CSIRO PUBLISHING
Animal Production Science, 2011, **51**, 904–919 www.publish.csiro.au/journals/an

The role of tillage, fertiliser and forage species in sustaining dairying based on crops in southern Queensland 2. Double-crop and summer sole-crop systems

R. G. Chataway[A,C], *J. E. Cooper*[B], *W. N. Orr*[A] and *R. T. Cowan*[A]

[A]Department of Employment, Economic Development and Innovation, University of Queensland, Gatton Campus, John Mahon Building 8105, Lawes, Qld 4343, Australia.
[B]Department of Employment, Economic Development and Innovation, PO Box 2282, Toowoomba, Qld 4350, Australia.
[C]Corresponding author. Email: robert.chataway@gmail.com

Abstract. Dairy farms located in the subtropical cereal belt of Australia rely on winter and summer cereal crops, rather than pastures, for their forage base. Crops are mostly established in tilled seedbeds and the system is vulnerable to fertility decline and water erosion, particularly over summer fallows. Field studies were conducted over 5 years on contrasting soil types, a Vertosol and Sodosol, in the 650-mm annual-rainfall zone to evaluate the benefits of a modified cropping program on forage productivity and the soil-resource base. Growing forage sorghum as a double-crop with oats increased total mean annual production over that of winter sole-crop systems by 40% and 100% on the Vertosol and Sodosol sites respectively. However, mean annual winter crop yield was halved and overall forage quality was lower. Ninety per cent of the variation in winter crop yield was attributable to fallow and in-crop rainfall. Replacing forage sorghum with the annual legume lablab reduced fertiliser nitrogen (N) requirements and increased forage N concentration, but reduced overall annual yield. Compared with sole-cropped oats, double-cropping reduced the risk of erosion by extending the duration of soil water deficits and increasing the time ground was under plant cover. When grown as a sole-crop, well fertilised forage sorghum achieved a mean annual cumulative yield of 9.64 and 6.05 t DM/ha on the Vertosol and Sodosol, respectively, being about twice that of sole-cropped oats. Forage sorghum established using zero-tillage practices and fertilised at 175 kg N/ha.crop achieved a significantly higher yield and forage N concentration than did the industry-standard forage sorghum (conventional tillage and 55 kg N/ha.crop) on the Vertosol but not on the Sodosol. On the Vertosol, mean annual yield increased from 5.65 to 9.64 t DM/ha (33 kg DM/kg N fertiliser applied above the base rate); the difference in the response between the two sites was attributed to soil type and fertiliser history. Changing both tillage practices and N-fertiliser rate had no affect on fallow water-storage efficiency but did improve fallow ground cover. When forage sorghum, grown as a sole crop, was replaced with lablab in 3 of the 5 years, overall forage N concentration increased significantly, and on the Vertosol, yield and soil nitrate-N reserves also increased significantly relative to industry-standard sorghum. All forage systems maintained or increased the concentration of soil nitrate-N (0–1.2-m soil layer) over the course of the study. Relative to sole-crop oats, alternative forage systems were generally beneficial to the concentration of surface-soil (0–0.1 m) organic carbon and systems that included sorghum showed most promise for increasing soil organic carbon concentration. We conclude that an emphasis on double- or summer sole-cropping rather than winter sole-cropping will advantage both farm productivity and the soil-resource base.

Additional keywords: farming systems, forage lablab, forage sorghum, livestock, manure, oats, rain-grown, soil nitrate-N, soil organic carbon, zero-till.

Introduction

In the subtropical cereal belt of Australia, dairy farming is based on a succession of cereal crops, grown predominantly as sole-crops in winter or summer, rather than pastures. Forage crops are also grown in this region for beef and prime lamb production (Harris *et al*. 1999; Stuart 2002) and there is increased interest in their use in dairying in southern Australia (Chapman *et al*. 2008; Jacobs and Ward 2011). Dairy farms based on annual crops in this region face threats to long-term productivity from soil erosion (Harris *et al*. 1999), fertility decline (Dalal and Mayer 1986) and suboptimal productivity (Ashwood *et al*. 1993; Kerr *et al*. 2000). Winter forage systems are particularly vulnerable to erosion because conventional farming practices leave the soil with little or no plant cover over the summer period, when rainfall can be intense (Webb *et al*. 1997).

Strategies to improve productivity and minimise negative impacts on the soil-resource base of the dominant forage system, namely oats (*Avena sativa*) grown as a sole-crop, was investigated by Chataway *et al*. (2011). Changes to tillage practices, increased rates of nitrogen (N) fertiliser or a rotation of oats with annual legumes had some benefits on forage quality but were generally ineffectual in raising productivity above that

 10.1071/AN11032 1836-0939/11/100904

achieved using industry-standard practices. The low productivity of these systems (typically 2–5 t DM/ha.annum) also left limited residue following grazing to protect soil from erosion over the fallow and contribute to the soil organic matter (SOM) pool. While the temperate perennial legume lucerne (*Medicagao sativa* L.) can be a partial substitute for oats (Minson *et al*. 1993; Chataway *et al*. 2011), and has some soil-resource benefits, cereal crops are still required to provide the bulk of winter forage production in rain-grown systems. An alternative to sole-cropped oats would be growing oats within a double-cropping program. Growing two crops in the 1 year would increase the potential quantity of plant residue available to contribute to the SOM pool (Peterson *et al*. 1998) and the soil would be better protected from erosion (Freebairn *et al*. 1997; Buxton *et al*. 1999). However, while double cropping for forage production is common where temperature and water conditions are favourable (Lloveras-Vilamanya 1987; Garcia *et al*. 2008), it is less common in semiarid agricultural regions (Chataway *et al*. 2003). For cereal crops grown for grain, double-cropping on a routine basis is not regularly practiced due to the risk of crop failure as a result of water stress (Russell and Jones 1996) and opportunity cropping, rather than fixed sole- or double-cropping, is recommended (Wylie 1993). More recently, Singh *et al*. (2009*a*) determined that a profitable wheat crop (>1 t grain/ha) could be grown in just over 50% of years in the 600-mm-rainfall isohyet when double-cropped with forage lablab. Because forage crops offer greater management flexibility than do grain crops (Muldoon 1984), they have more scope in a double-cropping program. However, given adequate nutrition and water, they have a potentially longer growing season (French 1981), which may be underutilised in a double-cropping program.

Insufficient plant nutrients and time for ground preparation are also cited by dairy farmers as limiting factors (Chataway *et al*. 2003). The adoption of 'zero' or 'no-tillage' planting (Thomas *et al*. 2007) would go a long way to addressing the latter issue, and increasing the application of plant nutrients, in fertilisers and/or manure, should address the other. In the present study, we hypothesise that a short-term summer crop can be combined with a winter crop, with resultant productivity and soil-resource benefits over a winter sole-crop.

With respect to summer crops, hybrid forage sorghums (*Sorghum* spp.) are the most commonly grown species (Kerr *et al*. 1996). These crops are typically sown into a cultivated seedbed, following a period of fallow over winter, with N fertiliser applied at a rate similar to that for winter forage crops of ~50 kg N/ha (Kerr *et al*. 1996; Chataway *et al*. 2003). In the present study, we refer to these agronomic practices as 'industry standard'. Forage sorghum is noted for its high potential yield, efficient use of water and, particularly under irrigated conditions, its response to higher rates of N fertiliser (Muldoon 1985; Rahman *et al*. 2001). If improvements could be made to the productivity of *Sorghum* spp., and in turn residue production, this would have benefits for soil erosion and the soil C balance (Paustian *et al*. 1997; Strong and Holford 1997). These benefits would be enhanced if crops could be successfully established using zero-tillage methods (Unger *et al*. 1991). In sole-crop systems, unless crops are planted into stubble, considerable erosion can be caused by early summer storms (Wockner and Freebairn 1990). The inclusion of an annual legume in the system would reduce system requirements for N fertiliser, improve overall forage quality (Muldoon 1985*b*; Minson *et al*. 1993) and meet farmers desire to increase the proportion of legumes in the forage base (Chataway *et al*. 2003). However, potential biomass production relative to well fertilised sorghum crops would be reduced (Stuart 2002). We hypothesise that productivity and soil-resource benefits could be achieved by modifying current industry-standard practices for summer sole-crops.

In the present paper, we consider the merits or otherwise of combining a short-term summer crop with a winter oats crop (double-cropping) against oats grown predominantly as a sole-crop. Three possible double-cropping systems are considered, with one variation being the use of manure as an additional input and the second variation being the replacement of the summer cereal with a legume. As a further contrast, summer sole-crop systems with variation in terms of N fertiliser, tillage and the inclusion of a legume are considered and compared with each other and against the winter and double-cropping systems.

Materials and methods

This experiment was conducted at two farm sites, on contrasting soil types, on the central Darling Downs, north of the township of Oakey. Site details, rainfall and general management practices are given in Chataway *et al*. (2011). In brief, the Kulpi site was located on a self-mulching black Vertosol considered well suited to forage cropping, but depleted in its capacity to grow crops. The second site at Acland was located on a texture contrast soil (brown Sodosol) and represented a more structurally difficult soil type. The recent fertiliser history at this site had been one of higher N inputs than that on the Vertosol.

