied anthelmintic worm treatments were implemented.

A supplement consisting of oats and lupins in a 2 : 1 ratio was fed when pasture quality and quantity declined and sheep lost liveweight at >100 g/day, with the quantities fed being based on the rate of weight loss.

Measurements

Climate. Rainfall and air temperature were measured alongside the control plot about 100 m from the tree belt, on the eastern side of the annual pasture paddock (Fig. 1), using the equipment described by Andrew and Lodge (2003).

Pastures. For pasture measurements, plots were divided into sampling units. The size of each unit was determined by dividing the boundary of each plot, alongside the tree belt, into 4 and then the width of the plot into 0–10 m, 10–20 m, 20–30 m and 30–50 m distances from the tree–pasture interface. Control plots were divided into sampling units based on one-quarter of the total plot area. The number of sampling units per plot is shown in Table 1.

Pasture species composition, percentage green and total herbage mass were estimated every 4 weeks throughout the experiment using BOTANAL procedures (Andrew and Lodge 2003). For each sampling unit, 5 estimates were taken in plots alongside the tree belt and 10 in the control plots, resulting in between 40 and 80 estimates per plot. Herbage accumulation was estimated by measuring herbage mass accumulation in 1 m^2 exclusion cages. Herbage mass was determined using the calibrated visual assessment technique of Campbell and Arnold (1973). One exclusion cage was placed in each sampling unit in plots adjoining trees and 3 exclusion cages were evenly spaced in each sampling unit in control plots. Measurements were taken every 3–4 weeks, depending on herbage accumulation rate. At each sampling, 15–20 calibration quadrats (0.1 m^2) were cut to ground level with a scalpel, to relate visual estimates to actual herbage mass. Annual herbage accumulation was determined by totalling growth for the calendar year.

Animals. Liveweight and wool production were measured according to the SGS protocols (Lodge 1998). Clean wool production (kg/ha) was calculated using the following equation:

$$CW = GF \times CWY \times P \times (SGD/D),$$

where CW is clean wool (kg/ha), GF is greasy fleece weight (kg/head), CWY is clean wool yield (%), P is the proportion of fleece grown on plot calculated by dividing days spent on plot by the number of days taken to grow fleece, SGD is cumulative sheep grazing days for the period on the plot while growing the fleece and D is the number of days sheep grazed the plot during the period taken to grow the fleece.

Average liveweight per hectare was calculated using only core sheep that remained on the plots from their initial allocation until replacement, the only exception being the removal of core sheep from annual pasture treatments during autumn each year. Core sheep numbered 6 per plot on the annual pasture treatments and 7 per plot on the kikuyu treatments.

Soil water content. Six neutron moisture meter (NMM) access tubes were installed in November 1998 to a depth of 6 m beneath the trees and the annual and kikuyu pasture at the locations described in Figure 1. Soil water content was measured at a depth of 20 cm, then at 20-cm intervals to 400, 450 and 500 cm each month using a Campbell Pacific Nuclear Corporation Hydroprobe Moisture Depth Gauge Model 503 DR. For further detail, including calibration, refer to Andrew and Lodge (2003). Soil water deficits were calculated as described by White *et al.* (2003).

Statistical analyses

Annual herbage accumulation and clean wool production data were analysed using a linear mixed model that included fixed effects of year, treatment and year × treatment (Payne 2002). Treatment effects were subdivided into a contrast between annual pasture and kikuyu plots, and comparisons of tree–pasture combinations within annual and kikuyu pasture treatments. Several different variance–covariance structures for the between-plot variance were fitted to the data, and the simplest model which did not significantly increase model deviance from the minimum deviance was chosen to estimate treatment means and standard errors.

Herbage mass and cumulative sheep grazing days were transformed (square-root scale) to stabilise variance and then analysed using a linear mixed model with autoregressive correlation between sampling dates (Payne 2002). The fixed-effects model was the same as that described for annual herbage accumulation and wool data. Liveweight data were not analysed since treatment effects were confounded by changes in stocking rate.

Results

Seasonal conditions

The monthly temperature and rainfall patterns spanning the 4 years of the experiment are shown in Figure 2*a* and *b*. Annual rainfall was 705, 706, 642 and 745 mm for 1998, 1999, 2000 and 2001, respectively. All years were below the long-term average of 810 mm, but this is not unusual since annual rainfall has been declining on the south coast of Western Australia. Typically, opening rains occur in April and, on this basis, there was an early break (March) to the season in 1998, 2000 and 2001 and a late break (May) in 1999. Monthly rainfall was adequate to support pastures from March to November in 1998 and from May to November in 1999. After the early break in 2000, rainfall for every month except July was well below average (Fig. 2*b*). As a consequence of the dry spring, herbage accumulation was limited by moisture in this year. Summer rain was recorded in 1998–99, 1999–2000 and 2001–02 (Fig. 2*b*).

Botanical composition

The influence of tree competition on botanical competition was minor and confined to the zone within 10 m of the tree–pasture interface. For this reason, only the botanical composition of the control pastures is presented (Fig. 3) to illustrate the difference between the perennial and annual pastures and general changes that occurred because of season and grazing.

The annual pasture (Fig. 3*a*) typically consisted of large amounts of subterranean clover mixed with broadleaf weeds (capeweed and erodium) and annual grasses (silver grass, barley grass and winter grass). In contrast, the kikuyu treatments comprised mainly of subterranean clover in winter–spring and kikuyu in summer–autumn (Fig. 3*b*). The clover component provided feed in winter, at a time when kikuyu growth was poor, while kikuyu supported production in summer–autumn when the clover existed as dry residue.

Broadleaf weeds and annual grasses were minor components in the kikuyu pasture.

In winter of 1998, capeweed and erodium dominated the annual pasture treatments (92% of total herbage mass), as a result of the early break and delayed grazing pressure (Fig. 3*a*). A subsequent 'spray-graze' in late August successfully reduced the broadleaf weed component (down to 39%) and subterranean clover dominated the pasture for the remainder of the experiment, with the exception of an early break to the season (March) in 2000 (Fig. 2). In the growing season of 1998, clover content in the kikuyu control plots averaged only 20% of the herbage mass (Fig. 3*b*). Intensive grazing throughout the summer and autumn of 1998–99 (Fig. 4) and sowing of subterranean clover in May 1999 resulted in an increase of clover up to 70% in spring of that year and 84% in spring 2000.

Herbage mass

The pattern of herbage mass throughout each year was typical of that of pastures in a Mediterranean environment, with a peak in spring and minimum availability in autumn. Because of its summer–autumn activity, the perennial pasture had between 350 and 4900 kg DM/ha more herbage through the autumn period than the annual pasture (Fig. 5).

