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Exploring short-term ley legumes in subtropical grain systems: production, water-use, water-use efficiency and economics of tropical and temperate options

Lindsay W. Bell[A,B,E], *John Lawrence*[A,B], *Brian Johnson*[C], *and Anthony Whitbread*[D]

[A]CSIRO Sustainable Agriculture Flagship.
[B]CSIRO Ecosystems Sciences/APSRU, 203 Tor St, Toowoomba, Qld 4350, Australia.
[C]Department of Agriculture, Fisheries and Forestry Queensland, 203 Tor St, Toowoomba, Qld 4350, Australia.
[D]Crop Production Systems in the Tropics, Georg-August-Universität, Grisebachstr. 6, 37077 Göttingen, Germany.
[E]Corresponding author. Email: Lindsay.Bell@csiro.au

Abstract. Biomass production, soil water extraction, and water-use efficiency (WUE, kg dry matter (DM)/ha.mm growing-season water use) of tropical, summer-growing and temperate, winter-growing forage legumes suited to short-term rotations with crops were compared over several growing seasons in southern Queensland. Tropical legumes lablab (*Lablab purpureus* cvv. Highworth and Endurance), burgundy bean (*Macroptillium bracteatum* cvv. Cardarga/Juanita mix), and butterfly pea (*Clitoria ternatea* cv. Milgara) were compared with forage sorghum (*Sorghum* spp. cv. Silk and cv. Sugargraze). Temperate legumes snail medic (*Medicago scutellata* cv. Sava), lucerne (*Medicago sativa* cv. UQL-1), sulla (*Hedysarum coronarium* cv. Wilpena), and purple vetch (*Vicia benghalensis* cv. Popany) were compared with forage oats (*Avena sativa* cv. Taipan/Genie). Production and WUE of winter legumes was highly variable, with oats producing more biomass than the legumes, except in 2009 where oat establishment was poor. In years with good establishment, WUE of oats (14–28 kg DM/ha.mm), snail medic (13–25 kg DM/ha.mm), and sulla (12–20 kg DM/ha.mm) were similar, but the production and WUE of vetch were generally lower (6–14 kg DM/ha.mm). Sulla dried the soil profile by 60–100 mm more than the annual species, but less than lucerne. Summer legumes, burgundy bean, and lablab performed similarly, although always produced less biomass and had lower WUE than forage sorghum. Lucerne extracted more water and maintained a drier profile by 70–150 mm and had lower WUE (<10 kg DM/ha.mm) than burgundy bean or lablab (9–30 kg DM/ha.mm). Of the legumes tested, burgundy bean and lablab seem the most likely to be profitably integrated into subtropical cropping systems. Further evidence of the rotational benefits provided by these legumes is required before they will be favoured over the perceived reliability and higher productivity of annual grass-type forages.

Additional keywords: alfalfa, forage, persistence, root depth, rotation.

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Introduction

Pasture legumes have been an integral part of crop rotations in southern Australia for many years (Puckridge and French 1983), yet similar systems have not evolved to the same extent in subtropical cropping systems. In part, this has been due to the highly fertile clay soils in the subtropical region being favoured for cropping, and these soils have not required legume pastures to provide nitrogen (N) to sustain crop production (Lloyd *et al*. 1991). However, declining soil fertility and increasing N prices, the emergence of hard-to-kill or herbicide resistant weeds, and increases in soil-borne diseases and pests (e.g. crown rot, root lesion nematodes) have prompted increased interest in diversifying crop rotations in these regions. Rotations involving annual or short-term perennial legume pastures can have several benefits in crop rotations, including increasing soil N and soil carbon, and managing pests, diseases, and weeds (Lloyd *et al*. 1991; Dalal *et al*. 2004*a*, 2004*b*; Thomas *et al*. 2009). Despite these benefits, adoption of short-term pasture legumes is still low (Singh *et al*. 2009). This is thought to be due to the lack of pasture legume cultivars that suit subtropical crop rotations, problems when transitioning between crop and pasture phases (Whitbread *et al*. 2009), and the relative productivity and profitability of these legumes compared with the most commonly used forage options such as forage sorghum and oats (Singh *et al*. 2009).

The continental subtropical climate of Australia's northern cropping zone presents opportunities and challenges for growing temperate and tropical legumes. Lucerne (*Medicago sativa*) and the annual barrel (*M. truncatula*) and snail (*M. scutellata*) medics have been the main temperate legumes used in crop rotations (Lloyd *et al*. 1991). However, winter rainfall (30–35% of the total annual rainfall in these regions) is highly variable and does not reliably support winter-growing, temperate legumes. For example, annual medic production has coefficients of variation of annual yield ranging between 50 and 100% in southern Queensland (Clarkson *et al*. 1987). Frequent frost events further constrain production and persistence of tropical legumes. Annual tropical legumes lablab (*Lablab purpureus*) and cowpea (*Vigna unguiculata*) have been used for many years, and the perennial legume butterfly pea (*Clitoria ternatea*) has been used successfully in pasture phases of ≥3 years in central Queensland (Pengelly and Conway 2001; Cullen and Hill 2006). However, butterfly pea requires higher temperatures for growth, and hence its productivity in southern regions of the subtropics is low (Pengelly and Conway 2001). In the last 10 years, three newer legume options, sulla (*Hedysarum coronarium*), perennial/biennial lablab cv. Endurance, and burgundy bean (*Macroptillium bracteatum*) have been developed to fill gaps in the array of pasture legumes that are adapted to alkaline clay soils and suited to short pasture phases (2–3 years) in crop rotations in the region (Whitbread *et al*. 2005; Nichols *et al*. 2007). Burgundy bean can germinate and grow at lower temperatures than butterfly pea, and hence has a longer growing season in southern regions of the subtropics (Whitbread *et al*. 2005). Because sulla and burgundy bean have lower risk of causing bloat in livestock, they are attractive alternatives to lucerne and medics for beef producers.

Some attributes of ley pasture legumes make transitioning between pastures and crops in subtropical crop rotations complex and risky (Weston *et al*. 2000). Difficulties in reliably establishing smaller seeded perennial grasses or legumes and achieving desirable species composition require careful agronomic and grazing management (Whitbread *et al*. 2009). Difficulty in reliably removing legumes such as lucerne after a pasture phase, and long-lasting residual hard seed left by annual medics, are seen as problems by many farmers using them in crop rotations. In this environment, cropping relies on stored soil water but the capacity of perennial pastures, especially lucerne, to dry the soil profile more than annual crops means that either substantial rainfall is required to refill the profile before cropping can resume or yields of subsequent crops are reduced significantly (Holford *et al*. 1998; Dalal *et al*. 2004*b*; Thomas *et al*. 2009). This reduces the flexibility of crop rotations and increases the challenges of maintaining both surface cover after pasture legumes and the ability to refill the soil profile. Hence, information on the water use of other pasture legumes such as burgundy bean, sulla, and lablab is needed to inform the management required and suitability of their use in crop rotations.

Few studies have compared the relative productivity and the water-use efficiency (WUE) of currently available, short-term pasture legumes in the southern inland areas of the subtropics. Comparisons of production of some short-term tropical legumes have been made in warmer northern environments; for example, lablab, siratro, lucerne, and desmanthus were compared over four growing seasons in Central Queensland (Armstrong *et al.* 1999); lablab, *Macroptillium* spp., *Desmanthus* spp., and *Stylosanthes* spp. were compared in the Burnett region (Clem 2004; Clem and Cook 2004); and lucerne and annual medics have been widely studied in subtropical systems (e.g. Thomas *et al.* (2009), Weston *et al.* (2002). Yet, comparisons of the current range of both summer- and winter-growing legumes for production and WUE in a common environment have not been made. This series of experiments set out to compare the biomass production, soil water extraction, and WUE (kg dry matter (DM)/ha.mm growing-season water use) of both new and existing summer- and winter-growing forage legume options over several growing seasons in southern Queensland. Annual forage sorghum (*Sorghum* spp.) and oats (*Avena sativa*) were also included as current forage crop benchmarks for comparison with the legumes.