Long-term mean annual rainfall for the area is 660 mm (Clewett *et al*. 2003). During the study period, annual rainfall was below average in 5 of 6 years at Kulpi and 3 of 6 years at Acland, with periods of moderate to severe rainfall deficiency in the calendar years of 1997 and 2000 (Clewett *et al*. 2003). Winter rainfall was most affected by these deficiencies. Median annual rainfall over the study period was 548 and 585 mm at Kulpi and Acland respectively.

Treatments

In the present paper, 7 of the 11 forage systems evaluated are reviewed. One forage system (S1) was based predominantly on sole-crop oats. Three systems (S2, S3, S4) had an increased emphasis on summer crops, with a winter and summer crop grown in 4 of every 5 years. These systems varied in the type of summer crop grown (cereal or legume) and the addition of feedlot manure. For the three remaining systems (S5, S6, S7) the emphasis was solely on summer cropping, with variation between the systems in crop choice (legume or cereal), the amount of tillage and N fertiliser. The seven systems under review are detailed in Table 1. In total, 11 systems (4 not reviewed in the present paper) were established in a randomised block design with three replications, in plots 30 by 9 m in size.

Techniques

Crop termination and fallow management

For sole-crops, to manage the fallow and prepare a seedbed, plots were either cultivated (CT) two or three times or sprayed

Table 1. The seven forage systems and their associated cropping sequence for experiments conducted at Kulpi and Acland
CT, conventionally tilled; ZT, zero tillage; low N, 50 kg nitrogen (N)/ha as urea; high N, described in Table 2; +, plus feedlot manure

Forage system	1996		1997		1998		1999		2000	2001
	Year 1		Year 2		Year 3		Year 4		Year 5	
Winter-dominant forage system										
S1. Oats (ZT high N)	Sorghum[A]	Oats	Oats		Oats		Oats		Oats	
Double-cropping forage systems										
S2. Sorghum–oats (ZT high N)	Sorghum	Oats	Sorghum	Oats	Sorghum	Oats	Sorghum	Oats	–	Oats
S3. Sorghum–oats (ZT high N+)	Sorghum	Oats	Sorghum	Oats	Sorghum	Oats	Sorghum	Oats	–	Oats
S4. Lablab–oats (ZT high N)	Lablab	Oats	Lablab	Oats	Lablab	Oats	Lablab	Oats	–	Oats
Summer-forage systems										
S5. Sorghum (CT low N)	Sorghum		Sorghum		Sorghum		Sorghum		Sorghum	
S6. Sorghum (ZT high N)	Sorghum		Sorghum		Sorghum		Sorghum		Sorghum	
S7. Lablab–sorghum (ZT low N)	Lablab		Lablab		Sorghum		Lablab		Sorghum	

[A]This sorghum crop (S1) was terminated after one grazing, 60 days before summer crops in S2–S4 were terminated. At Acland, no sorghum crop was grown in Year 1 in S1 but a sorghum crop (unfertilised) was grown across all systems (S1–S7) in an additional sixth year.

(zero-tillage, ZT) two to four times with glyphosate herbicide (450 g a.i./L) at 1–2 L/ha. Conventional tined implements were used for cultivation with the initial tillage down to 15-cm depth and subsequent cultivations down to 10 cm. For summer crop systems (S5, S6, S7), the first cultivation or spraying usually took place in June/July after cessation of plant growth. Where systems were double-cropped, the summer component was routinely terminated in February/March with glyphosate (450 g a.i./L) at 1–1.5 L/ha to enable a short period of fallow before planting the winter crop. The winter crops in both the sole-cropping (S1) and double-cropping program were terminated with the same herbicide, typically in mid-November. The exception was in the high-rainfall Year 2 when oats remained productive longer and termination of oat plots in the sole-cropping program (S1) was delayed until mid-December.

Planting

All crops, regardless of fallow management, were sown with the same nine-row combine planter on a row spacing of 25 cm. The planter was fitted with high breakout tines, narrow ground-engaging tools and press wheels.

Crop types, planting rates and time of planting

Oats *Avena sativa* L. cv. Graza 50 (Years 1 and 2), cv. Nugene (Years 3–5) at 40 kg/ha, sorghum sudangrass hybrid cv. Nectar [*Sorghum bicolour* (L.) Moench × *Sorghum sudanese* (Piper) Stapf.] at 8 kg/ha and lablab (*Lablab purpureus* L.) cv. Rongai at 30 kg/ha were planted as early as possible within their established crop-planting windows (Harris *et al*. 1999) following rainfall considered sufficient for germination and establishment. Oats was planted between April and July inclusive, with May being the most common month. In 4 of the 5 years, oats was sown in both double- and single-crop programs on the same date. In the other year, oats planted in double-crop plots was delayed by 20 days (Kulpi, Year 4) and 50 days (Acland, Year 2). Summer crops were planted between October and December inclusive. On average, summer crops in double-crop programs were planted 30 days later than sole-crop plots and all crops at Acland were generally established later than those at Kulpi due to shorter and less frequent planting windows, and a need to replant summer crops in Years 2 and 4 due to insufficient plant establishment in both CT and ZT plots (<6 sorghum plants/m^2).

Fertiliser

At planting, a mixed fertiliser, Granulock ST-Z (Zn 2.5) (N : P : K, 10.5 : 19.5 : 0) was applied to all plots with the seed at 50 kg/ha. N fertiliser, as urea, was applied between every second crop row via an inter-row tine. For low N systems (S1, S7), all urea fertiliser was applied at planting. For cereal crops grown in high-N systems, it was intended to apply 100 kg N/ha at planting and 50 kg N/ha after the first and second grazing. A maximum of 200 kg N/ha was to be applied to each crop. As Table 2 shows, the actual rates applied were generally lower, and N rates were reduced after Year 3 for Systems 1–4 in response to lower than expected crop yields and observed soil nitrate-N concentrations (0–1.2 m). Survey data were originally used to determine current industry-practice rates (Anon 1988; Kerr *et al*. 1996) and these rates are described in the study as ‘low N’ (S5, S7), while ‘high N’ concentrations were based on the expert opinion of project scientists and past research work conducted with forage sorghum (Muldoon 1985; Chataway *et al*. 1994).

For one double-crop treatment (S3), feedlot manure was also applied at 10 t DM/ha in October 1997 (containing 2.5% N, 1.1% P and 3.2% K).

Grazing

Forage plots at each site were grazed by the dairy herd one replicate at a time, with back-fencing used to exclude animals from previously grazed replicates. Grazing of a replicate was normally completed in 1–2 days. Electric fencing was also used to exclude cattle from plots that were not ready for grazing or were being fallowed. The level of grazing intensity was comparable to other fields being grazed on the farm at the same time. It varied according to seasonal conditions and stage of crop growth and there was a tendency for removal to be higher at the Acland site. Animals typically grazed for 2–4 h per day before being moved out of the field for watering and lounging. The time to first grazing varied according to climatic conditions, but was typically 6–8 weeks following planting for the sorghum sudangrass hybrid, 10–12 weeks for lablab and 8–10 weeks for oats. The

Table 2. The rate of nitrogen applied as fertiliser (kg N/ha) to forage crops at Kulpi and Acland
See Table 1 for explanation of codes

Forage system	1996 1997 Year 1	1998 Year 2	1999 Year 3	2000 Year 4	2001 Year 5	Mean annual rate
			Winter-dominant forage system			
S1. Oats (ZT high N)	160/105[A]	205	105	55	55	115/105[A]
			Double-cropping forage systems			
S2. Sorghum–oats (ZT high N)	210	210	260	160	0	168
S3. Sorghum–oats (ZT high N+)	210	210	260	160	0	168
S4. Lablab–oats (ZT high N)	105	155	105	55	0	84
			Summer-forage systems			
S5. Sorghum (CT low N)	55	55	55	55	55	55
S6. Sorghum (ZT high N)	105	205	205	205/155[A]	155/105[A]	175/155[A]
S7. Lablab–sorghum (ZT low N)	5	5	55	5	55	25

[A]Where different rates were applied, values are expressed as Kulpi/Acland.

timing of subsequent grazings was dependent on the incidence and extent of in-crop rainfall and associated growing conditions. A target height at grazing was 1–1.5 m for sorghum and 0.4 m for oats.

Plant measurements and analysis

Harvestable forage

Prior to each grazing, five 1-m^2 samples were cut from within the two central planter runs. For first harvest, summer forage crops were harvested at 0.15 m above ground level and the winter crop at 0.075 m. For repeat samplings, only new growth was harvested. Samples were handled to collect yield, N and neutral detergent fibre (NDF) data as per Chataway *et al*. (2011). Following sample preparation, N content was determined using Kjeldahl digestion, followed by automated continuous-flow methods (Crooke and Simpson 1971; Technicon 1976), while the analysis for NDF used a modified version of the method of Van Soest *et al*. (1991).

An estimate of forage utilisation was made immediately following grazing. This was done by first selecting plots that represented the range of forage systems and pre-grazing yields. In each of these plots, within five sampling locations (each 1 m^2) that had not been harvested for yield, forage remaining above the sampling height was cut and fresh detached material collected. Residues for each plot were weighed, compared against the pre-grazing (wet) yields of the same plot, and expressed as a percentage utilisation. The remaining plots were aligned with harvested plots of similar pre-grazing yield and forage type, and visually assessed for their conformity to the representative plots. For plots that did not conform, residues were collected and weighed for each of these plots.