Herbage mass should have been independent of treatment as we attempted to maintain herbage at a maximum of 3000 kg DM/ha and 4000 kg DM/ha for annual and kikuyu treatments, respectively, by manipulating grazing pressure (Fig. 4; see stocking rate section). However, there were differences among the annual pasture treatments ($P<0.001$) and the kikuyu pasture treatments ($P<0.05$) in 1998 (Fig. 5). Control of herbage mass in annual pastures was poor due to an early break, low stocking rate in autumn and early winter, and a 'spray-graze' in August to control broadleaf weeds. In 1998, the kikuyu treatments accumulated low-quality herbage (Fig. 5) without the benefit of high-quality winter growth of subterranean clover, which compromised the performance of the livestock. Control of herbage mass in all treatments was more successful in 1999 and 2000.

Annual herbage accumulation

Herbage accumulation for the annual and kikuyu control pastures was similar in 1998 and 2000, and the kikuyu pasture only out-yielded its annual counterpart in 1999 as a

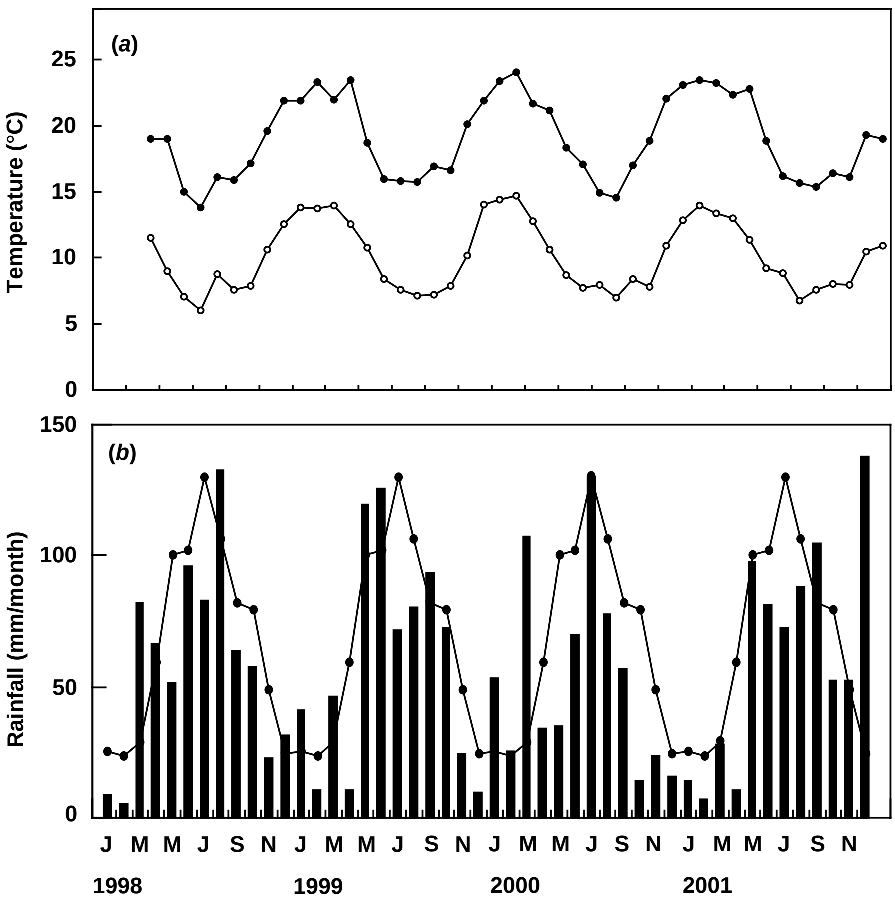

Figure 2. Average monthly (*a*) mean minimum (○) and maximum (●) air temperature (°C) and (*b*) rainfall (mm, bar), and long-term average monthly rainfall (line) from January 1998 to December 2001 at Albany, Western Australia.

consequence of growth outside the annual growing season (autumn 1999).

Overall, annual herbage accumulation (Table 2) declined with increasing competition from trees. The average effect of competition on annual pasture was significant ($P<0.01$, 16% reduction), but there were no significant differences among the levels of competition. There was also a significant interaction between year and effect of competition, with a significant ($P<0.05$) effect in 1999, but not in 1998 or 2000. The effect of aspect was not significant. There was no significant effect of tree competition on kikuyu annual herbage accumulation. Kikuyu (K20W) accumulated more herbage annually in competition with trees than the corresponding annual pasture (A20W), irrespective of year.

Stocking rate

It was necessary to vary stocking rates considerably throughout the experimental period in response to changing herbage mass and herbage accumulation rates (Fig. 4). In summer, stocking rates on kikuyu were increased to 25–30 sheep/ha. Conversely, all sheep were removed from annual pastures in this period for 98 days in 1999 and for 64 days in 2000, but increased in spring depending on treatment (Fig. 4).

Cumulative sheep grazing days per hectare (Table 3) was used as a simple measure of carrying capacity. Kikuyu pasture had a greater ($P<0.001$) carrying capacity than annual pasture in 1999 and 2000. Competition with trees significantly ($P<0.001$) reduced the carrying capacity of both annual and kikuyu pasture by an average of 10%. However, even competing with trees, kikuyu pasture (K20W) had a greater ($P<0.01$) carrying capacity than annual pasture (A20W) in 1999 and 2000. There were pasture and year effects and the interactions were significant ($P<0.01$). For example, annual control plots had significantly more sheep grazing days than annual treatments competing with trees in 1998 and 1999, but not in 2000. On the other hand, the kikuyu control had about 43 and 16% more sheep grazing days than kikuyu in competition with trees in 1999 and 2000, respectively, but not in 1998. There was a