Methods

Experimental locations and design

A series of experiments was conducted between 2005 and 2010 at five locations spanning the mixed crop–livestock farming regions of southern Queensland. All sites were on Vertosol soils predominantly used for cropping in each district (Table 1). The first experimental period, between 2005 and 2007 at Roma Research Station (26°34′49″S, 148°45′51″E), compared four summer-growing legumes (burgundy bean, butterfly pea, annual lablab cv. Highworth, perennial lablab cv. Endurance) with a perennial forage sorghum (*Sorghum* spp. hybrid cv. Silk). Three replicate plots (6 m by 15 m) of each of the forages were sown in a randomised block design. The soil was a brown Vertosol (Isbell 1996) with cracking clay to 80–100 cm over decomposed mudstone (Table 1), with native vegetation of Mitchell grass (*Astrebla* spp.) grassland.

The second experimental period, between 2007 and 2010, compared three winter- and three summer-growing, short-term ley legumes with annual forage grasses for periods of 2–3-years at four locations in southern Queensland (Table 1). Winter-growing legumes included snail medic, sulla, and purple vetch (*Vicia benghalensis*), and these were compared with forage oats. Summer-growing legumes (lucerne, burgundy bean, and annual lablab) were compared with annual forage sorghum cv. Sugargraze. Four replicate plots (5 m by 8 m) of each of the forages were sown in a randomised block design with winter- and summer-growing species separated into two separate but adjacent areas to allow easier management.

Experimental sites were on farms in the Chinchilla, Roma, Condamine, and Goondiwindi districts. The Chinchilla site operated from summer 2007–08 to winter 2010 and was at ‘Wychie’ (26°39′53″S, 148°53′33″E), 20 km east of Chinchilla township. The soil was a grey Vertosol (Isbell 1996) which had significant chloride (Cl) constraints to root growth below 1.2 m (Table 1); native vegetation was brigalow (*Acacia harpophylla*) scrub. The site had been sown to forage oats or sorghum for the previous 3 years. The Roma site operated from winter 2008 to winter 2010 and was on ‘Richmond Downs’ (26°55′46″S, 149°40′25″E), 15 km south-east of Roma township. The soil was a black Vertosol (Isbell 1996) (native vegetation of Mitchell grass grassland) and deeper (~1.5 m) than at the Roma Research Station, and had few other constraints. This site had been sown to grazing oat crops for the previous 3 years and had a history of grain wheat and forage oat production. The Condamine site operated from winter 2008 to winter 2010 and was on ‘Callitris’ (26°44′51″S, 150°49′45″E), 45 km west of Condamine township. The soil was a brown Vertosol (Isbell 1996) with a sandy clay loam surface graduating to clay at depth (Table 1), with native vegetation of belah (*Casuarina cristata*)/brigalow scrub. The site had a history of grain cropping and had

Table 1. Description of soil profile bulk density (BD), pH, electrical conductivity (EC), chloride concentration (Cl), available phosphorus (P), organic carbon (OC), and total nitrogen (N) content at five experimental sites in southern Queensland

Site	Depth (cm)	BD (g/cm^3)	pH (1 : 5 water)	EC (dS/m) (1 : 5 water)	Cl (mg/kg) (1 : 5 water)	P (mg/kg) (0.5 M $NaHCO_3$, pH 8.5)	OC (%) (Walkley and Black)	N (%) H_2SO_4 digest
Roma Research Station, Roma	0–15	1.29	7.9	0.31	34	15	0.66	
	15–30	1.32	8.2	0.36	34	11	0.48	
	30–60	1.33	8.4	0.72	81	8	0.27	
	60–90	1.39	7.9	2.06	194	11	0.15	
	90–120		7.6	1.02	512			
	120–150		7.3	1.17	715			
‘Wychie’, Chinchilla	0–15	1.27	8.4	0.17	21	41	0.95	0.076
	15–30	1.30	8.7	0.23	22	17	0.50	0.055
	30–60	1.30	8.8	0.46	119	11	0.33	0.037
	60–90	1.31	7.9	2.09	374	4	0.23	0.024
	90–120	1.28	7.0	1.59	954			
	120–150	1.37	5.9	1.31	1319			
	150–180	1.35	4.7	1.34	1514			
‘Richmond Downs’, Roma	0–15	1.19	8.1	0.19	41	5	0.71	0.060
	15–30	1.32	8.2	0.22	49	3	0.62	0.052
	30–60	1.32	8.3	0.25	72	3	0.54	0.051
	60–90	1.37	8.6	0.26	78	3	0.48	0.042
	90–120	1.52	7.9	1.48	134			
	120–150	1.56	8.2	0.88	281			
	150–180	1.63	8.8	0.36	222			
‘Callitris’, Condamine	0–15	1.38	6.8	0.051	<10	18	0.71	0.02
	15–30	1.50	8.3	0.116	<10	2	0.35	0.02
	30–60	1.51	9.3	0.259	36	<1	0.20	<0.01
	60–90	1.55	9.4	0.465	202	<1	0.12	<0.01
	90–120	1.55	9.1	0.504	373			
	120–150	1.56	8.6	0.581	486			
	150–180	1.68	7.3	0.606	511			
‘Birribindibil’, Toobeah	0–15	1.22	8.1	0.212	38	37	1.61	0.06
	15–30	1.30	8.4	0.216	104	8	0.70	0.01
	30–60	1.31	8.4	0.361	300	6	0.58	<0.01
	60–90	1.31	7.9	0.791	750	6	0.38	<0.01
	90–120	1.40	7.7	1.117	1248			
	120–150	1.44	7.8	1.218	1439			
	150–180	1.46	8.0	1.218	1472			

been sown to wheat for the previous 2 years. The Goondiwindi site, which operated from summer 2008–09 to summer 2010–11, was on ‘Birribindibil’, Toobeah (28°25′14″S, 149°50′12″E), 50 km west of Goondiwindi township. The soil was a grey Vertosol (Isbell 1996), which also had high concentrations of Cl below 0.9 m that may limit plant root growth (Table 1); native vegetation was coolabah (*Eucalyptus coolabah*)/brigalow forest. The site had a history of grain cropping, and had been sown to wheat the previous 2 years.

Agronomic management

Oats, annual forage sorghum, lablab, and purple vetch were re-sown each year at the first opportunity after rainfall in their respective growing seasons. Regenerating annual legumes (snail medic), perennial legumes (lucerne, burgundy bean, sulla, lablab cv. Endurance, and butterfly pea), and the perennial forage sorghum cv. Silk were sown only in the first year at each experimental site. Table 2 shows the sowing dates for each experimental year at each location. Lucerne, while predominantly summer-growing, was sown in autumn–early winter at the same time as the winter-growing species at each location. Sowing rates and row spacing for each species were

Table 2. Sowing dates for summer- and winter-growing forages at experimental sites in southern Queensland between 2005 and 2010
n.r., Lablab and forage sorghum not re-sown

Spring–summer	2005–06	2006–07	2007–08	2008–09	2009–10
Roma RS	31 Jan.	7 Nov.	n.r.		
Chinchilla			02 Jan.	14 Oct.	11 Nov.
Roma				17 Oct.	11 Jan.
Condamine				17 Oct.	n.r.
Toobeah				05 Dec.	12 Jan.
Autumn–winter			2008	2009	2010
Chinchilla			19 June	07 May	
Roma			11 June	07 May	
Condamine			12 June	06 May	
Toobeah			–	02 July	23 Mar.

consistent with regional recommendations and are shown in Table 3. All legumes were inoculated with appropriate commercial strains of root nodule bacteria with peat slurry before sowing. In 2005 at Roma Research Station, 46 mm of irrigation was applied in the 4 days after sowing to facilitate establishment under dry conditions; apart from this, all other forages were entirely rainfed.