Crop residue cover

Soil cover measurements over the fallow period were conducted for summer sole-crops (S5, S6, S7) before crops were sown in Years 5 and 6. Visual estimates of soil cover were made within a 1-m^2 quadrat placed at three random sites within the two centre planting runs in each plot. The soil cover percentage for each plot was the mean of the percentage values for the three random sites. The visual estimates were based on photo-standards for summer and winter cereals (Molloy 1988).

Soil sampling and analysis

Sampling and analysis for soil nitrate-N, organic carbon and plant-available water was conducted in the same manner, and using the same parameters, as per Chataway *et al*. (2011).

Calculations

To determine plant N and %NDF, the apparent recovery of fertiliser N and fallow water-storage efficiency, calculations were conducted as per Chataway *et al*. (2011).

Statistical analysis

Analysis of variance, using GENSTAT (Payne *et al*. 2007), was performed to assess the effect of soil and crop-management practices on measured parameters. Data were analysed as a complete set of the 11 forage systems (treatments) for soil organic carbon concentration but as subsets of relevant forage systems for forage dry matter yield, forage N concentration, soil nitrate-N, soil water and soil cover. Significant differences between treatment means were compared using the protected least significant difference (l.s.d.) procedure at the 5% level of significance. Regression analysis was carried out using the data-analysis tools in GENSTAT.

Results

Forage production

General comparisons

Year-to-year yield variation within systems was high, with forage yields for the same systems generally lower at Acland than at Kulpi (Tables 3, 4). At both sites, production (DM t/ha) from well fertilised sorghum (S6) was about double that from well fertilised oats (S1) (Tables 3, 4). At Acland, double-cropping gave a yield similar to that from summer sole-cropping, while at Kulpi, the yield from double-cropping was intermediate between those from winter and summer sole-cropping systems (Tables 3, 4); the different relative yields at each site were influenced by the contribution sorghum made to the system, which is reflected in mean annual NDF values (Tables 5, 6). There was less inter-site difference for NDF than for yield. Nitrogen content of the forage was lowest in systems dominated by forage sorghums

Table 3. Annual harvestable forage yield and estimated utilisation for seven forage systems evaluated at Kulpi over 5 years
Rainfall is based on water year, from 1 October to 30 September. In Year 1 of the winter-dominant forage systems. a sorghum crop (1 grazing) was grown. This summer crop contributed 3.0 t DM/ha to total yield. Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined. See Table 1 for explanation of codes

Forage system	Annual harvestable forage yield (t DM/ha)						Mean utilisation (%)
	Year 1 (1996–1997)	Year 2 (1997–1998)	Year 3 (1998–1999)	Year 4 (1999–2000)	Year 5 (2000–2001)	Mean (1996–2001)	
Rainfall (mm)	445	926	596	508	554	606	
Winter-dominant forage system							
S1. Oats (ZT high N)	6.75d	7.38d	3.24a	2.07a	4.43bc	4.78a	75
Double-cropping forage systems							
S2. Sorghum–oats (ZT high N)	5.48c	10.18e	8.65cd	5.19b	4.54cd	6.81c	69
S3. Sorghum–oats (ZT high N+)	5.24bc	13.56f	9.57d	5.75bc	4.68cd	7.76d	65
S4. Lablab–oats (ZT high N)	3.68a	9.46e	6.40b	2.44a	3.05a	5.01a	69
Summer forage systems							
S5. Sorghum (CT low N)	4.63b	5.12b	6.91b	6.28c	5.31d	5.65b	69
S6. Sorghum (ZT high N)	5.62c	6.45c	11.39e	14.41e	7.34e	9.64e	70
S7. $Lablab_{1,2,4}sorghum_{3,5}$ (ZT low N)	5.12bc	3.84a	8.42c	7.35d	7.51e	6.47c	69
l.s.d. ($P = 0.05$)	0.78	0.87	1.03	0.97	0.85	0.61	n.d.

Table 4. Annual harvestable forage yield and estimated utilisation for seven forage systems evaluated at Acland over 6 years
Rainfall is based on water year, from 1 October to 30 September. In Year 6, assay crop of forage sorghum planted across all systems (no N fertiliser applied). Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined. See Table 1 for explanation of codes

Forage system	Annual harvestable forage yield (t DM/ha)							Mean yield utilisation (Years 1–5) (%)
	Year 1 (1996–1997)	Year 2 (1997–1998)	Year 3 (1998–1999)	Year 4 (1999–2000)	Year 5 (2000–2001)	Mean (Years 1–5)	Year 6 (2001–2002)	
Rainfall (mm)	484	1124	665	544	474	658	711	
Winter-dominant forage system								
S1. Oats (ZT high N)	3.58b	5.06b	2.56a	1.45a	1.12a	2.75a	7.66d	85
Double-cropping forage systems								
S2. Sorghum–oats (ZT high N)	2.98ab	13.80d	7.48c	3.58bc	1.57ab	5.88c	5.3a	72
S3. Sorghum–oats (ZT high N+)	3.83b	16.20e	7.50c	4.88c	2.07b	6.89d	6.76bcd	70
S4. Lablab–oats (ZT high N)	2.10a	7.66c	5.16b	2.19ab	1.23a	3.67b	7.05cd	72
Summer forage systems								
S5. Sorghum (CT low N)	3.32b	8.46c	6.61c	8.42d	3.24c	6.01d	6.45a	74
S6. Sorghum (ZT high N)	3.05b	8.27c	7.42c	8.42d	3.11c	6.05d	5.93ab	75
S7. $Lablab_{1,2,4}sorghum_{3,5}$ (ZT low N)	2.10a	3.15a	7.45c	4.66c	4.41d	4.43b	6.21abc	72
l.s.d. ($P = 0.05$)	0.90	1.15	1.42	1.56	0.71	0.70	1.01	

(Tables 5, 6) and there was a predictable influence of forage species on the system's NDF concentration; for example, mean NDF of oats (S1) at both sites was 44% compared with that of sorghum (S5, S6) at 59–60% (Tables 5, 6).

In all systems, the majority of forage was harvested during the spring–summer period (September–February inclusive) and ranged from 60% for the winter system (S1) to 80% for sole-cropped sorghum. Winter forage production (June–August) was low, even for the winter sole-crop system which provided grazing of 1.5–2.5 t DM/ha during this period in only 3 of the 5 years; for double-cropping systems, this was reduced to 2 of 5 years at Kulpi and 1 of 5 years at Acland. With respect to forage utilisation, this was generally higher at Acland than at Kulpi, and at both sites, utilisation was inferior for all systems alternative to S1.

Double-cropping systems

For these systems, where sorghum or lablab was grown before the oats crop in 4 of the 5 years (Table 1), there was a general increase in total annual production (Tables 3, 4) above that achieved in the winter-dominant oats system (S1); however, double-cropping had a substantial and negative overall impact on the productivity of the oats crop. For similar systems, but with a different cropping frequency (S1, S2), the increased emphasis on

Table 5. Annual weighted nitrogen (N) and neutral detergent fibre (NDF) content (%DM) for seven forage systems evaluated at Kulpi over 5 years
Rainfall is based on water year, from 1 October to 30 September. In Year 1 of the winter-dominant forage system (S1), a sorghum crop (1 grazing) was grown as well as oats. Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined. See Table 1 for explanation of codes

Forage system	Year 1 (1996–1997)		Year 2 (1997–1998)		Year 3 (1998–1999)		Year 4 (1999–2000)		Year 5 (2000–2001)		Mean (Years 1–5)	
	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF
Rainfall (mm)	445		926		596		508		554		606	
Winter-dominant forage system												
S1. Oats (ZT high N)	1.97d	45.4	2.79c	47.3	3.82e	39.4	2.52d	38.4	2.89c	43.5	2.69d	44.2
Double-cropping forage systems												
S2. Sorghum–oats (ZT high N)	1.50bc	57.5	2.80c	48.7	2.88c	54.5	2.09bc	56.1	3.21d	43.5	2.58d	51.9
S3. Sorghum–oats (ZT high N+)	1.60c	57.6	2.89c	50.0	3.02cd	54.7	2.28cd	55.3	3.05cd	43.3	2.67d	52.1
S4. Lablab–oats (ZT high N)	1.99d	38.6	3.25e	40.0	3.26d	42.7	3.24f	35.0	3.04cd	42.3	3.03e	40.3
Summer forage systems												
S5. Sorghum (CT low N)	1.22a	57.5	1.85a	55.1	1.57a	61.2	1.19a	57.3	1.51a	63.5	1.47a	59.1
S6. Sorghum (ZT high N)	1.43b	58.5	2.50b	55.3	2.20b	62.0	1.96b	59.0	2.32b	62.5	2.09b	59.7
S7. Lablab$_{1,2,4}$ sorghum$_{3,5}$ (ZT low N)	2.21e	37.4	3.16de	30.9	1.79a	61.5	2.9e	39.2	2.22b	62.5	2.36c	49.0
l.s.d. ($P = 0.05$)	0.15	n.d.	0.25	n.d	0.26	n.d	0.30	n.d.	0.22	n.d.	0.13	n.d.