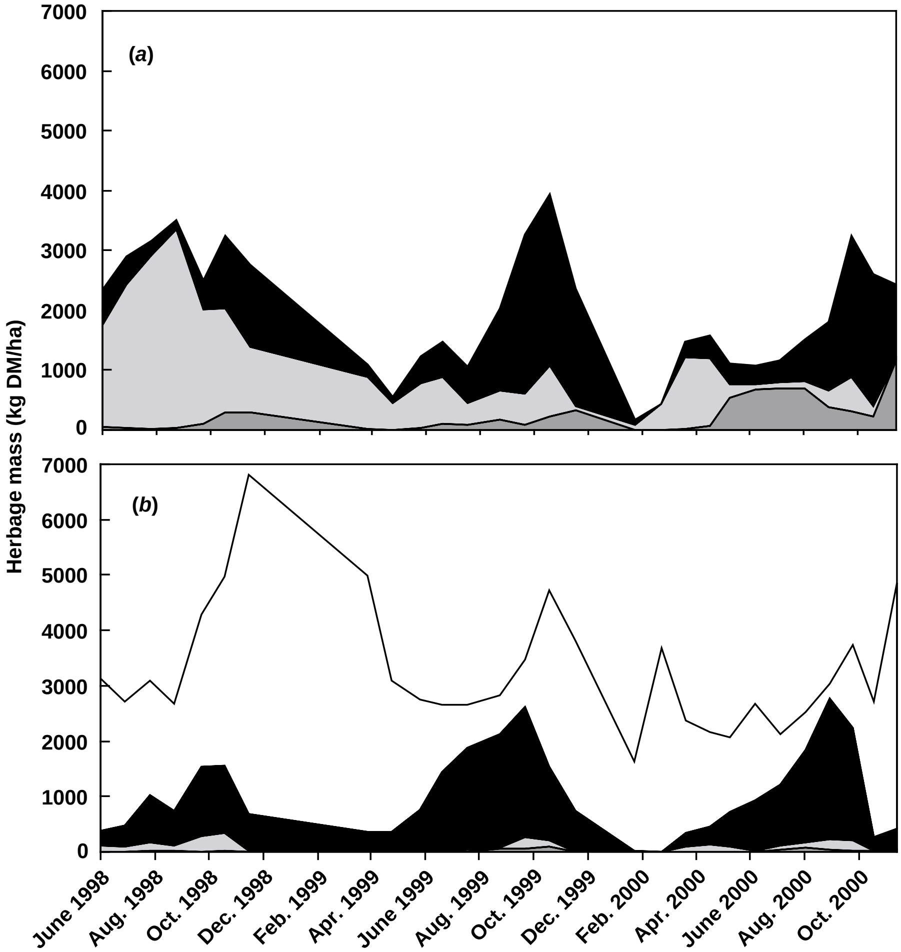

Figure 3. Botanical composition on control plots of (*a*) annual pasture and (*b*) kikuyu pasture from June 1998 to November 2000 at Albany, Western Australia. Dark shading, annual grasses; light shading, broadleaf weeds; black, legumes; white, perennial grass.

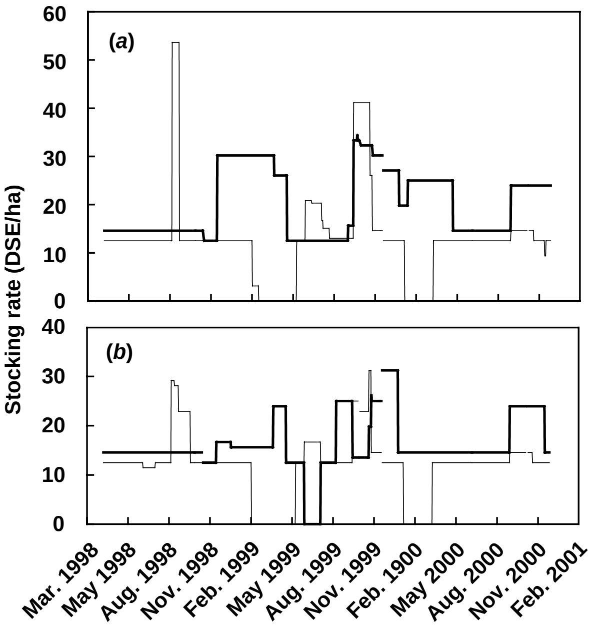

Figure 4. Seasonal pattern of stocking rate for (*a*) sheep grazing control annual (——) and kikuyu (▬▬) pasture, and (*b*) a similar comparison where 20% of the plot was in competition with a tree belt facing west.

significant (P<0.05) effect of tree-line orientation, but no effect of level of intensity of tree competition. Generally, south- and west-facing treatments carried fewer sheep than east-facing treatments.

Supplementary feed

No grain was fed to sheep grazing the annual pasture in 1998 because of the early break and timing of the commencement of the experiment (Table 4). However, sheep on this pasture were fed grain from January to March in 1999 and from December 1999 to August in 2000. On the kikuyu pasture, grain was fed in 1998 from June to September (Table 4), because of internal parasitic worm problems and a lack of subterranean clover in the winter period. Sheep grazing these pastures were not fed grain in 1999 and 2000, following adequate control of internal worms (Table 4).

Sheep liveweight

The effect of treatment and changes in stocking rate on liveweight were confounded, therefore only general differences are reported.

In 1998, the average liveweight (Fig. 6) for sheep grazing the kikuyu pasture was much lower than that of sheep grazing annual pasture (45 *v.* 60 kg/head, respectively, at finishing). This reflected the effect of intestinal worms and low subterranean clover content in the kikuyu pasture. In 1999 and 2000, the average liveweight was similar for sheep grazing annual and kikuyu pastures in winter and spring (Fig. 6). However, sheep grazing dry annual pasture in summer lost liveweight rapidly and were removed when dry residues declined to less than 1000 kg DM/ha. Sheep grazing kikuyu pasture maintained liveweight during summer–autumn (Fig. 6) in both of these years at a stocking rate of about 24 sheep/ha (Fig. 4) without supplementary feed (Table 4).

Wool production

In 1998, clean wool production per head and per hectare was lower (P<0.05) for sheep grazing the kikuyu control than that for sheep grazing the annual pasture. In 1999 and 2000, this result was reversed, with the kikuyu control recording significantly (P<0.01) higher clean wool