Weeds were controlled before sowing and during fallow periods using applications of glyphosate (360 g a.i./L) at 2 L/ha, and with 2,4-D amine (500 g a.i./L) at 1.5 L/ha at the Condamine site where fleabane (*Conyza sumatrensis*) was a problem. In-crop control of weeds, particularly barnyard grass (*Echinochloa colona*) and turnip weed (*Rapistrum rugosum*), was performed when high levels of weed competition were emerging, with the selective herbicides Broadstrike® (800 g flumetsulam/kg) at 25 g/ha or Fusilade® (128 g fluazifop-P-butyl/L) at 1.5 L/ha.

Fertiliser applications were made according to district farmer practice. At Roma in 2005, 40 kg mono-ammonium phosphate was applied to all species at sowing. No fertiliser was applied to forage sorghum in the first summer at all sites due to high levels of soil mineral N (>150 kg N/ha). At the Chinchilla site in the second year (2008), 100 kg N as urea was applied to forage sorghum plots before sowing, but no fertiliser was applied to forage sorghum in 2009. In 2008, 50 kg N/ha as urea was also applied to the oats before sowing at all sites, but not in 2009.

Plant growth measurements

Every 6–8 weeks during the growing season, plant biomass cuts were taken from 2 quadrats each of area 0.5 m^2 (3 quadrats each of area 0.25 m^2 at Roma 2005–07) in each replicate plot, to determine accumulated growth during each growing season. Once peak biomass was reached (mid-flowering) and/or at the end of each growing season, the plots were cut to a height of ~5–10 cm, biomass was removed, and plants were allowed to regrow. Plant density in each growing season was measured by plant counts in 2 quadrats each of area 0.5 m^2 quadrats in each plot at peak biomass (3 quadrats each of area 0.25 m^2 at Roma 2005–07).

Soil water extraction and water-use efficiency

For the second experimental period (2007–10), gravimetric soil water content was measured to a depth of 1.8 m in each plot before sowing or before the start of each growing season, and then again after the end of each growing season, using a hydraulically driven, 25-mm soil corer (at the Condamine site, soil cores typically only penetrated to 1.5 m). In the first experimental period at Roma Research Station, gravimetric soil water content was measured only at sowing.

The core was separated into layers 0–0.15, 0.15–0.3, 0.3–0.6, 0.6–0.9, 0.9–0.12, 0.12–0.15, and 0.15–0.18 m. Each sample was weighed immediately and then dried at 105°C for ≥3 days. An aluminium access tube was installed in the centre of each plot at, or just after, sowing to a depth of 1.8 m (in some cases, access tubes could only be installed to 1.4–1.8 m). Neutron moisture meter (NMM) measurements were taken at depths 0.075, 0.225, 0.45, 0.75, 1.05, 1.35, 165, and 1.85 m every 4–6 weeks to monitor changes in profile soil water content over the experimental period. At Roma Research Station 2005–07, access tubes were installed only in annual lablab and butterfly pea plots, and to a depth of 1.3 m, and NMM measurements taken at 0.2, 0.4, 0.6, 0.8, 1.0, and 1.2 m.

The NMM used at each site was calibrated against soil moisture at each site using the samples taken throughout the experiment; these were all taken within 0.75 m of the access tube. At each site, the wet soil bulk density and soil drained upper limit were determined from a 'pond' installed approximately central to the experimental area, according to methods outlined by Dalgliesh and Foale (1998). A NMM access tube was also installed into the centre of each 'pond' to ensure that NMM counts at high soil moisture were available for the NMM calibration at each site.

Growing season water use was estimated from the change in profile soil water content between sowing and when maximum accumulated biomass was measured, and incident rainfall over this period. Estimated crop water use included all loss components of the water balance (evaporation, drainage, and runoff). Rainfall measured by collaborating farmers was used wherever possible, and where this record had gaps, rain from the

Table 3. Details of cultivar, seeding rate (bare seed), and row spacing for ley pasture legumes and annual forage grasses used in experiments

Common name	Species	Cultivar	Seed rate (kg/ha)	Row spacing (cm)
		Species sown summer–spring		
Sorghum (annual)	*Sorghum* spp. hybrid	Sugargraze	10	50
Sorghum (perennial)^{A}	*Sorghum* spp. hybrid	Silk	8	50
Lablab (annual)	*Lablab purpureus*	Highworth	20/15^{A}	50
Lablab (perennial)^{A}	*Lablab purpureus*	Endurance^{A}	12	50
Burgundy bean	*Macroptillium bracteatum*	Juanita/Cadarga	5	50/20^{A}
Butterfly pea^{A}	*Clitoria ternatea*	Milgara	8	20
		Species sown autumn–winter		
Lucerne	*Medicago sativa*	UQL-1	3	13
Oats	*Avena sativa*	Taipan^{B}	30	13
Snail medic	*Medicago scutellata*	Sava	5	13
Purple vetch	*Vicia benghalensis*	Popany	12	13
Sulla	*Hedysarum coronarium*	Wilpena	5	13

^{A}Only at Roma Research Station in 2005.

^{B}Except in 2010 when Genie was used.

closest location available in the Bureau of Meteorology SILO database was used (i.e. Brigalow Post Office No. 41 007 for Wychie, Chinchilla; Roma Downs No. 43 031 for 'Richmond Downs', Roma; Warkon No. 43 052 for 'Callitris', Condamine; Goondiwindi Airport No. 41 521 for 'Birribindibil', Toobeah). Growing season WUE of each forage species was calculated as the ratio of accumulated biomass at peak production in each year and water use from sowing to that time.

Statistical analyses

Analysis of variance in GENSTAT 13.1 (VSN International Ltd, Hemel Hempstead, UK) was used to determine where statistical differences in annual biomass production, water use, and WUE occurred amongst summer- or winter-growing species at each site separately. Tukey's confidence intervals ($P < 0.05$) were used to make multiple comparisons amongst species.

Economic analyses

To calculate the relative economic returns from the range of forages tested, mean biomass production over all experimental years reported in the study was calculated. For perennials (i.e. lucerne, sulla, and burgundy bean), production in the first year was considered separately from subsequent years. Using the mean biomass yield per year, the potential livestock production for each forage was estimated using approximations of forage utilisation (the proportion of biomass grown eaten by grazing livestock), and a feed conversion ratio (the liveweight gain obtained per kg forage eaten). Based on herbage acceptability and proportion of inedible or stem biomass, utilisation was assumed to be 0.45 for burgundy bean and lucerne; 0.40 for oats, vetch, sulla, and lablab; and 0.30 for forage sorghum. Feed conversion ratio was assumed to be 0.12 for oats, vetch, lucerne, and sulla; 0.10 for lablab and burgundy bean; and 0.08 for forage sorghum.

Income from livestock was calculated assuming a price of AU $1.75/kg liveweight, minus associated livestock costs of freight, animal health, and selling costs ($22/head). Growing costs were calculated to include three fallow herbicide applications before sowing, seed and sowing costs for each forage, fertiliser inputs for forage sorghum (60 kg N/ha) and oats (20 kg N/ha), and two suitable in-crop selective herbicide applications per year. Fallow and sowing costs were only incurred in the first year for the perennial legumes, and removal costs including herbicide application and cultivation were incurred in the final year of the phase. Annual gross margins and the break-even biomass and livestock production required were calculated for each of the forages. Estimates of fixed N were made for legumes assuming 20 kg fixed N per t biomass produced (Peoples *et al*. 2001).

Results

Seasonal conditions

A wide range of seasonal conditions were experienced over the five experimental years. The first experimental period 2005–07 at Roma Research Station was very dry, with rainfall well below average (decile 1–2) in both 2005–06 and 2006–07 summers and the intervening winter period (Table 4). During the second experimental period, summer rainfall across all sites was generally above average, with the exceptions of Chinchilla and Roma sites in 2008–09 (decile 3–4) (Table 4). The 2009–10 summer was particularly wet at the Condamine and Roma sites (>550 mm, decile 10). Rainfall was close to average in winter 2008, but below average in winter 2009 (decile 3–4), except at Chinchilla. In 2009, most of the winter rain occurred early in May–June, with a dry period with <25 mm of rain falling between July and September at all sites. The 2010 winter rainfall at Toobeah was well above average.