Table 6. Annual weighted nitrogen (N) and NDF contents (%DM) for seven forage systems evaluated at Acland over 6 years
Rainfall is based on water year, from 1 October to 30 September. In Year 6, assay crop of forage sorghum planted across all systems (no N fertiliser applied). Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined. See Table 1 for explanation of codes

Forage system	Year 1 (1996–1997)		Year 2 (1997–1998)		Year 3 (1998–1999)		Year 4 (1999–2000)		Year 5 (2000–2001)		Mean (Years 1–5)		Year 6 (2001–2002)	
	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF
Rainfall (mm)	484		1124		665		544		474		667		711	
Winter-dominant forage system														
S1. Oats (ZT high N)	2.19a	38.7	3.46d	44.0	2.43c	49.8	1.80b	47.5	2.26c	37.2	2.82d	43.6	1.78bc	60.2
Double-cropping forage systems														
S2. Sorghum–oats (ZT high N)	2.31a	62.8	1.88ab	55.9	2.04b	56.3	1.77b	59.7	2.28c	37.2	2.04b	55.8	1.27a	60.8
S3. Sorghum–oats (ZT high N+)	2.14a	60.5	2.01b	55.5	2.03b	55.9	1.77b	60.5	2.27c	37.2	2.00b	55.8	1.55ab	60.3
S4. Lablab–oats (ZT high N)	3.05b	34.1	2.64c	44.3	2.63c	42.3	2.57c	31.3	2.22bc	37.2	2.61c	41.0	1.98c	60.5
Summer forage systems														
S5. Sorghum (CT low N)	2.15a	58.2	1.64a	59.3	1.44a	66.6	1.17a	56.3	1.89a	58.7	1.55a	59.6	1.41a	60.4
S6.Sorghum (ZT high N)	2.17a	59.7	1.85ab	59.1	1.55a	66.5	1.30a	56.1	1.93ab	56.5	1.67a	59.7	1.73abc	60.1
S7. Lablab$_{1,2,4}$sorghum$_{3,5}$ (ZT low N)	3.08b	39.8	1.94b	42.4	1.20a	67.2	3.02d	35.5	1.98abc	58.4	2.03b	52.4	1.53ab	60.0
l.s.d. ($P = 0.05$)	0.37	n.d.	0.25	n.d.	0.35	n.d.	0.25	n.d.	0.30	n.d.	0.15	n.d.	0.34	n.d.

a summer crop reduced mean annual oats production by ~50%; from 4.1 to 2.2 t/annum at Kulpi and from 3.2 to 1.5 t/annum at Acland. On a year-to-year basis, the reduction in oats production was variable (Fig. 1) and similar at both sites; in Years 1–4, respectively, the reduction was 100%, 20%, no reduction ($P > 0.05$) and 85% at Kulpi and 100%, 25%, 20% and 90% at Acland. For the sole (S1) or double-cropping systems (S2), the mean fallow length preceding the oats crop was reduced from 158 to 90 days at Kulpi and from 168 to 81 days at Acland. This reduced average fallow and in-crop rainfall per crop by 261 mm at Kulpi and 194 mm at Acland. The reduction in forage yield was least at both sites in Years 2 and 3 (Fig. 1), when rainfall was at or above average. Fallow plus in-crop rainfall accounted for 90% of the variation in annual oats forage yield in the double-cropping systems (S2, S3) (Fig. 2).

For the summer-crop component of the double-crop system (S2), forage was typically harvested in two grazings, with the total mean annual production at both sites during Years 1–4 being similar at 5.2 and 5.4 t DM/ha.annum. However, the relative contribution sorghum made to annual forage yield (S2) was lower at Kulpi (64%) than at Acland (82%). This different proportional contribution of sorghum to double-crop yields is reflected in the lower mean annual NDF value for S2 at Kulpi (51.9%) than at Acland (55.8%) (Tables 5, 6).

The addition of feedlot manure to the double-crop sorghum–oats system (S3) increased ($P < 0.05$) the mean annual forage yield at both sites (Tables 3, 4). Most of this increased yield was in the high-rainfall Year 2. There was no difference ($P > 0.05$) in the N concentration of harvestable material between S3 and S2 (Tables 5, 6).

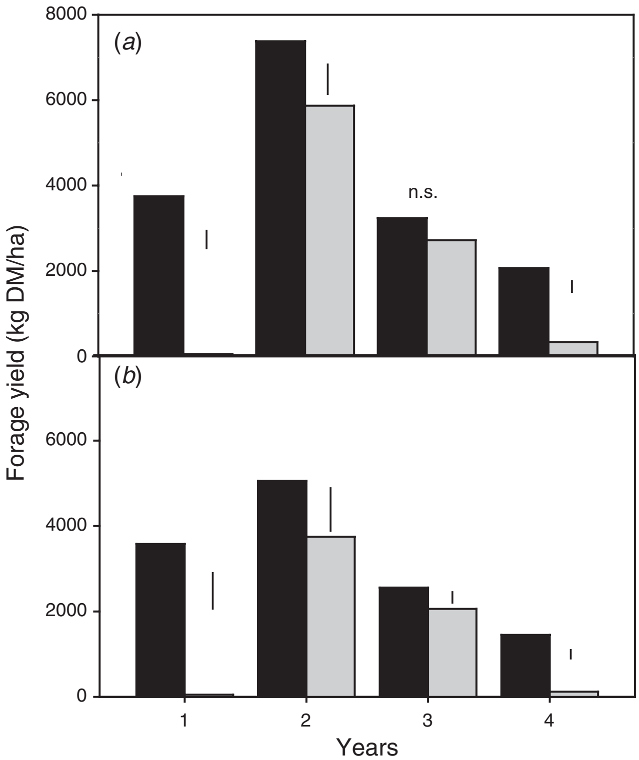

Fig. 1. Yield of oats in winter-dominant (S1) (solid fill) and double-crop (S2) (grey fill) systems in Years 1–4 at (*a*) Kulpi and (*b*) Acland. The vertical bar shows l.s.d. at $P = 0.05$.

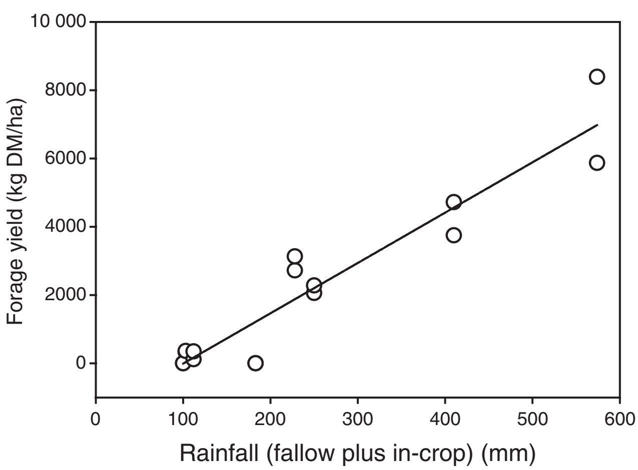

Fig. 2. Annual forage production from oats under double-cropping cereal crop systems (S2, S3) for both Kulpi and Acland in Years 1–4. The equation for the line is: $y = -1480.7 + 14.74x$ ($r^2 = 0.90$, $P < 0.01$).

Changing the summer component from forage sorghum to lablab (S4) reduced ($P < 0.05$) the overall production at both sites (Tables 3, 4). This was principally due to a reduction in the mean annual summer production in Years 1–4, from 5.20 to 3.25 t DM/ha at Kulpi and from 5.40 to 2.65 t DM/ha at Acland. In the double-cropping systems, due to the slower growth rate of lablab than that of sorghum, lablab was grazed only once. At both sites, the overall N concentration of harvestable forage was higher ($P < 0.05$) in this system (S4) than in S2 and S3 and the NDF concentration was reduced by 10–15 units (Tables 5, 6). The overall forage quality in this system was similar to that achieved by the winter-dominant forage system (S1).

Summer sole-crop systems

For industry-standard sorghum (S5), the mean annual yields were similar at both sites, 5.65 and 6.0 t DM/ha, while year-to-year variation was greater at Acland than at Kulpi (Tables 3, 4). Mean annual weighted concentrations of forage N and NDF at both sites were also similar, at ~1.5% and 59% respectively (Tables 5, 6). When N-fertiliser inputs were increased and the fallow period was managed with herbicides rather than tillage (S6), both the annual forage production and N concentration increased ($P < 0.05$) over industry-standard sorghum (S5) in all years at Kulpi, whereas there was no difference at Acland (Tables 3–6). At Kulpi, where the mean application of N in S6 was 175 kg N/ha, the response was 33 kg DM/ha per kg N fertiliser applied above the industry-standard rate of 55 kg N/ha.annum. Year-to-year variation also increased under the higher rate of N application at Kulpi, with a production peak in Year 4 at 14.4 t/ha. Peak forage production was associated with a spring–summer (September to February inclusive) rainfall of ~450 mm at both sites. Changed management practices (S5 *v.* S6) had no effect on forage yield at first grazing, which was typically ~3.0 t/ha (Fig. 3).

When lablab replaced sorghum in Years 1, 2 and 4 (S7) and the fallow period was managed with herbicides rather than tillage, there was a rise ($P < 0.05$) in the mean annual forage yield and N concentration over the industry standard (S5) at Kulpi (Tables 3, 5). At Acland, the overall N concentration of forage increased ($P < 0.05$) but there was a fall in the mean annual production, relative to industry-standard sorghum (Tables 4, 6). For Years 3 and 5, when sorghum was grown, yield from this forage system (S7) was higher ($P < 0.05$) than yield from the industry-standard sorghum (S5) in both years at Kulpi (Table 3) and in 1 year at Acland (Table 4).