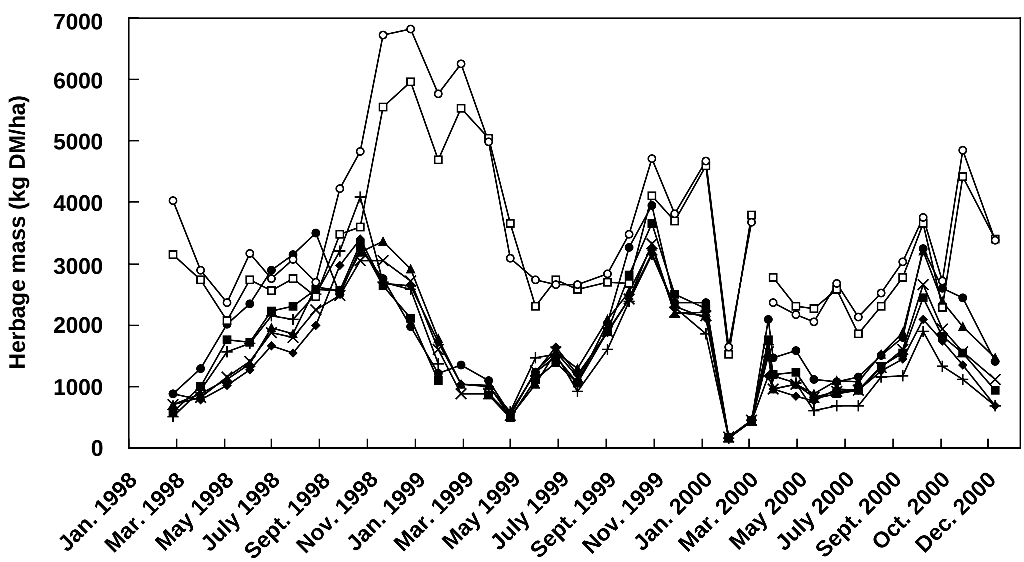

Figure 5. Herbage mass from March 1998 to December 2000 at Albany, WA. ANO (●), A20W (■), A20E (▲), A20S (◆), A36W (+), A36E (×), KNO (○), K20W (□). See Table 1 for legend. To compare herbage mass among treatments at each time l.s.d. ranges from 4.60 to 9.20 on square-root scale.

Table 2. Effect of tree competition and pasture type on annual herbage accumulation (± s.e.; kg DM/ha.year) at Albany, Western Australia, from 1998 to 2000

Standard errors are for comparing treatments within years

Treatment	1998	1999	2000
ANO	11100 ± 510	9800 ± 530	9000 ± 470
KNO	11100 ± 510	11900 ± 730	7600 ± 570
A20W	9900 ± 720	8100 ± 750	7900 ± 660
K20W	10500 ± 720	11800 ± 750	8700 ± 660
A20E	11000 ± 720	7700 ± 750	9200 ± 660
A20S	9000 ± 1020	6900 ± 1060	7000 ± 930
A36W	9700 ± 1020	6700 ± 1060	7100 ± 930
A36E	9900 ± 720	7300 ± 750	8400 ± 660

production per hectare. However clean wool production per head (Table 5) was similar.

On annual pastures, competition with trees significantly (P<0.05) reduced clean wool production per hectare, by an average of 13%. Sheep also produced less (P<0.05) clean wool per hectare if they were grazing south- and west-facing tree lines as opposed to the east-facing treatments. Both kikuyu treatments produced similar amounts of clean wool in 1998. However, sheep grazing away from the trees (KNO) yielded more wool than those grazing along the tree line (K20W) in 1999 (91.8 *v.* 60.1 kg/ha) and slightly less in 2000 (70.5 *v.* 75.1 kg/ha).

Soil water deficit

The soil water deficit (SWD) that developed in autumn each year beneath the kikuyu pasture was consistently larger than that for the annual pasture by 115, 57 and 132 mm in 1999, 2000 and 2001, respectively (Fig. 7). It was not possible to estimate the total size of the SWD that developed beneath the tree belt, as the trees had root systems that extended beyond the depth of measurement. However, to a depth of 5 m, the trees created a SWD that prevented the soil reaching field capacity in winter and exceeded the autumn SWD below both pastures by 297–442 mm (Fig. 7).

Table 3. Cumulative grazing sheep days per hectare for sheep grazing annual and kikuyu pasture

Means within columns followed by the same letters are not significantly different at P = 0.05

Treatment	1998	1999	2000
ANO	3368a	5105bc	3847c
KNO	3165b	8553a	7608a
A20W	3207ab	4307d	3858c
K20W	3165ab	5943b	6542b
A20E	3128b	4596cd	4085c
A20S	2714c	4020d	3763c
A36W	2975b	4260d	3763c
A36E	2951bc	4478cd	3858c

Discussion

Pasture

The major difference between the 2 pasture types studied occurred in the summer–autumn period. At that time, a large proportion of kikuyu grass remained green compared with the annual pasture which existed as dry residue. By autumn, the herbage mass in the annual pasture had declined to a level (800–1000 kg DM/ha) where sheep had to be removed from the pasture to prevent soil erosion. In comparison, depending on the year, the kikuyu pasture had 2100–6300 kg DM/ha, much of which was green. The availability of herbage in the perennial pasture had a positive effect on the carrying capacity because it occurred during the autumn feed gap, as previously reported by Sanford *et al.* (1997).

Within the growing season, the 2 pasture types performed similarly in their herbage accumulation, presumably because production in both was driven by subterranean clover. The only notable differences were greater herbage mass early in the season in the annual pasture and the large quantity of herbage the kikuyu pasture carried through the 1998 season.

These findings are consistent with previous studies that have demonstrated that kikuyu grass is summer-active in south-western Western Australia (Elliott 1933; Hawley 1978; Sanford *et al.* 1997; Greathead *et al.* 1998), eastern Australia (Kemp 1975; Fulkerson *et al.* 1999) and New Zealand (Lambert *et al.* 1979), when provided with adequate soil moisture and/or summer rain.

Kikuyu originated from the highland plateaux of east and central Africa where it is subjected to minimum and maximum temperatures of 2–8 and 16–22°C, respectively (Mears 1970). The success of kikuyu in temperate climates is partly explained by its cold tolerance and C_4 photosynthetic pathway. In theory, C_4 species should exhibit higher efficiencies of radiation, nutrient and water use than C_3 species, enabling them to maintain green herbage mass through summer on relatively infertile and moisture-limiting soils.

Absence of broadleaf weeds in the kikuyu pasture indicated that capeweed and erodium were displaced by kikuyu, possibly through competition for resources (e.g. moisture; Dear and Cocks 1997), allelopathy (Chou

Table 4. Total grain fed (kg/ha) to sheep grazing annual and kikuyu pasture

Treatment	1998	1999	2000
ANO	0	70	336
KNO	264	0	0
A20W	0	59	451
K20W	264	0	0
A20E	0	113	429
A20S	0	113	585
A36W	0	49	585
A36E	0	81	455