Summer-growing legumes

Experimental period 1: 2005–07, Roma Research Station

First-year production of sorghum was twice that of the best legumes, but in the second year, plant numbers of the short-lived perennial sorghum cv. Silk were greatly reduced and biomass production tended to be less than for all legumes, although not significantly lower ($P = 0.16$) (Table 5). Burgundy bean, and annual and perennial lablab produced similar biomass in their first year, ~3 t DM/ha. In the second year, burgundy bean and perennial lablab tended to be the most productive of the species, although not significantly more so than other species ($P = 0.16$). These two perennial species were able to commence growing after the first summer rains and had produced significant biomass before annual lablab could be re-sown. In both years, butterfly pea annual production tended to be lower than burgundy bean,

Table 4. Rainfall during the experimental seasons for winter forages (April–September) and summer forages (October–May) between 2005 and 2010 at five sites in southern Queensland

Deciles (1–10) are compared with long-term (122 years) seasonal rainfall for closest meteorological station

Growing season	Roma Research Station		Chinchilla		Roma		Condamine		Toobeah	
	(mm)	Decile	(mm)	Decile	(mm)	Decile	(mm)	Decile	(mm)	Decile
Oct.–May 2005–06	293	2								
Apr.–Sept. 2006	88	1								
Oct.–May 2006–07	273	2								
Apr.–Sept. 2007										
Oct.–May 2007–08			511	8						
Apr.–Sept. 2008			198	6	184	6	156	5		
Oct.–May 2008–09			367	4	285	3	372	6	402	7
Apr.–Sept. 2009			267	7	146	4	122	3	157	3
Oct.–May 2009–10			478	7	598	10	561	10	355	5
Apr.–Sept. 2010									344	9

Table 5. Plant density, biomass production, growing-season water use (growing-season rainfall in parentheses), and water-use efficiency (WUE, calculated assuming the mean water use in each year for all species) of tropical legumes and forage sorghum at Roma for growing seasons 2005–06 and 2006–07

Within columns, means followed by the same letter are not significantly different at $P = 0.05$

	Plant density (plants/m^2)		Accumulated DM (t DM/ha)		Growing-season water use (mm)		WUE (kg DM/ha.mm)	
	2005–06	2006–07	2005–06	2006–07	2005–06	2006–07	2005–06	2006–07
					(135)	(135)		
Sorghum (perennial)	36		6.8a	1.0a			28a	
Lablab (annual)	4	15	3.2b	1.2a	227a	133a	14b	9a
Lablab (perennial)	4	4	2.7b	2.7a			11b	21a
Burgundy bean	8	81	2.8b	2.9a			12b	22a
Butterfly pea	9	24	1.6b	1.5a	247a	132a	7b	11a

mainly due to slower growth during spring, although again, this was not statistically significant ($P > 0.05$).

No difference in water use was detected between annual lablab and butterfly pea (Table 5), with both species having fully exploited the soil profile during their first year and maintained a dry profile thereafter (Fig. 1*a*). With the dry conditions over the experimental period, it is probable that the other species also extracted all available water from the soil profile. Assuming all species had similar lower limit of water extraction, estimated WUE in the first year for burgundy bean and both of the lablab cultivars were 11–14 kg DM/ha (Table 5), while WUE of forage sorghum cv. Silk was significantly higher (28 kg DM/ha). The second year WUE of burgundy bean and perennial lablab were estimated to be much higher (20–22 kg DM/ha) than the other species. Soil water extraction by forage sorghum in the second year may have been reduced by its poor persistence; hence, WUE was not calculated.

Experimental period 2: 2007–10

In all experimental years, forage sorghum biomass production was 2–3.5 times higher than the best of the summer legumes (Table 6). The one exception was in the first year at Chinchilla, where maximum biomass from forage sorghum was underestimated due to an unintended grazing of these plots by livestock. Of the summer legumes, lablab production was generally more than burgundy bean in the first year due to slower and/or variable establishment of burgundy bean. This was especially evident at Toobeah in 2008–09, where established densities of burgundy bean were low. In subsequent years, burgundy bean production was similar to lablab, with burgundy bean densities increased by recruitment of seedlings (Table 6). Lucerne production in the first summer was similar to lablab and burgundy bean, but production in the second year dropped off substantially and was <50% of that of burgundy bean and lablab.

In 2007–08 and 2008–09 seasons at all sites, growing-season crop water-use was greater than rainfall over the period, and hence, all species extracted stored soil water during this period (Table 6). In its first year, lucerne extracted more stored soil water than the other species and, hence, had higher growing-season water use in its first year ($P < 0.05$) (Table 6; Fig. 1). Lucerne then maintained 70–150-mm drier soil profiles than other species (Fig. 1), although water use in subsequent years was similar to the other species. At all sites, profile soil water content and growing season water use was similar ($P > 0.05$) between burgundy bean, lablab, and forage sorghum throughout; however, it appeared that in autumn 2010, burgundy bean extracted more soil water than lablab or forage sorghum (Fig. 1*c*, *e*).

Forage sorghum had much higher WUE than the legumes, ranging from 22 to 47 kg DM/ha.mm. Lucerne always had the lowest WUE at each site (<10 kg DM/ha.mm). In addition, there was evidence that lucerne roots explored below the monitoring depth (1.5–1.8 m), and hence, additional water extraction below this depth would result in even lower WUE. There was significant variation between years and locations in WUE of lablab (8–30 kg DM/ha.mm) and burgundy bean (7–20 kg DM/ha.mm). Lablab WUE was higher than that of burgundy bean in the first year at three of the four experimental sites, but in subsequent years there was little difference in WUE between these species.

Winter-growing legumes

Biomass production from forage oats was significantly higher than all legumes in 2008 and 2010 ($P < 0.05$), but not in the winter season of 2009 (Table 7). In 2009, oats established and grew poorly due to dry conditions following sowing, whereas the regenerating legumes (sulla and snail medic) were already well established and growing and able to utilise the early-season rain in this winter. Of the winter legumes, production and WUE of snail medic and sulla was quite variable between seasons (Table 7). Snail medic establishment and production was poor in the first year (2008) at all sites, but in 2009 (including first year at Toobeah), when good snail medic stands were established, production was significantly ($P < 0.001$) better than oats and vetch (Table 7). First-year production of sulla was similar to or greater than other annual legumes in 2008. Sulla production was best in seasons with good spring rainfall (e.g. 2008 at Roma and 2010 at Toobeah), where it was the most productive legume. At three of the four sites there were large reductions in sulla plant densities over the summer, with 19–34% of plants surviving and low plant numbers present in the second year (Table 7). Purple vetch was never the most productive legume and produced <1.8 t DM/ha in all seasons except 2010 at the Toobeah site, where it produced 2.7 t DM/ha.