At both sites, harvestable yield at grazing was typically between 2.0 and 4.0 t DM/ha but reached 6.0 t DM/ha at times (data presented only for Kulpi, Fig. 3). At Kulpi, N concentration was commonly increased ($P < 0.05$) for the first and subsequent grazings with the application of additional N fertiliser (S5 *v.* S6) (Fig. 3), but at Acland, there was no difference between the systems in the N concentration of forage sorghum at any individual grazing (data not presented).

Soil water

Plant-available water (PAW) to 1.2 m (mm) before sowing winter crops was reduced ($P < 0.05$) in 3 of the 4 years of double-cropping (S2, S3, S4) when fallow length was reduced relative to sole-cropped oats (S1). Over the 4 years, mean PAW to 1.2-m depth of single- and double-cropping systems was 81 and 40 mm at Kulpi and 66 and 31 mm at Acland respectively (data not

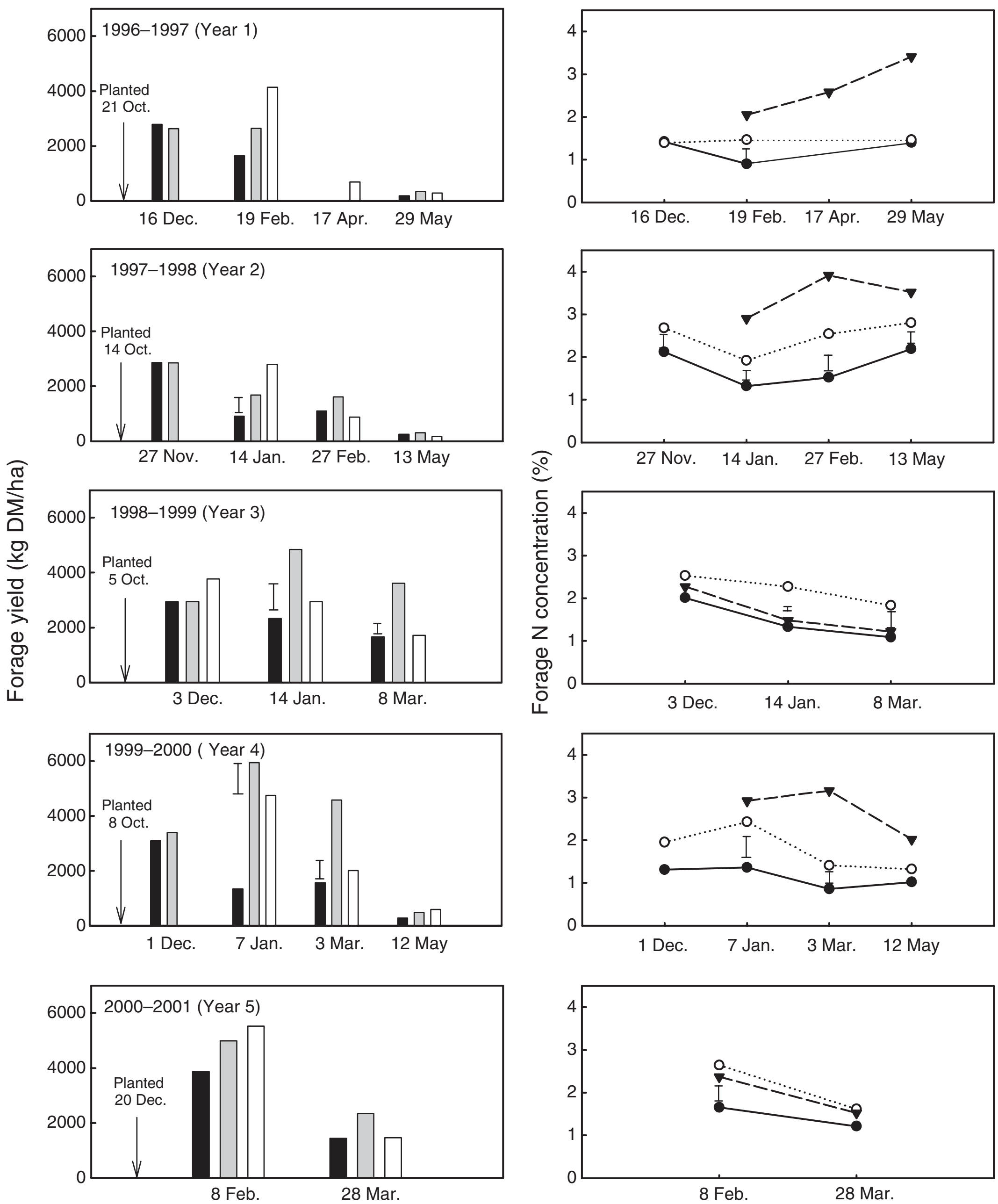

Fig. 3. Forage yield (t DM/ha) and N content (%) of individual grazings for the following three forage systems at Kulpi: S5, sorghum (CT low N) (solid bar, solid circle); S6, sorghum (ZT high N) (lightly shaded bar, open circle); and S7, lablab$_{1,2,4}$ sorghum$_{3,5}$ (ZT low N) (white bar, solid triangle). Vertical bars show l.s.d. ($P = 0.05$) between systems at specific grazings. See Table 1 for explanation of codes.

presented). For the double-cropping systems (S2, S3, S4), there was no difference in PAW before the oats crops were sown. For the summer sole-crop systems (S5, S6, S7), there was also no difference in pre-sowing PAW among these three systems in any year at either site (data not presented). For Years 1–6, the mean pre-sowing PAW (mm, 1.2 m) for all summer systems was 138, 19, 157, 100, 40 and 87 mm at Kulpi and 56, 26, 104, 29, 31 and 61 mm at Acland. The overall mean was 90 mm at Kulpi and 51 mm at Acland.

Fallow water-storage efficiency

Mean fallow water-storage efficiency for the summer sole-crop systems (S5, S6, S7) varied from 10% to 25% on a year-to-year basis at Kulpi and from 15% to 18% at Acland. Mean water-storage efficiency over all years was similar at both sites at 16% and 17% (Table 7). The unusually low fallow water-storage efficiency of 10% recorded in Year 1 at Kulpi was for a short fallow that received well below-average rainfall. Fallow efficiency could not be calculated for the double-crop systems

Table 7. Mean fallow water-storage efficiency (at 0–1.2-m depth) over five fallow periods (Years 2–6) for the three summer forage systems (S5, S6, S7) at Kulpi and Acland

PAW, plant-available water. See Table 1 for definition of S5–S7

Cropping year	Year 2	Year 3	Year 4	Year 5	Year 6	General mean
			Kulpi			
Fallow rainfall (mm)	79	277	154	198	244	190
Fallow length (days)	110	140	136	201	195	156
PAW, fallow start (mm)	11	104	62	13	50	48
PAW, fallow end (mm)	19	157	100	40	87	81
Change in PAW (mm)	8	53	38	27	37	33
Efficiency (%)	10	19	25	14	15	17
			Acland			
Fallow rainfall (mm)	122	248	155	203	160	178
Fallow length (days)	114	112	136	225	152	148
PAW, fallow start (mm)	4	63	5	1	37	22
PAW, fallow end (mm)	26	104	29	31	61	50
Change in PAW (mm)	22	41	24	30	24	28
Efficiency (%)	18	17	15	15	15	16

because only one soil-sampling event was conducted between crops.

Pre-sowing nitrate-N

For the double-cropping systems, with the exception of Year 5, nitrate-N concentrations remained relatively constant across years and among systems at Acland, while at Kulpi there was a general increase in nitrate-N concentrations from the low levels present at the commencement of the study (Fig. 4). At Kulpi, there was a difference ($P < 0.05$) between manured (S3) and non-manured systems in Years 3–5 (Fig. 4). At both sites, there was a pronounced rise in nitrate-N concentrations before the winter crop was sown in Year 5 (Fig. 4). We attribute this rise to the contribution of unused fertiliser by the Year 4 winter crop (failed crop) and the land remaining fallow over the following summer due to no crop being planted because of late planting rains.

For the summer sole-cropping systems (S5, S6, S7), mean nitrate-N concentrations at the commencement of the summer cropping program at Kulpi and Acland were 5 and 67 kg/ha to 1.2 m (Fig. 5). At both sites, pre-sowing nitrate-N concentrations remained at or close to these concentrations for industry-standard managed forage sorghum fertilised with 55 kg N/ha.crop (S5). Changing fallow-management practices (ZT) and increasing the mean annual application rate of N fertiliser by another 100 kg/ha at Acland and 120 kg/ha at Kulpi (S6) did result in some differences ($P < 0.05$) in pre-sowing nitrate N concentrations compared with industry-standard management practices, particularly towards the end of the study period (Fig. 5). When a legume forage crop was grown instead of industry-standard forage sorghum in Years 1, 2 and 4 (S7), the concentration of soil nitrate-N at the commencement of the subsequent cropping year was higher ($P < 0.05$) than that following industry-standard sorghum (S5) in 2 of the 3 years at Kulpi, but not in any years at Acland (Fig. 5). At Kulpi, the difference in soil nitrate-N following legumes in Year 1, relative to industry-standard sorghum (S5), was 35 kg nitrate-N/ha. This difference remained relatively unchanged after a second legume crop.