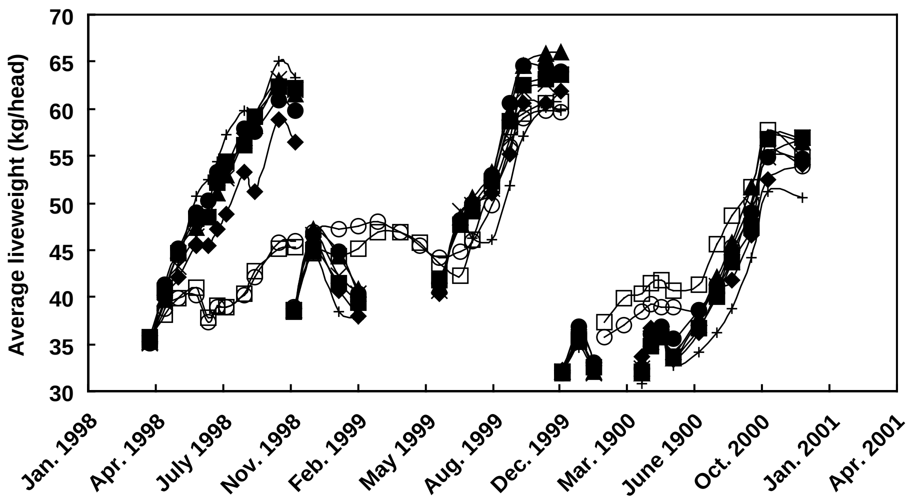

Figure 6. Seasonal pattern of average liveweight (kg/head) for sheep grazing annual and kikuyu pasture in 1998, 1999 and 2000. ANO (●), A20W (■), A20E (▲), A20S (◆), A36W (+), A36E (×), KNO (○), K20W (□).

et al. 1987) or an inability to recruit new plants (Bourdôt 1996).

On the basis of these findings, kikuyu was an ideal companion species for subterranean clover in pastures in the HRZ of south-western Western Australia. Clover drives pasture production in the growing season and provides nitrogen to the grass. Outside the normal growing season, kikuyu remains green and responds to summer moisture. To maintain this relationship, farmers need to control red-legged earth mite (Wallace and Mahon 1963) and apply considerable grazing pressure before the break of season in autumn to allow subterranean clover to establish.

In this experiment, tree competition consistently reduced annual herbage accumulation in annual pastures. This confirmed the results of a number of studies undertaken in southern Australia that have observed lower yields by annual crops and pastures within the root zone of windbreaks or tree belts (Bicknell 1991; Burke 1991; Lefroy and Stirzaker 1999; Bird *et al.* 2002; Knight *et al.* 2002; Nuberg *et al.* 2002; Sudmeyer *et al.* 2002; Woodall and Ward 2002). The reduction in plant growth has been attributed to competition between trees and pasture for soil moisture, nutrients and light (Bird 1998; Nuberg 1998; Schroth 1999). Unpublished data from our study suggested that most of the variation in annual herbage accumulation within the root competition zone could be accounted for by a decline in soil fertility and moisture. This is consistent with the effect of tree belts that are moderately permeable to wind and do not provide shelter to livestock immediately adjacent to the belt, so that they transfer nutrients close to the tree–pasture interface. In New Zealand, Hawke and Gillingham (1996) showed that impermeable tree belts can increase pasture production close to the belt as a result of nutrient transfer by livestock seeking shelter from the wind.

In contrast to annual pasture, there was no significant decline in kikuyu pasture herbage accumulation as a result of tree competition in our experiment. Since both kikuyu (Samarakoon *et al.* 1990) and subterranean clover (Watson *et al.* 1984) are shade-tolerant, kikuyu was presumably more successful in competing with the trees for soil nutrients and

Table 5. Clean wool production (± s.e.; kg/head and kg/ha) for sheep grazing annual and kikuyu pasture

Standard errors are for comparing means of the treatments within years

Year	ANO	KNO	A20W	K20W	A20E	A20S	A36W	A36E
				Clean wool production (kg/head)				
1998	4.30 ± 0.12	3.03 ± 0.11	4.11 ± 0.16	3.11 ± 0.15	4.15 ± 0.16	3.96 ± 0.23	4.68 ± 0.23	4.13 ± 0.16
1999	4.36 ± 0.12	4.44 ± 0.12	4.32 ± 0.16	4.19 ± 0.16	4.31 ± 0.16	4.36 ± 0.23	4.00 ± 0.23	4.46 ± 0.16
2000	3.84 ± 0.12	3.92 ± 0.15	3.73 ± 0.16	4.86 ± 0.15	4.09 ± 0.16	3.42 ± 0.23	3.41 ± 0.23	3.99 ± 0.16
				Clean wool production (kg/ha)				
1998	34.3 ± 1.22	22.6 ± 1.15	31.1 ± 1.72	23.2 ± 1.60	30.7 ± 1.72	25.4 ± 2.44	32.9 ± 2.44	28.8 ± 1.72
1999	53.7 ± 2.20	91.8 ± 6.50	44.7 ± 3.09	60.1 ± 9.20	47.7 ± 3.09	42.2 ± 4.37	41.0 ± 4.37	48.0 ± 3.09
2000	34.7 ± 1.54	70.5 ± 4.92	33.8 ± 2.17	75.1 ± 4.92	39.3 ± 2.17	30.2 ± 3.07	30.2 ± 3.07	36.3 ± 2.17

moisture, or was less affected by the decline in soil nutrients and periodic moisture stress. Schroth (1999) also concluded that perennial forage species were generally more competitive with trees in comparison with annual crops and pasture because of their deeper and denser root systems. This offers the prospect of developing agroforestry systems based on trees and perennial pasture plants that are little affected by tree competition, yet maximise the efficient use of water and nutrients.

Beyond the tree root zone, but within the wind shelter of the trees (about 20 tree heights), an increase in yield is expected as a result of favourable changes in the microclimate (e.g. improved warmth and humidity; Cleugh 1998). Unfortunately, at the site used in this study there were no pastures studied that were greater than 20 tree heights from tree belts and so outside the shelter zone. Therefore, it was not possible to draw any conclusions regarding the possible positive effect of tree belts on annual herbage accumulation. However, the characteristic peak in crop yield that some other studies have identified at a particular distance from the tree–pasture interface (Bicknell 1991; Burke 1991; Lefroy and Stirzaker 1999) was not observed (data not shown). The current study broadly supports the findings of Bird *et al.* (2002) that the effect of shelter on pasture growth is effectively zero. Therefore, producers in south-western Western Australia are unlikely to regain lost pasture production beneath tree belts through yield increases in the shelter zone.

Livestock

Results from this experiment suggested that pastures based on kikuyu would increase returns per hectare compared with an annual pasture. These increased returns were related to the kikuyu pasture supporting a production system that produced more clean wool per hectare, while requiring less supplementary feed. Significantly higher clean wool production per hectare resulted from higher stocking rates and so more sheep grazing days. These results were consistent with the findings of Greathead *et al.* (1998) that demonstrated that sheep grazing kikuyu pasture in south-western Western Australia consistently produced more wool, because the pasture could sustain higher stocking rates.