At the Chinchilla and Toobeah sites, there was no significant difference in the growing-season crop water use between any species ($P > 0.05$). At Roma in 2008, sulla had significantly higher growing-season water use than snail medic or vetch ($P = 0.01$),

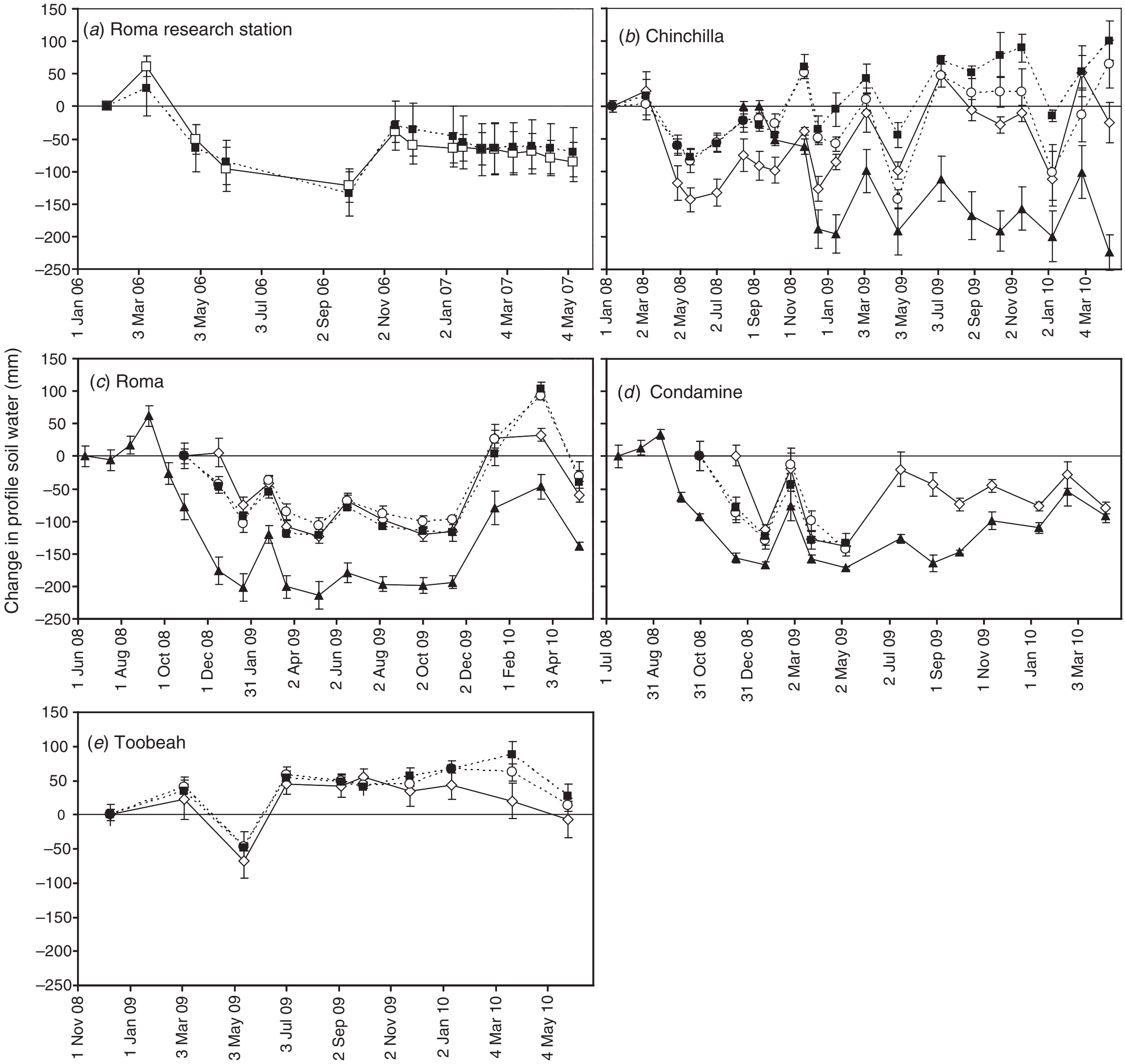

Fig. 1. Change in profile soil water content under forage sorghum (○), butterfly pea (□), burgundy bean (◇), lablab (■), and lucerne (▲) over five experimental periods at: (*a*) Roma, January 2005–December 2007, 0–1.2 m depth; (*b*) Chinchilla, January 2008–April 2010, 0–1.8 m depth; (*c*) Roma, June 2008–May 2010, 0–1.5 m depth; (*d*) Condamine, July 2008–May 2010, 0–1.2 m depth; (*e*) Toobeah, December 2008–June 2010, 0–1.8 m depth. Error bars show the standard error of mean ($n = 4$).

and oats at Condamine had significantly higher water use than other species in both years ($P < 0.001$). Sulla also used significantly less water than other species in 2009 at Condamine ($P < 0.001$), possibly due to the low second-year plant populations at the site. At all sites, there was evidence that sulla extracted more soil water, and hence, the soil profile was 60–100 mm drier than under the other winter-growing annual forages, particularly during late spring and early summer (Fig. 2). Because water use at this time of the year was outside the growing season, it was not evident in greater in-crop water use, as calculated in Table 7. However, sulla did not dry the soil profile as much as lucerne, with a profile a further 60–100 mm drier than under sulla (Fig. 2).

The WUE of all the winter-growing species was highly variable between seasons and locations (Table 7); forage oats WUE ranged from 4 to 28 kg DM/ha.mm, snail medic from 3 to 25 kg DM/ha.mm, vetch from 3 to 14 kg DM/ha.mm, and sulla from 5 to 19 kg DM/ha.mm. This variability seemed to be driven

Table 6. Comparison of summer-growing ley pasture legumes and forage sorghum cumulative annual biomass production, in-crop water use (in-crop rainfall in parentheses), and water-use efficiency (WUE) at four experimental sites for growing seasons 2007–2010 in southern Queensland

Within site-years, means followed by the same lower case letter are not significantly different at $P = 0.05$. n/a, Measurements not taken

	Plant density (plants/m^2)			Accumulated DM (t DM/ha)			In-crop water use (rainfall) (mm)			WUE (kg DM/ha.mm)		
	2007–08	2008–09	2009–10	2007–08	2008–09	2009–10	2007–08	2008–09	2009–10	2007–08	2008–09	2009–10
Chinchilla							(213)	(462)	(395)			
Forage sorghum	20	n/a	17	7.6[A]a	22.2a	14.5a	272a	578b	401a	28[A]a	38a	36a
Lablab	5	16	10	8.1a	8.6b	7.8b	274a	462c	373a	30a	19b	23ab
Lucerne		41	25		7.2b	0.8[A]c		740a	392a		10c	2[A]c
Burgundy bean	33	52	89	4.9b	9.2b	6.2b	331a	462c	392a	15a	20b	16b
Roma								(341)	(591)			
Forage sorghum		21	11		9.0a	15.4a		407b	521a		22a	30a
Lablab		10	7		4.0b	4.2b		441b	515a		9b	8b
Lucerne		39	18		4.0b	1.4c		701a	531a		6b	3c
Burgundy bean		n/a	68		3.5b	4.8b		430b	531a		8b	9b
Condamine								(360)	(576)			
Forage sorghum		n/a			14.9a			433b			35a	–
Lablab		n/a			4.5b			424b			11b	–
Lucerne		48	22		5.8b	1.9a		632a	503b		9b	4a
Burgundy bean		18	42		4.7b	4.5a		429b	612a		11b	7a
Toobeah[B]								(281)	(283)			
Forage sorghum		14	16		12.8a	15.6a		329a	335a		39a	47a
Lablab		8	7		4.6b	4.4b		329a	323a		14b	14b
Burgundy bean		8	90		2.4c	4.6b		349a	333a		7c	14b

[A] Maximum DM was underestimated due to crop senescence or other problems.

[B] Lucerne was sown but was not measured because establishment and growth were impacted by feral animal grazing.