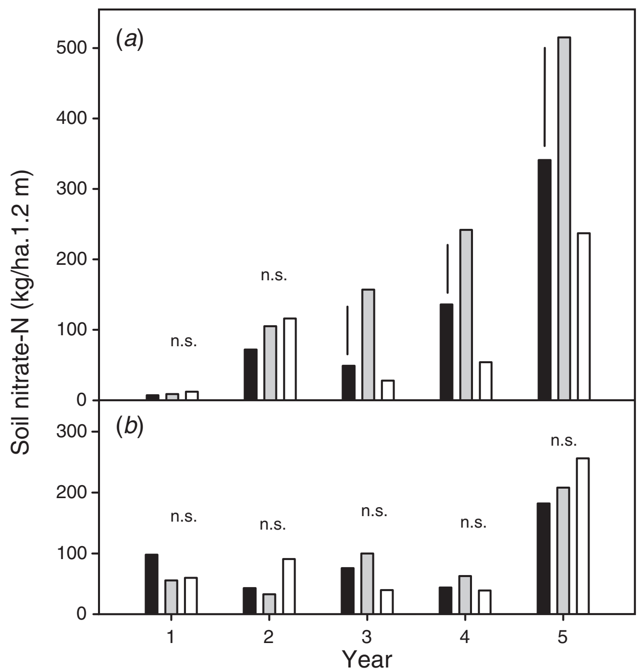

Fig. 4. Pre-sowing nitrate-N (kg/ha per 1.2-m soil layer) for the winter phase of double-cropping forage systems over 5 years at (*a*) Kulpi and (*b*) Acland. S2, sorghum–oats (ZT high N) (solid bar); S3, sorghum–oats (ZT high N+) (lightly shaded bar); and S4, lablab–oats (ZT high N) (white bar). The vertical bar shows l.s.d. at $P = 0.05$. Note: summer crop was grown before winter crop in all years except Year 5. See Table 1 for explanation of codes.

Apparent N recovery from fertiliser

For the sole-cropping systems at Kulpi, the apparent recovery of N fertiliser applied above the industry-standard rate (S5 *v.* S6) was 91%. This was in contrast to Acland where the recovery rate was very low at 8%. At Acland, there was evidence that some of this unutilised N remained present in the soil profile at the completion of the present study (Fig. 6).

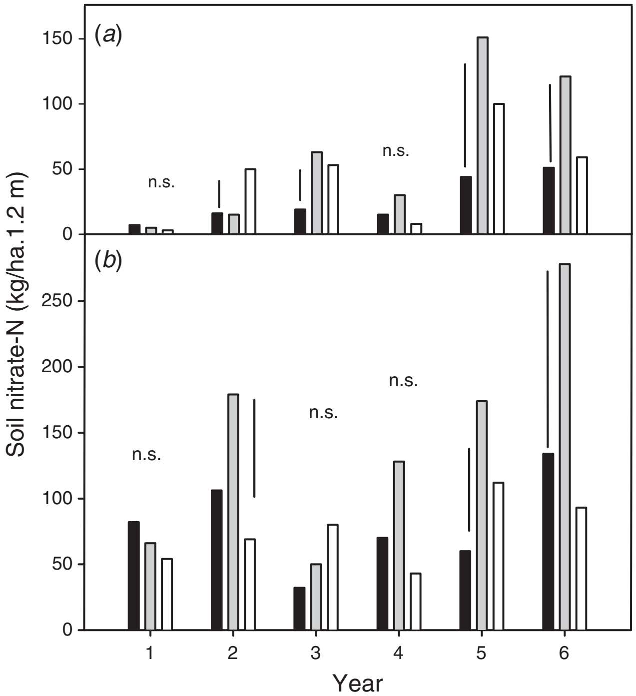

Fig. 5. Pre-sowing soil nitrate-N (kg/ha per 1.2-m soil layer) for summer cropping forage systems at (*a*) Kulpi and (*b*) Acland. S5, sorghum (CT low N) (solid bar); S6, sorghum (ZT high N) (lightly shaded bar); and S7, $lablab_{1,2,4}sorghum_{3,5}$ (ZT low N) (white bar). The vertical bar shows l.s.d. at $P = 0.05$. See Table 1 for explanation of codes.

Fallow stubble cover (summer systems S5, S6, S7)

At Kulpi, stubble cover was consistently lower ($P < 0.05$) in the 2 years assessed for the industry-standard system (S5) than that in the two alternative systems using changed crop-management practices (S6, S7). For the industry-standard system (S5), stubble cover ranged between 15% and 20% at all sampling events, while for the two alternative systems (S6, S7), cover was always above 30%, ranging between 70% and 40% following sorghum in Years 4 and 5 and from 40% to 30% following lablab in Year 4 (data not presented).

At Acland, there was substantially less stubble cover, with the levels remaining only above 30% in the untilled sorghum system (S6) following the Year 4 crop. This was higher ($P < 0.05$) than that for S5 and S7 following the Year 4 crop; however, following the low-yielding Year 5 crop, cover remained between 20% and 10% for all systems (S5, S6, S7), with no differences ($P > 0.05$) between systems (data not presented).

Soil Organic Carbon (SOC)

The mean SOC concentration (0–10 cm) taken in the first year of the study was 1.47% and 0.81% at Kulpi and Acland, respectively, with no difference ($P > 0.05$) among the forage systems within a site. Sampling 2 years later showed a general increase in SOC at each site, with some differences ($P < 0.05$) among the systems. At Kulpi, all alternative systems to sole-crop oats (S1), except S5, had higher SOC ($P < 0.05$) concentrations. At Acland, only double-cropping systems were higher ($P < 0.05$) (Table 8). At the third sampling, there was a substantial rise in the mean SOC at Kulpi, while at Acland, values tended to decline. However, the difference between the S1 and other systems remained relatively unchanged. At the final sampling, 2 years later at Kulpi and 2.5 years at Acland, the relative difference between the systems at each site generally remained. When variable starting concentrations of SOC were also considered, all systems alternative to continuous oats (S1), with the exception of S4 at Kulpi, experienced a positive change ($P < 0.05$) in SOC concentration. At both sites, double-cropping systems based on forage sorghum and oats (S2, S3) had a consistently positive impact on SOC relative to sole-crop oats (S1). When the total forage production between the first and final sampling points was considered, a logarithmic relationship, with a modest predictability between the forage production and change in SOC concentration (0–10 cm) ($r^2 = 0.61$, $P < 0.05$), was established (Fig. 7).

With respect to the 10–20-cm soil layer, SOC concentration at the first and last sampling points was 1.24% and 1.27% at Kulpi and 0.67% and 0.70% at Acland. There was no difference ($P > 0.05$) among the systems at any of the sampling points (data not presented).

Discussion

Double-cropping

Our results showed that with early termination of the summer crop, double-cropping could be successfully undertaken in years of average or above-average rainfall, with a yield penalty of 25% or less compared with winter sole-crop production, and improved soil-resource benefits. However, as a routine practice, double-cropping will come at a cost to security of winter production and overall forage quality. Other studies on double-cropping in semiarid environments have drawn similar conclusions. Using a combination of field studies and simulations, Singh *et al.* (2009*a*) determined that in the 600-mm-rainfall isohyet of the subtropical cropping zone, a forage lablab–grain wheat system would yield a profitable crop of lablab (>3 t forage DM/ha) in 90% of years and a profitable wheat crop (>1 t grain/ha) in 54% of years. Compared with sole-crop wheat, environmental benefits associated with this system included reduced potential rainfall runoff and drainage. In southern Iowa, USA (800 mm annual rainfall), Buxton *et al.* (1999) found that forage sorghum double-cropped with winter rye had a positive influence on reducing soil loss on a 2–7% slope over sole-cropped sorghum, but costs increased significantly and the double-crop systems was more vulnerable to drought. They concluded that if winter rye were to be grown as a double-crop with sorghum, it would be for environmental rather than yield benefits. In our situation, further strategies could be adopted to reduce the risk of crop failure in multi-crop systems. This could include use of seasonal forecasting tools (Carberry *et al.* 2000; Bureau of Meteorology 2010) to better predict the likelihood of success of a second crop. Second, the duration of the summer crop could be restricted to just one grazing or mechanical harvest 6–8 weeks after planting (~3 t DM/ha); with a commensurate reduction in fertiliser requirement. This would further reduce the risk of winter crop failure, while still achieving environmental benefits (reduced runoff, improved ground cover) over a sole-crop oats system.