Sheep grazing kikuyu pasture maintained higher liveweight in summer, in the absence of supplementary feed. In contrast, sheep on annual pasture lost weight rapidly, were fed supplement and eventually had to be removed from the plots, as pasture dry residues became critically low. Sanford *et al.* (1997) found that during summer and autumn, sheep maintained weight on both annual and kikuyu pasture until April–May, at which time liveweight declined on the annual sward as feed availability limited intake. On the basis of this study and previous investigations, this suggested that in environments where kikuyu remains green in summer and autumn, producers could expect to consistently run higher stocking rates and maintain heavier liveweights.

Low animal production on the kikuyu pasture in 1998 was attributed to intestinal parasites and low clover content. Joyce (1974) pointed out that poor performance of sheep grazing kikuyu grass could be related to inadequate intake, complicated by protein deficiency. However, the main nutritional limitation of kikuyu is a lack of readily digestible energy and a relatively low digestibility of structural carbohydrates (Marais 2001). Unpublished data from our study showed that in winter the feed value of kikuyu was below that of clover, but in summer and autumn, the dry

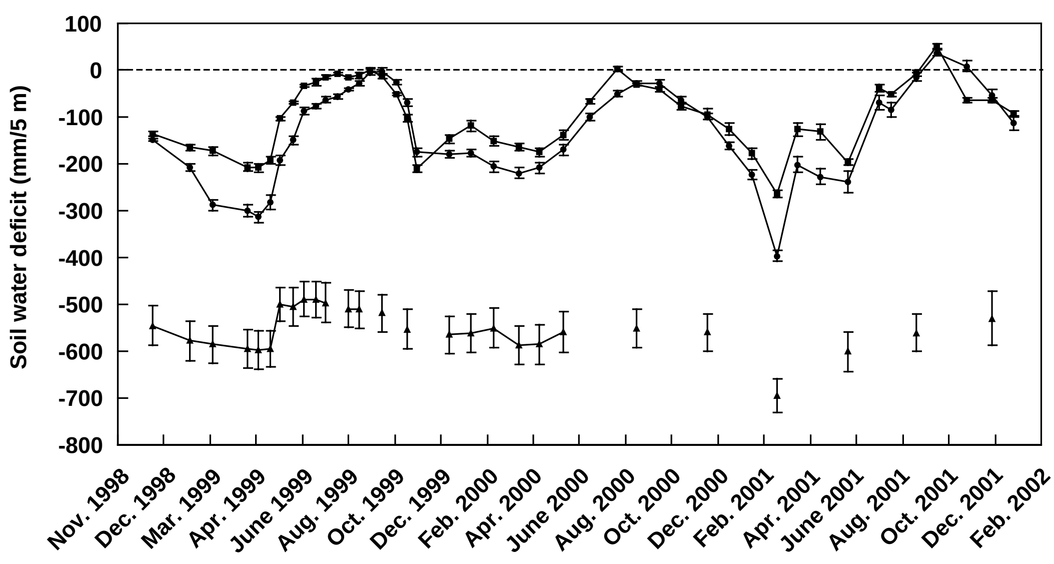

Figure 7. Soil water deficit (mean ± s.e., mm per 5 m depth) beneath annual pasture (■), kikuyu pasture (●) and centre of blue gum tree belt (▲) from December 1998 until January 2002 at Albany, Western Australia.

matter digestibility of clover declined to <50% while kikuyu remained >60%. This suggested that in winter a high proportion of subterranean clover was essential in a kikuyu pasture for satisfactory animal production.

Irrespective of pasture type, competition with trees significantly reduced carrying capacity and clean wool production per hectare, primarily due to reduced herbage accumulation. In a review of factors affecting animal performance in pine agroforestory, Percival *et al.* (1986) reported that ewe liveweights, wool weights and lamb growth rates were generally lower with increasing tree density, possibly because of lower herbage availability rather than lower feed quality.

Groundwater recharge

On the basis of the SWD that developed beneath the tree belt during the experimental period, groundwater recharge did not occur below the trees unless water moved down the soil profile *via* preferred pathways. This finding was supported by other studies that have demonstrated that trees can lower water tables under a wide range of landscape conditions in Western Australia (Schofield *et al.* 1989; George 1992; Stolte *et al.* 1997; Raper 1998). However, a survey of 80 sites by George *et al.* (1999) in Western Australia found that at 77 sites trees had little or no effect on groundwater more than 10–30 m from the planted area. Thereby limiting substantial off-site effects of trees on groundwater to situations were trees intercept lateral flow.

On the basis of the SWD results, kikuyu used on average 101 mm more water than the annual pasture, presumably because of higher amounts of green leaf in summer and deeper root system. As a consequence, it was likely that groundwater recharge declined beneath kikuyu and this pasture type could assist in delaying the onset of salinisation by decades (McDowall *et al.* 2003; White *et al.* 2003). Analysis by White *et al.* (2003), using the Sustainable Grazing Systems Pasture Model (Johnson *et al.* 2003), supported this conclusion, suggesting that kikuyu would reduce groundwater recharge at the site by about 137 mm/year. Furthermore, other studies indicated that in the HRZ kikuyu was able to use more water than phalaris (Scott and Sudmeyer 1993; Ridley *et al.* 1997; Chapman *et al.* 2003) and similar amounts to lucerne (Ridley *et al.* 2001).

The best compromise between production and sustainability in this investigation was kikuyu pasture in combination with blue gum tree belts. Future work within the HRZ needs to focus on developing profitable grazing systems that include perennial pastures and trees.

Acknowledgments

The authors thank Ron Adams for the use of his farm and assistance with the experiment. We are also indebted to John Boultwood, Giles Glasson, Bonnie Cole and Arjen Ryder for their technical assistance, the staff at the Western Australian Chemistry Centre for support with soil analysis, and the staff at the Department of Agriculture Wool Laboratory for their help with wool analysis. Funding for this work was provided by the Department of Agriculture Western Australia, Meat and Livestock Australia and Land and Water Australia.

References

Albertsen T, Eckersley P, Blennerhassett S, Moore R, Hingston B (2000) 'Blue gum timberbelt design for alley farming.' Rural Industries Research and Development Corporation, Publication No. 00/154. (Rural Industries Research and Development Corporation: Barton, ACT)

Allison GB, Cook PG, Barnett SR (1990) Land clearance and river salinisation in the western Murray basin. *Journal of Hydrology* **119**, 1–20.

Andrew MH, Lodge GM (2003) The Sustainable Grazing Systems National Experiment. 1. Introduction and methods. *Australian Journal of Experimental Agriculture* **43**, 695–709.

Angus JF, Gault RR, Peoples MB, Stapper M, van Herwaarden AF (2001) Soil water extraction by dryland crops, annual pastures, and lucerne in south-eastern Australia. *Australian Journal of Agricultural Research* **52**, 183–192.