Table 7. Comparison of winter-growing forage legumes and forage oat accumulated annual biomass production, in-crop water use (in-crop rainfall in parentheses), and water-use efficiency (WUE) for growing seasons 2008–2010 at four experimental sites in southern Queensland

Within site-years, means followed by the same lower case letter are not significantly different at $P = 0.05$. n/a, Measurements not taken

	Plant density (plants/m^2)			Accumulated DM (t DM/ha)			In-crop water-use (rainfall) (mm)			WUE (kg DM/ha.mm)		
	2008	2009	2010	2008	2009	2010	2008	2009	2010	2008	2009	2010
Chinchilla							(271)	(174)				
Oats	44	10		3.8a	1.1b		275a	243a		14a	4c	
Snail medic	24	60		0.8b	3.4a		291a	243a		3b	14ab	
Purple vetch	21	22		1.5b	1.4b		249a	205a		6b	7bc	
Sulla	25	20		1.5b	4.0a		295a	239a		5b	17a	
Roma							(145)	(110)				
Oats[B]	15	7		5.1a	n/a		185ab			15a		
Snail medic	8	n/a		0.7[A]c	2.0a		132b	169a		4[A]b	13a	
Purple vetch	8	4		1.7c	n/a		120b			14ab		
Sulla	33	10		3.4[A]b	1.0a		205a	116a		17[A]a	14a	
Condamine							(100)	(97)				
Oats	28	15		4.9a	1.4b		232a	218a		21a	6b	
Snail medic	17	n/a		1.8b	2.9a		134b	133b		14ab	22a	
Purple vetch	12	28		1.8b	0.5b		161b	149b		11b	3b	
Sulla	30	8		0.8[A]b	1.7b		117b	92c		8b	19a	
Toobeah								(48)	(298)			
Oats		24	13		1.7b	7.7a		126a	290a		15b	28a
Snail medic		33	n/a		3.6a	1.3b		147a	325a		25a	4b
Purple vetch		13	10		1.4b	2.7b		116a	347a		12b	8b
Sulla		36	5		1.5[A]b	4.1b		117a	362a		13b	12b

[A] Maximum DM was underestimated due to crop senescence or other problems.

[B] DM peak measured 16 Dec., but water use and WUE calculated to 17 Oct. to correspond with other species.

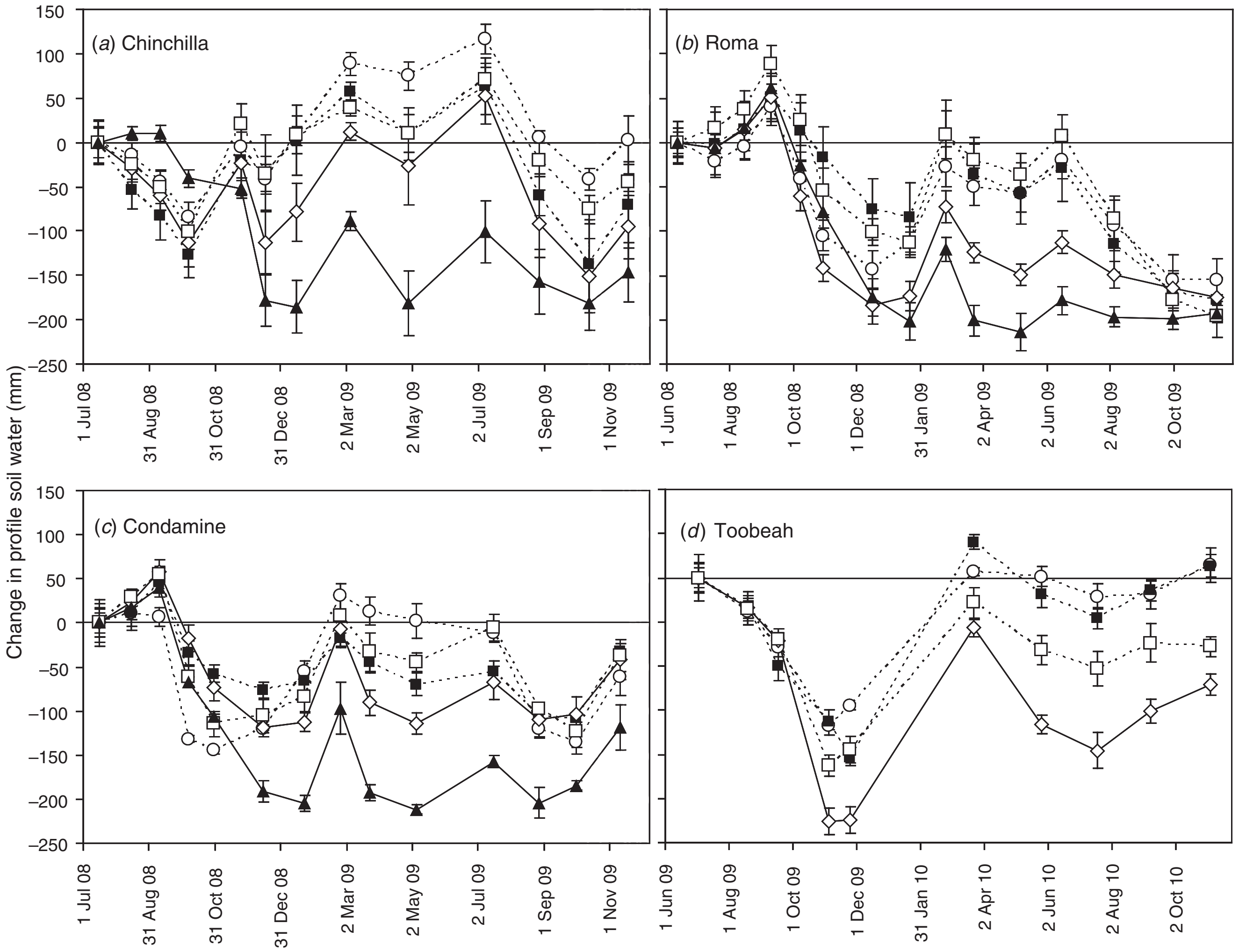

Fig. 2. Change in profile soil water content under forage oats (○), snail medic (■), vetch (□), sulla (◇), and lucerne (▲) over four experimental periods at: (*a*) Chinchilla, July 2008–November 2009, 0–1.8 m depth; (*b*) Roma, June 2008–December 2009, 0–1.5 m depth; (*c*) Condamine, July 2008–November 2009, 0–1.5 m depth; (*d*) Toobeah, July 2009–November 2010, 0–1.8 m depth. Error bars show the standard error of mean (*n* = 4).

largely by the ability of the forages to establish a dense sward; low WUE values were measured where lower plant densities were present. In seasons where oats performed well, it had higher WUE than the legumes, i.e. at Chinchilla and Condamine 2008 and Toobeah 2010. Apart from those seasons where production was poor due to poor establishment or where maximum DM was underestimated, sulla, snail medic, and vetch had similar WUE.

Economics of ley legumes and forages

Estimates of average economic returns from the various forages revealed that while biomass yield of forage sorghum may be higher than that of the forage legumes, economic returns were not necessarily better (Table 8). Allowing for assumptions of lower forage utilisation and feed conversion rate for livestock grazing forage sorghum, estimated livestock production and income were still higher than from the forage legumes, but growing costs were higher due to N fertiliser requirements and annual sowing and fallow costs. Over a 3-year phase of burgundy bean, estimated average gross margin was the equivalent of forage sorghum, and $80–100/ha higher than lucerne or lablab. In burgundy bean, high initial growing costs and lower first-year production meant that first-year returns were minimal ($35/ha), yet higher productivity and low growing costs in subsequent years were sufficient to make up for this deficit. Lucerne, on the other hand, was most profitable in its first year; declining productivity in the second and third year reduced mean returns over a 3-year phase. Estimated gross margin returns from winter-growing forages were lower than summer-growing options due to lower productivity. Average gross margin from forage oat was higher than purple vetch or sulla. Sulla had higher growing costs in the first year due to higher seed costs ($115/ha), and hence, break-even production was significantly higher than other options. In all cases, the economic returns of the forage legumes would be greatly enhanced if the atmospherically fixed N contributions were considered. Estimated N contributions were 50–100 kg/ha.year, which, if valued, would increase average annual returns

Table 8. Estimated gross margins (GM, AU$), growing costs, livestock weight gain (LWG) and income predicted from mean biomass yield of experimental seasons from summer-growing (*n* = 11) and winter-growing (*n* = 8) forage legumes compared with forage sorghum and forage oats, respectively

Break-even biomass yield and livestock production to cover growing costs over the whole phase length and estimated fixed nitrogen value (based on 20 kg N fixed/t DM growth) were also calculated

Forage option (length of phase, years)	GM ($/ha.year)	Growing costs ($/ha.year)	Livestock production^{A} (kg LWG/ha.year)	Livestock income ($/ha.year)	Break-even production over phase DM yield (t/ha)	Break-even production over phase LWG (kg/ha)	Mean biomass yield (t DM/ha.year)	Estimated fixed N^{B} (kg/ha)
Summer-growing species								
Forage sorghum (1)	209	232	330	442	8.8	211	13.8	0
Lablab (1)	114	157	200	275	3.4	135	5.0	100
Burgundy bean (3)	205	81	215	228	7.3	327	4.8	286
Year 1	35	190	166	225			3.7	74
Year 2	277	47	239	324			5.3	106
Year 3	240	83	239	324			5.3	106
Lucerne (3)	90	112	147	203	5.3	285	2.7	163
Year 1	255	160	284	416			5.2	105
Year 2	48	49	79	97			1.5	29
Year 3	–32	128	79	97			1.5	29
Winter-growing species								
Oats (1)	63	175	178	238	2.9	142	3.7	0
Vetch (1)	–33	119	66	86	1.8	85	1.4	28
Sulla (2)	16	136	118	151	4.5	217	2.5	98
Year 1	–86	217	106	131			2.2	44
Year 2	118	55	130	173			2.7	54

^{A}LWG = Yield_{DM} × utilisation (kg forage consumed/kg grown) × feed conversion rate (kg LWG/kg forage consumed).