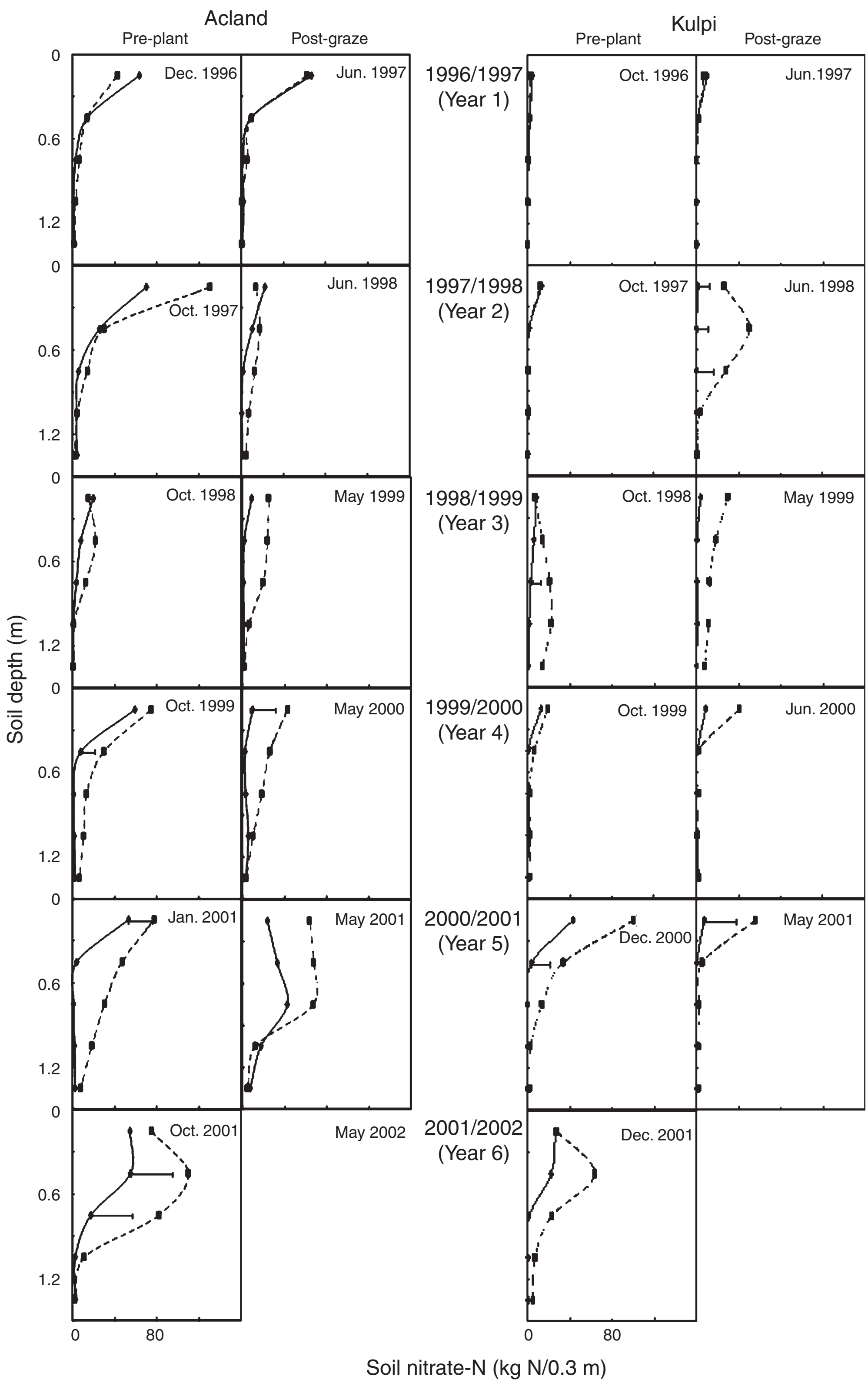

Fig. 6. The distribution of nitrate-N in the soil profile of summer forage systems at Acland and Kulpi. S5, sorghum (CT low N) (solid line); and S6, sorghum (ZT high N) (broken line). The horizontal bar width represents l.s.d. at $P = 0.05$. See Table 1 for explanation of codes.

Table 8. Soil organic carbon concentration (%) (at 0–10-cm depth) at Kulpi and Acland on four sampling occasions, and the difference, in percentage points, between the first and last sampling

Means followed by the same letter do not differ significantly at $P = 0.05$; n.s., not significant. See Table 1 for explanation of codes

Forage system	Kulpi					Acland				
	May 1997 (1st)	May 1999 (2nd)	Dec. 1999 (3rd)	Dec. 2001 (4th)	Difference (4th and 1st)	May 1997 (1st)	May 1999 (2nd)	Dec. 1999 (3rd)	May 2002 (4th)	Difference (4th and 1st)
Winter-dominant forage system										
1. Oats (ZT high N)	1.45	1.38a	1.57ab	1.44a	–0.01a	0.78	0.77a	0.78a	0.79a	0.01a
Double-cropping forage systems										
2. Sorghum–oats (ZT high N)	1.50	1.59bc	1.70c	1.62bcd	0.12bc	0.80	0.99b	0.91b	0.96bc	0.16c
3. Sorghum–oats (ZT high N+)	1.52	1.64c	1.86d	1.67d	0.15cd	0.84	1.13c	0.97bc	1.00c	0.16c
4. Lablab–oats (ZT high N)	1.53	1.57bc	1.68bc	1.53abcd	0.00a	0.80	0.90b	0.80a	0.86a	0.06b
Summer forage systems										
5. Sorghum (CT low N)	1.38	1.49ab	1.53a	1.52abc	0.14cd	0.81	0.82a	0.83ab	0.87ab	0.06b
6. Sorghum (ZT high N)	1.48	1.59bc	1.70c	1.66cd	0.18d	0.77	0.78a	0.80a	0.86a	0.09b
7. Lablab–sorghum (ZT low N)	1.42	1.59bc	1.56ab	1.51ab	0.09b	0.83	0.78a	0.79a	0.89b	0.06b
Mean	1.47	1.55	1.66	1.57	0.10	0.81	0.88	0.82	0.89	0.08
l.s.d. ($P = 0.05$)	n.s.	0.15	0.13	0.15	0.05	n.s.	0.11	0.10	0.10	0.05

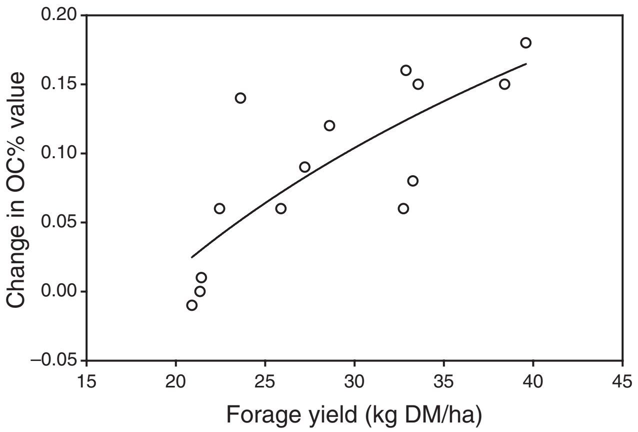

Fig. 7. The relationship between forage yield (kg DM/ha) between the first and last soil sampling and the change in soil organic carbon concentration (percentage points) in the surface soil (0–10 cm) at both Kulpi and Acland sites for seven forage systems. The equation for the line is: $y = 0.2191 \times \ln(x) - 0.641$ ($r^2 = 0.61$, $P < 0.05$).

While the present study could not replicate the priorities and issues a farmer would consider in determining whether to double-crop or not, it has shown that herbicides, variable fertiliser rates and zero-tillage are effective tools in addressing factors – other than water supply – that limit double-cropping (Chataway *et al.* 2003). This flexibility is not available in conventional systems that require a fallow period to build up plant-available nutrients and prepare a fine, stubble-free seedbed for planting. Double-cropping has environmental benefits over sole-cropping in reducing the days land is fallow and thereby increasing the period of soil water deficits and increasing surface cover through a living crop or crop stubble (Freebairn *et al.* 1997; Buxton *et al.* 1999).

We have reservations about the use of lablab in a double-cropping program. Its thick twining stems, which remain after grazing, make it difficult to sow crops into before it has undergone a period of decomposition. While breaking down the stubble through mowing would reduce this problem, it would increase costs. An alternative to grazing would be to mechanically harvest the crop for hay or silage; this would minimise the problem caused by stubble. One other limitation of lablab in a double-cropping program is that it is most useful as a source of fodder in late autumn (Minson *et al.* 1993), so removing it earlier – to enable a period of fallow before the winter crop – negates one of its major strengths.

The addition of feedlot manure to the double-cropping systems was beneficial in raising forage production and indicates benefits from this alternative fertiliser source when applied in addition to inorganic fertilisers. As manure is relatively rich in P, and also a source of most other elements (Strong and Holford 1997) and organic matter (Haynes and Naidu 1998), we believed that it would be mostly beneficial to the Sodosol soil which has greater nutrient and structural impairments than does the Vertosol (Harris *et al.* 1999). However, benefits were similar at both sites, indicating that the additional N provided was beneficial; particularly during Year 2 when rainfall was high. Of the N in manure, up to one-half may be available in the year of application (Jokela 1992) and, after allowing for volatilisation losses at spreading (Stevenson *et al.* 1998), it could be expected that up to 100 kg N/ha was available for summer and winter crops in Year 2. This would have been sufficient to account for the additional forage produced. These findings provide support for valuing manure as a fertiliser, in addition to its recognised role as a soil ameliorant (Strong and Holford 1997).