Bicknell D (1991) The role of trees in providing shelter and controlling erosion in the dry temperate and semi-arid southern agricultural areas of Western Australia. In 'Proceedings of a national conference: the role of trees in sustainable agriculture'. Albury. pp. 21–39. (National Agroforestry Working Group-Bureau of Rural Resources, Department of Primary Industries and Energy: Canberra, ACT)

Bird PR (1998) Tree windbreaks and shelter benefits to pasture in temperate grazing systems. *Agroforestry Systems* **41**, 35–54.

Bird PR, Jackson TT, Kearney GA, Williams KW (2002) The effect of two tree windbreaks on adjacent pastures in south-west Victoria, Australia. *Australian Journal of Experimental Agriculture* **42**, 809–830.

Bond WJ, Cresswell HP, Simpson RJ, Paydar Z, Clark SG, Moore AD, Alcock DJ, Donnelly JR, Freer M, Keating BA, Huth NI, Snow VO (1997) 'Pre-experimentation water balance investigation final report.' MRC Sustainable Grazing Systems Key Program Project SGS.130. CSIRO Land and Water Consultancy Report 97-31.

Bourdôt GW (1996) Interference between pasture plants and thistles — a review. *Plant Protection Quarterly* **11**, 265–270.

Burke S (1991) Effect of shelterbelts on crop yields at Rutherglen, Victoria. In 'Proceedings of a national conference at Albury: the role of trees in sustainable agriculture'. pp. 89–99. (National Agroforestry Working Group-Bureau of Rural Resources, Department of Primary Industries and Energy: Canberra, ACT)

Campbell NA, Arnold GW (1973) The visual assessment of pasture yield. *Australian Journal of Experimental Agriculture and Animal Husbandry* **13**, 263–267.

Chapman DF, McCaskill MR, Quigley PE, Thompson AN, Graham JF, Borg D, Lamb J, Kearney G, Saul GR, Clark SG (2003) Effects of grazing method and fertiliser inputs on the productivity and sustainability of phalaris-based pastures in Western Victoria. *Australian Journal of Experimental Agriculture* **43**, 785–798.

Chou CH, Hwang SY, Peng CI, Wang YC, Hsu FC, Chung NC (1987) The selective allelopathic interaction of a pasture–forest intercropping in Taiwan. *Plant and Soil* **98**, 31–41.

Cleugh HA (1998) Effects of windbreaks on airflow, microclimates and crop yields. *Agroforestry Systems* **41**, 55–84.

Dear BS, Cocks PS (1997) Effect of perennial pasture species on surface soil moisture and early growth and survival of subterranean clover (*Trifolium subterraneum* L.) seedlings. *Australian Journal of Agricultural Research* **48**, 683–693.

Dolling PJ (2001) Water use and drainage under phalaris, annual pasture, and crops on a duplex soil in Western Australia. *Australian Journal of Agricultural Research* **52**, 305–316.

Eastham J, Scott PR, Steckis R (1994) Components of water balance of tree species under evaluation for agroforestry to control salinity in the wheatbelt of Western Australia. *Agroforestry Systems* **26**, 156–170.

Elliott HG (1933) Kikuyu grass. *Journal of Agriculture Western Australia* **10**, 253–255.

Ferdowsian R, George RJ, Lewis MF, McFarlane DJ, Short R, Speed R (1996) The extent of dryland salinity in Western Australia. In 'Proceedings of the productive use of saline lands conference'. Albany, Western Australia. pp. 89–97. (Promaco Conventions: Perth, WA)

Ferdowsian R, Greenham K (1992) 'Integrated catchment management — Upper Denmark catchment.' Division of Resource Management Technical Report 130, Western Australian Department of Agriculture, South Perth, WA.

Fulkerson WJ, Slack K, Havilah E (1999) The effect of defoliation interval and height on growth and herbage quality of kikuyu grass (*Pennisetum clandestinum*). *Tropical Grasslands* **33**, 138–145.

George RJ (1992) Groundwater processes, sandplain seeps and interactions with perched groundwater systems. *Journal of Hydrology* **134**, 247–271.

George R, McFarlane DJ, Nulsen RA (1997) Salinity threatens the viability of Agriculture and ecosystems in Western Australia. *Hydrogeology Journal* **5**, 6–21.

George RJ, Nulsen RA, Ferdowsian R, Raper GP (1999) Interactions between trees and groundwaters in recharge and discharge areas — a survey of Western Australian sites. *Agricultural Water Management* **39**, 91–113.

Greathead K, Sanford P, Cransberg L (1998) 'Perennial grass for animal production in the high rainfall areas of western Australia.' Miscellaneous Publication No. 2/98. (Agriculture Western Australia: South Perth, WA)

Hatton TJ, Nulsen RA (1999) Towards achieving functional ecosystem mimicry with respect to water cycling in southern Australian agriculture. *Agroforestry Systems* **45**, 203–214.

Hawke M, Gillingham A (1996) Nutrient transfer by livestock adjacent to managed and unmanaged shelterbelts. *New Zealand Tree Grower* **17**, 35–37.

Hawley K (1978) Seed kikuyu performs well. *Journal of Agriculture Western Australia* **19**, 92.

Heislers D, Reid M (1996) Evidence for the effects of perennial pastures on groundwater levels. In 'Perennial pastures for recharge control: report on a workshop'. 20–21 July 1995, Bendigo, Victoria. LWRRDC Occasional Paper Series No. 04/96. pp. 66–65. (Land and Water Resources Research and Development Corporation: Canberra, ACT)

Isbell RF (1996) 'The Australian soil classification.' (CSIRO: Australia)

Johnson IR, Lodge GM, White RE (2003) The Sustainable Grazing Systems Pasture Model: description, philosophy and application to the SGS National Experiment. *Australian Journal of Experimental Agriculture* **43**, 711–728.

Joyce JP (1974) Nutritive value of kikuyu grass. *New Zealand Journal of Agriculture Research* **17**, 197–202.

Kemp DR (1975) The growth of three tropical pasture grasses on the mid-north coast of New South Wales. *Australian Journal of Experimental Agriculture and Animal Husbandry* **15**, 637–644.

Knight A, Blott K, Portelli M, Hignett C (2002) Use of tree and shrub belts to control leakage in three dryland cropping environments. *Australian Journal of Agricultural Research* **53**, 571–586.

Lambert JP, Rumball PJ, Boyd AF (1979) Comparison of ryegrass–white clover pastures with and without paspalum and kikuyu grass. 1. Pasture production. *New Zealand Journal of Experimental Agriculture* **7**, 295–302.