^{B}Calculated based on 20 kg N.

from most forage legumes to levels similar or higher than annual forage grasses.

Discussion

Productivity of ley legumes and forages

In this study, we showed that the summer-growing forage legumes lablab and burgundy bean can be very productive, producing >8 t DM/ha under favourable conditions. Other studies have also reported similar annual biomass yields of 7–8 t DM/ha from burgundy bean and lablab in this environment (Jones and Rees 1997; Whitbread *et al*. 2005). Lablab and burgundy bean out-yielded butterfly pea in both years during the Roma experiment, which validates their advantage over butterfly pea in the cooler regions of the subtropics (Pengelly and Conway 2001). Although lucerne production in the first year matched lablab, lucerne productivity declined substantially in subsequent years. On the other hand, burgundy bean biomass production in its first year was lower than, or equal to, lablab, but in subsequent years their production was similar. This increase in productivity is related to the longer period of establishment required for burgundy bean in its first year and the subsequent seedling recruitment and increased plant density in subsequent years. From this study and previous reports, first-year burgundy bean production ranges from 50% to 108% (77% average) of lablab (includes cvv. Rongai, Highworth, and Endurance) (Jones and Rees 1997; Clem and Cook 2004; Whitbread *et al*. 2005). However, the ability of burgundy bean to persist and recruit from seed means it has both agronomic and economic advantages over lablab because it can produce for ≥3 years.

Despite the positive performance of burgundy bean and lablab, it is clear that these legumes, when managed as legume-only pastures, are rarely capable of producing as much biomass for grazing as forage sorghum, with annual forage sorghum producing between twice and three times as much biomass as the summer-growing legumes in every year. Jones and Rees (1997) reported first-year production of annual lablab similar to forage sorghum cv. Silk, whereas in both first and second years, burgundy bean and siratro (*Macroptillium atropurpureum*) production was 50% and 60–65% of Silk sorghum, respectively. In contrast, we found that forage sorghum cv. Silk produced more biomass than lablab in its first year but persisted poorly and that relative productivity dropped off in the second year and was inferior to both perennial lablab and burgundy bean. The lower production in forage sorghum cv. Silk in the second year was probably related to low mineral-N availability.

A major gap in current information is the relative forage quality and potential livestock production from burgundy bean and lablab compared with forage sorghum. Current experimental evidence does not suggest that growth rates of livestock grazing summer-growing ley legumes are high enough to compensate for the higher biomass production of forage sorghum to achieve similar total livestock production per hectare. In two separate studies in Queensland, average beef cattle growth rates were 0.63 kg/head.day for lablab, burgundy bean, and butterfly pea (Clem 2004), which are not substantially higher than growth rates reported on forage sorghum (French *et al*. 1988). Despite their lower productivity, our economic analysis shows that the ley legumes could be equally as profitable as, or more profitable than, forage sorghum, due to lower input costs, particularly in the second and third years of burgundy bean and if N inputs are considered.

Similar to the summer forages, in the seasons where forage oats established well, its production exceeded the ley legumes. However, the results in the 2009 season demonstrate a situation where a perennial (sulla) or regenerating annual (snail medic) legume is advantaged by utilising early winter rainfall compared with waiting to sow an annual forage crop such as oats or vetch. It was clear that under favourable conditions in spring, sulla could be very productive; our results suggest that biomass yields of 2–6 t DM/ha are more likely in most years for sulla in this environment. Mean snail medic production of 2.25 t DM/ha in this study was the equivalent of production reported by Weston *et al*. (2002) in seasons with similar growing season rainfall (130–200 mm), but this was much lower than measured under favourable conditions (e.g. 5.4 and 8.8 t DM/ha; Thomas *et al*. 2009). Compared with the other two ley legumes, purple vetch was visually impressive but its production averaged only 1.4 t DM/ha over the eight experimental years, and was less than 2.0 t DM/ha in all but one year. This study further demonstrates the high variability in production from winter-growing temperate forages in the subtropics. For example, in both the present study and other studies, the variability in medic production is high, with a coefficient of variation (i.e. ratio of standard deviation to mean) in biomass yield of >69% (Clarkson *et al*. 1987; Weston *et al*. 2002).

Water-use efficiency and water use of ley legumes and forages

Forage sorghum displayed the highest WUE of the forage species tested here (22–47 kg DM/ha.mm); the only exception being the second year of Silk sorghum at Roma in 2006–07, where low plant populations reduced production. Since sorghum is a C4 plant, it is expected to achieve a higher WUE than the C3 legumes and oats. Forage sorghum transpiration efficiency (i.e. biomass production per mm water transpired) has been reported to be 61 kg DM/mm (Ferraris and Charles-Edwards 1986), compared with 25–35 kg DM/ha.mm reported in C3 forage legumes cow pea and subterranean clover (Ashok *et al*. 1999; Bolger and Turner 1998); no measures of transpiration efficiency were found in the literature for the species included in this study. Plant resources diverted to biological nitrogen fixation would also reduce transpiration efficiency of legumes compared with a grass that is provided with a mineral nitrogen source.

Lablab WUE ranged from 9 to 30 kg DM/ha.mm (averaging 15.2 kg DM/ha.mm over 12 site-years) and burgundy bean from 7 to 20 kg DM/ha.mm (averaging 12.8 kg DM/ha.mm over 11 site-years). Burgundy bean WUE was typically lower than lablab in the first year, but similar in subsequent years. Our results are similar to reported lablab WUE of 9–14 kg DM/ha.mm in tropical northern Australia under irrigation regimes ranging from fully watered to dryland (Muchow 1985), and correspond to lablab WUE estimated using growing-season rainfall reported in other experiments and using a crop simulation model in the subtropics (13–17 kg DM/ha.mm in-crop rain) (Whitbread *et al*. 2005; Hill *et al*. 2006). However, McDonald *et al*. (2001) reported much higher WUE of partially and fully irrigated lablab in subtropical northern New South Wales (46–55 kg DM/mm); these values seem unrealistically high under dryland conditions, at least. The large variation in WUE of lablab and burgundy bean between sites and years indicates that there are environmental factors that can significantly influence WUE of these species; in particular, WUE was generally lower at the drier, western sites, presumably because a greater proportion of crop water use was evaporation.

In general, the potential WUE values of the winter-growing legumes and oats were similar, and higher than the summer-growing legumes. Excluding seasons where poor establishment reduced productivity, oats WUE ranged from 14 to 28 kg DM/ha.mm, snail medic from 13 to 25 kg DM/ha.mm, and sulla from 12 to 20 kg DM/ha.mm, although vetch WUE was generally lower (6–14 kg DM/ha.mm). However, in seasons where legume production was low due to poor establishment, WUE was often <7 kg DM/ha.mm. High variability in WUE, including seasons with very low WUE, for annual medics has been reported by others (e.g. 3–15 kg DM/ha.mm; Holford and Crocker 1997). The measured WUE values for annual medics reported elsewhere were at the lower end of our measurements (e.g. 11.5 and 13.0 kg DM/ha.mm, Thomas *et al*. 2009; 13.9 kg DM/ha.mm rain, Weston *et al*. 2002). These other studies typically calculated WUE from winter rainfall (Apr.–Oct.), whereas in our study, the water use was calculated over a shorter period from sowing or germination to maximum accumulated biomass.