Lefroy E, Scott P (1994) Alley farming: new vision for Western Australian farmland. *Journal of Agriculture Western Australia* **35**, 119–126.

Lefroy EC, Stirzaker RJ (1999) Agroforestry for water management in the cropping zone of southern Australia. *Agroforestry Systems* **45**, 277–302.

Lefroy E, Stirzaker RJ, Pate JS (2001) The influence of tagasaste (*Chamaecytisus proliferus* Link.) trees on the water balance of an alley cropping system on deep sand in south-western Australia. *Australian Journal of Agricultural Research* **52**, 235–246.

Lodge GM (1998) 'Themes and experimental protocols for sustainable grazing systems.' LWRRDC Occasional Paper No. 13/98. (Land and Water Resources Research and Development Corporation: Canberra)

Marais JP (2001) Factors affecting the nutritive value of kikuyu grass (*Pennisetum clandestinum*) — a review. *Tropical Grasslands* **35**, 65–84.

Mears PT (1970) Kikuyu (*Pennisetum clandestinum*) as a pasture grass — a review. *Tropical Grasslands* **4**, 139–152.

McCallum MH, Conner DJ, O'Leary GJ (2001) Water use by lucerne and effect on crops in the Victorian Wimmera. *Australian Journal of Agricultural Research* **52**, 193–201.

McDowall MM, Hall DJM, Johnson DA, Bowyer J, Spicer P (2003) Kikuyu and annual pasture: a characterisation of a productive and sustainable beef production system on the South Coast of Western Australia. *Australian Journal of Experimental Agriculture* **43**, 769–783.

Nuberg IK (1998) Effect of shelter on temperate crops: a review to define research for Australian conditions. *Agroforestry Systems* **41**, 3–34.

Nuberg K, Mylius SJ, Edwards JM, Davey C (2002) Windbreak research in a South Australian Cropping system. *Australian Journal of Experimental Agriculture* **42**, 781–795.

Payne RW (2002) (Ed.) 'The guide to Genstat release 6.1 — Part 2: statistics.' (VSN International: Oxford)

Percival NS, Hawke MF, Jagusch KT, Korte CJ, Gillingham AG (1986) Review of factors affecting animal performance in pine agroforestry. *Agroforestry Symposium Proceedings* **139**, 165–174.

Raper GP (1998) 'Agroforestry water use in mediterranean regions of Australia.' Water and Salinity Issues in Agroforestry, No. 2. Publication No. 98/63. (Rural Industries Research and Development Corporation: Canberra, ACT)

Ridley AM, Christy B, Dunin FX, Haines PJ, Wilson KF, Ellington A (2001) Lucerne in crop rotations on the Riverine Plains. 1. The soil water balance. *Australian Journal of Agricultural Research* **52**, 263–277.

Ridley AM, White RE, Simpson RJ, Callinan L (1997) Water use and drainage under phalaris, cocksfoot, and annual ryegrass pastures. *Australian Journal of Agricultural Research* **48**, 1011–1123.

Samarakoon SP, Wilson JR, Shelton HM (1990) Growth, morphology and nutritive value of shaded *Stenotaphrum secundatum*, *Axonopus compressus* and *Pennisetum clandestinum*. *Journal of Agricultural Science* **114**, 161–169.

Sanford P, Gladman J, Cransberg L (1997) Sheep production on an annual and perennial pasture in southwest Australia. In 'Proceedings of the XVIII international grassland congress'. Winnipeg and Saskatoon, Canada. (Eds JG Buchanan-Smith, LD Baily, P McCaughey) pp. 29-81–29-82. (Canadian Forage Council, Canadian Society of Agronomy, Canadian Society of Animal Science)

Schofield JJ, Loh IC, Scott PR, Battle JR, Ritson P, Bell RW, Borh H, Anson B, Moore R (1989) 'Vegetation strategies to reduce stream salinity of water resource catchments in south-west Western Australia.' Report No. WS 33. (Water Authority of Western Australia: Perth, WA)

Schroth G (1999) A review of below-ground interactions in agroforestry, focusing on mechanisms and management options. *Agroforestry Systems* **43**, 5–34.

Scott PR, Sudmeyer RA (1993) Evapotranspiration from agricultural plant communities in the high rainfall zone of the southwest of Western Australia. *Journal of Hydrology* **146**, 301–319.

Stirzaker R, Cook FJ, Knight JH (1999) Where to plant trees on cropping land for control of dryland salinity: some approximate solutions. *Agricultural Water Management* **39**, 115–133.

Stirzaker RJ, Lefroy EC, Ellis TW (2002) An index for quantifying the trade-off between drainage and productivity in tree-crop mixtures. *Agricultural Water Management* **53**, 187–199.

Stolte WJ, McFarlane DJ, George RJ (1997) Flow systems, tree plantations and salinisation in a West Australian catchment. *Australian Journal of Soil Research* **35**, 1213–1229.

Sudmeyer RA, Hall DJ, Eastham J, Adams MA (2002) The tree–crop interface: the effects of root pruning in south-western Australia. *Australian Journal of Experimental Agriculture* **42**, 763–772.

Walker G, Gilfedder M, Williams J (1999) 'Effectiveness of current farming systems in the control of dryland salinity.' (CSIRO Land and Water: Canberra, ACT)

Wallace MMH, Mahon JA (1963) The effect of insecticide treatment on the yield and botanical composition of sown pastures in Western Australia. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 39–50.

Ward PR, Dunin FX, Micin SF (2001) Water balance of annual and perennial pastures on a duplex soil in a Mediterranean environment. *Australian Journal of Agricultural Research* **52**, 203–209.

Ward PR, Dunin FX, Micin SF (2002) Water use and root growth by annual and perennial pastures and subsequent crops in phase rotation. *Agricultural Water Management* **53**, 83–97.

Watson VH, Hagedorn C, Knight WE, Pearson HA (1984) Shade tolerance of grass and legume germplasm for use in the southern forest range. *Journal of Range Management* **37**, 229–232.

Webb A (1993) 'Review of the status of technical options for salinity control in southern Victoria.' Victorian Salinity Program.

White RE, Christy BP, Ridley AM, Okom AE, Murphy SR, Johnston WH, Michalk DL, Sanford P, McCaskill MR, Johnson IR, Garden DL, Hall DJM, Andrew MH (2003) SGS Water Theme: influence of soil, pasture type and management on water use in grazing systems across the high rainfall zone of southern Australia. *Australian Journal of Experimental Agriculture* **43**, 907–926.

Woodall GS, Ward BH (2002) Soil water relations, crop production and root pruning of a belt of trees. *Agricultural Water Management* **53**, 153–169.

Received 29 November 2002, accepted 4 April 2003