Lucerne had the lowest WUE (ranging from 2.5 to 9.8 kg DM/ha.mm) of the ley legumes tested here. This was primarily because of its greater water use in the first year and poor conversion of rainfall to biomass in the second year. Our measures were a little lower than in other studies in Australia's subtropics, which report lucerne WUE between 5.5 and 14 kg DM/ha.mm (e.g. Lloyd and Hilder 1978; Holford and Croker 1997; Dalal *et al*. 2004*a*). However, these studies all relate biomass production to growing-season or annual rainfall; few others have accounted for changes in soil water. Others have also reported low WUE of lucerne during summer, <5 kg DM/ha.mm (Hirth *et al*. 2001; Dalal *et al*. 2004*b*; Thomas *et al*. 2009), especially under dry growing conditions. Overall, the lower lucerne WUE values found here and in past studies compare poorly to the efficiency with which other ley legumes converted water to biomass. However, it should be noted that here we have compared growing-season WUE, and hence the ability of lucerne to utilise rain and grow throughout the year means that its annual WUE is likely to be better than that of species that only grow for part of the year.

The degree to which lucerne extracts water from the soil profile has been found to be a major limitation for it profitable use in crop rotations in the subtropics (Murray-Prior *et al*. 2005), and has been shown to significantly reduce soil water available at sowing and yields of subsequent crops (Holford 1980; Holford *et al*. 1998; Dalal *et al*. 2004*a*; Thomas *et al*. 2009). In this study, we found that burgundy bean and sulla did not dry the soil profile to the same extent as lucerne, although sulla did extract 60–100 mm more soil water than the annual forage species. We believe this is the first study to compare soil water extraction between sulla and other pasture legumes. Water use and soil water extraction by burgundy bean was similar to annual forage sorghum and lablab in this study, but others have found it to dry the soil profile more than annual cropping systems. Whitbread *et al*. (2005) found the soil profile following 3 years of burgundy bean and before sowing a subsequent crop to be 24 mm drier than after lablab and 37 mm drier than after continuous wheat; however, the fallow was 3 months longer after wheat. This lower soil-water resulted in a wheat yield reduction of ~1 t/ha compared with continuous wheat and 0.35 t/ha compared with lablab. At another site, there was no difference in soil water content and grain yield following lablab or burgundy bean, but butterfly pea had dried the profile significantly more and reduced wheat yield by ~700 kg/ha (Whitbread *et al*. 2005). In this study, butterfly pea and lablab had similar soil water extraction. In central Queensland, lablab and siratro (closely related to burgundy bean) extracted ~50 mm more water from the soil (to 1.2 m) than mungbean or grain sorghum (Armstrong *et al*. 1999). Overall, it appears that the greater soil water extraction reported in lablab and burgundy bean is related to their longer growing season compared with grain crops and is not due to water extraction from deeper soil layers (>1.2–1.5 m).

New ley legumes in subtropical farming systems

Burgundy bean demonstrated several advantages over existing tropical ley legumes suited to short-term crop rotations in subtropical farming systems, but there are still several issues that need to be resolved to facilitate wider use. This study validated the greater productivity of burgundy bean than butterfly pea in the subtropics, which is most likely related to the lower temperature requirement for growth in burgundy bean (Pengelly and Conway 2001). Burgundy bean displayed the capacity to produce similar biomass to lablab under the same growing conditions, but its ability to persist for ≥3 years and maintain or increase its productivity has advantages over annual or perennial lablab, and lucerne. Longer phases of burgundy bean have economic advantages over lablab, despite higher seed expenses, because the sowing costs will be spread over several years. The lower soil water extraction than lucerne is a clear advantage of burgundy bean, allowing a shorter fallow period before cropping and hence greater flexibility in transitioning between a ley legume and cropping phase. Overall, in subtropical systems, burgundy bean seems to fit a similar role to butterfly pea in more tropical systems (Conway *et al*. 2001).

Nonetheless, there are several key information gaps that require further understanding before burgundy bean's potential role in crop rotations can be fully realised. First is its tolerance to herbicides and the ability to control crop weeds during a phase of burgundy bean. From our studies, it seems feasible to apply non-selective control of weeds during winter when burgundy bean is dormant. This could be a significant advantage in cropping systems, especially for managing weed populations that have resistance to selective herbicides. In-crop grass control with selective residual herbicides such as imazethapyr is possible, but the high cost is likely to be prohibitive. Second, since burgundy bean can set large quantities of seed, the persistence of this seed bank in the soil and the ability to control volunteer burgundy bean in a subsequent crop or strategies to reduce seed set before terminating a phase of burgundy bean requires greater understanding. Third, while estimates suggest burgundy bean could provide significant N fixation inputs to a cropping system, this has received little quantification experimentally. Whitbread *et al*. (2005) found similar levels of soil mineral N after burgundy bean and lablab (and higher than butterfly pea) before sowing a wheat crop, and this 100–110 kg more mineral N resulted in a 1.2–1.5% increase in wheat protein content compared with continuous wheat. Finally, information about techniques for harvesting seed from burgundy bean that allows growers to produce their own seed cheaply would reduce the high initial costs compared with other options and/or may enable higher seeding rates to establish denser stands of burgundy bean, which may improve its first year production.

Sulla has shown the capacity to produce large amounts of biomass, which can rival oats in good years, yet its production here was variable and seems to be favoured by moist spring conditions. Sulla's role in crop rotations would be similar to lucerne, involving rotations of 2–3 years but providing non-bloating forage and winter-dominant growth pattern as opposed to spring–summer growth in lucerne. However, a major problem observed in subtropical environments is the poor persistence of plants over the first summer, which may be due to the susceptibility of sulla to Rhizoctonia crown and root rot (Ryley *et al*. 2004). The current high seed costs of sulla require it to persist for >1 year to be economically viable. Sulla has the capacity to recruit from seed, which can increase or maintain sward density; however, this typically precludes grazing in its first year. Cheaper seed supplies may see sulla be used in single-year rotations, but difficulties threshing seed from pods restrict the ability of growers to harvest their own seed. There is large variability in hardseededness in sulla (Bell *et al*. 2003), and soft-seeded types might enable pod to be sown directly and reduce seed cost. As in burgundy bean, there is little information about the ability of sulla to tolerate herbicide and how weeds might be managed during a phase of sulla and the N inputs it could provide to a cropping system.

Lablab cv. Endurance showed some advantages over annual lablab in the present study and has also been shown to be more productive than burgundy bean and butterfly pea, although its persistence beyond 2 years seems to be poor (Whitbread *et al*. 2005). However, the perennial lablab cultivar is no longer available commercially due to low adoption by industry (Nichols *et al*. 2007).

Conclusions

We found that of the forage legumes available for integration into cropping systems in the northern cropping region, burgundy bean and lablab were the most reliably productive and profitable options. Burgundy bean dried the profile no further than annual forages and much less than lucerne and, hence, is unlikely to have the same issues refilling the soil profile when returning to a cropping after a phase of forage legume. Production from winter legumes was variable. Sulla showed high production potential under some conditions but its persistence to a second year was poor and its currently high growing costs impede its attractiveness to growers. Sulla dried the profile more than other winter-growing legumes but less than lucerne. The WUE of lucerne was the lowest of the legumes tested, due to its higher water use in the first year and poor production in the second year. Despite the positive performance of some of the new ley legume options here, further evidence of the rotational benefits provided by these legumes is required before farmers would be willing to accept the reduced productivity compared with other annual forages currently used.

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