While sampling for SOC was conducted only on a limited number of occasions and the concentrations did fluctuate between seasons (Wang *et al.* 2004), there was a strong indication that double-cropping was advantageous over predominantly sole-cropped oats. There are positive benefits to SOC from systems that generate higher levels of crop residue and reduce the time the soil is fallow (Peterson *et al.* 1998). The ability to have a positive impact on SOC concentrations, while continuing to crop, is an important finding when there are biophysical, economic and sociological impediments to the rotation of cropping with a pasture phase (Chataway *et al*. 2003; Singh *et al*. 2009*b*). We measured less benefit when lablab was substituted for sorghum and this concurs with Armstrong *et al*. (1999) who found cropping legumes to be generally ineffectual in raising SOM concentrations, with the larger residue input of fibrous grass roots being important (Clarke *et al*. 1967; Hossain *et al*. 1996). The addition of manure to the double-crop cereal systems increased SOC more quickly than did a similar treatment that used only inorganic fertiliser. However, this difference did not exist by the end of the study. This would suggest that continued applications of manure would be required to maintain an advantage over systems that use inorganic fertiliser only and rely on the return of crop residues to maintain or raise SOC (Anderson *et al*. 1990). While benefits of manure application on SOM are well recognised (McCalla 1974; Sommerfeldt *et al*. 1988), inorganic fertilisers are indirectly beneficial through increasing residue levels. Anderson *et al*. (1990) found, in a long-term study on a cultivated silt loam in Missouri, that there was no significant difference in soil physical properties between treatments applying either manure or inorganic fertiliser. Both were superior to where no fertiliser was used.

Summer sole-crop systems

At both sites, the mean annual biomass production of well fertilised multi-cut forage sorghum was about twice that of multi-cut oats grown at the same site. This difference was most likely due to the following two factors: the greater water constraints faced by winter crops than summer crops in the present study, and the lower inherent potential of C3 plants for radiant-energy conversion (Minson *et al*. 1993). Expected inherent differences in C3 and C4 grasses were also reflected in NDF concentration. With respect to the response to N fertiliser applied at above industry rates, the systems nature of the study means this response cannot be isolated from changes to tillage practices. However, as the main driver of increased crop yield from reduced tillage is increased water storage over the fallow period (Thomas *et al*. 2007), and in our study changes in tillage practices had no effect on water storage, improvement in forage yield could most likely be attributed to the higher N inputs.

For N fertiliser, our findings support the view that sorghum can be highly responsive (Muldoon 1985; Rahman *et al*. 2001) but that the response can be variable. In studies at four separate locations in the Darling Downs and West Moreton regions, Chataway *et al*. (1994) found that the response to additional N fertiliser ranged from 0 to 32 kg forage DM per kg N applied (0–150 kg N/ha). Low responses were recorded under conditions of low rainfall and high soil fertility or, conversely, where rainfall was very high, resulting in water logging, and conditions favoured denitrification (Strong *et al*. 1992). In southern Australia, Jacobs and Ward (2011) found variable yield responses of rain-grown summer forage crops to fertiliser N and identified available soil water as a major limiting factor. In our study, site differences were the main driver of overall variability, with the Kulpi site responding strongly to increased N fertiliser, reflecting an essentially N-constrained system, similar to that commonly seen in tropical perennial-grass systems (Cowan *et al*. 1995). The distribution of rainfall also appeared to be an important factor in determining yields, with the maximum yield being achieved at this site in a year of average but well distributed rainfall. In contrast, the Acland site was not N-constrained due to the combination of higher pre-trial inputs of fertiliser N and the inherently lower forage capacity of this soil (Harris *et al*. 1999).

At Acland, the lack of response to additional N fertiliser, in terms of plant yield and forage N concentration, and a relatively high concentration of nitrate-N present in the soil profile post-grazing (Fig. 6) provided evidence of an oversupply of this element. There were also likely to be losses from this site through denitrification (Craswell and Martin 1974) and some leaching. This was also indicated by the very low apparent recovery of N applied above the industry standard. In contrast, at Kulpi, the high rate of N fertiliser appears to have been relatively well matched to crop requirements, although the 98% apparent recovery of N fertiliser at this site appears unrealistically high. Possible error factors could include: first, a greater opportunity for recycling of N at higher levels, because a higher biomass of plant residues was returned to the forage system, given that a similar proportion (70%) of forage was utilised across low and high N-input systems. Second, a higher input of imported nutrients (in manure and urine) would potentially enter the higher-yielding systems due to a greater relative time this system was occupied by grazing animals. Third, there is the possibility that the high N-input regime led to a soil complex that was more conducive to higher rates of N mineralisation than was the low N-input system (Yan *et al*. 2006).

That there are benefits of including a legume in the summer sole-cropping program at Kulpi is an important finding for providing an alternative approach to increasing forage production on N-depleted soils, and is in line with the farmers' desire to increase the contribution of legumes to their forage base (Chataway *et al*. 2003). At this site, the yield of summer legumes ranged from 2.84 to 7.35 t DM/ha, which is in the range given by Hendricksen (1980) and Mullen and Watson (1999). The benefits of the legume phases at this site on soil nitrate-N concentrations, measured before following sorghum crops, were ~30–50 kg/ha fertiliser N equivalents, similar to those found by Armstrong *et al*. (1997) in studies in central Queensland but less than the 100 kg/ha N equivalents found by Herridge and Holland (1984) in northern New South Wales. On the Sodosol site, the production from sole-cropped lablab was lower and, when combined with higher soil nitrate-N concentrations, there were no clear soil nitrate-N benefits to subsequent crops (Doughton and Holford 1997). Where productivity was improved following lablab (Year 5), we believe this was mainly through a more friable seedbed (Wylie 1997), which could have improved plant establishment and/or initial plant growth. The usefulness of lablab in providing quality animal forage and benefiting subsequent cereal crops through N fixation has been noted in other studies in semiarid cropping environments (Singh *et al*. 2009*a*; Njarui and Mureithi 2010). The perennial temperate legume lucerne (*Medicago sativa*) has potential as an alternative legume forage. At both sites, its productivity in Years 1 and 2 exceeded that of lablab and, when terminated, it had positive benefits on soil nitrate-N concentrations (Chataway *et al*. 2011). While there are issues with bloat (Thompson 1988) and depletion of soil water (Strong *et al*. 2006) associated with lucerne, it does provide another legume alternative to lablab.

Soil erosion and organic carbon

Newly planted summer crops provide little surface cover, and unless crops are planted into stubble, considerable erosion can be caused by early summer storms (Wockner and Freebairn 1990). In the present study, successful establishment of summer crops using ZT was an important finding because ZT enables better preservation of stubble over the fallow period. As well as providing cover, summer crops also lower soil water content, which is critical for reducing runoff (Freebairn and Wockner 1986) and in turn erosion. The same attributes of a cropping program that minimise potential for erosion should also benefit SOM concentrations (Paustian *et al*. 1997). In our study, there was evidence from soil analysis that any of the summer cropping programs – industry standard (S5) and alternatives (S6, S7) – would be beneficial over a winter-dominant cropping program (Table 8). There was insufficient evidence from soil analysis to conclude that one summer cropping system was beneficial over another. However, other studies have found that a program that generates high plant residues, minimises tillage and favours grass species over legumes is more likely to benefit SOM (Hossain *et al*. 1996; Peterson *et al*. 1998; Armstrong *et al*. 1999).

Conclusion

Forage systems that include summer crops will have higher biomass production, reduced risk of erosion and improved SOC concentrations over winter sole-cropping systems. Double-cropping, while maintaining an emphasis on the winter crop, is possible and desirable but requires flexibility in management to respond to seasonal forecasts and determine a termination date for the summer crop. All forage systems need to move away from cultivation to zero tillage to preserve crop residue and enhance flexibility. On soils that are depleted in available N, higher rates of N fertiliser or legumes will be beneficial to both forage yield and quality.

Acknowledgements

We thank Dairy Australia for the funding support; host farmers Mr Bruce and Mrs Janelle Wieck and Mr Neville and Mrs Christine Vietheer for provision of land and managerial input; Mr Scott Lowe, Mr Wayne Ehrlich and Ms Anne Carlye for technical support; Mr Steve Childs and Mr James Henderson for field operations; Dr Pat Pepper and Mr Kevin Lowe for statistical and manuscript support, and Dr Wayne Strong for project development and scientific advice.

References

Anderson SH, Gantzer CJ, Brown JR (1990) Soil physical properties after 100 years of continuous cultivation. *Journal of Soil and Water Conservation* **45**, 117–121.

Anon (1988) Queensland Dairy Farmer Survey 1986–87. Queensland Department of Primary Industries, Brisbane.

Armstrong RD, McCosker KJ, Millar GR, Walsh K, Johnson S, Probert ME (1997) Improved nitrogen supply to cereals in central Queensland following short legume leys. *Australian Journal of Experimental Agriculture* **37**, 359–368. doi:10.1071/EA96129

Armstrong RD, Kuskopf BJ, Millar G, Whitbread AM, Standley J (1999) Changes in soil chemical and physical properties following legumes and opportunity cropping on a cracking clay soil. *Australian Journal of Experimental Agriculture* **39**, 445–456. doi:10.1071/EA99014

Ashwood A, Kerr D, Chataway RG, Cowan TM (1993) Northern Dairy Feedbase 2001. 5. Integrated dairy farming systems for northern Australia. *Tropical Grasslands* **27**, 212–228.

Bureau of Meteorology (2010) 'Seasonal outlooks.' Available at www.bom.gov.au/climate/ahead [verified 18 November 2010]

Buxton DR, Anderson IC, Hallam A (1999) Performance of sweet and forage sorghum grown continuously, double-cropped with winter rye, or in rotation with soybean and maize. *Agronomy Journal* **91**, 93–101. doi:10.2134/agronj1999.00021962009100010015x

Carberry PS, Hammer GL, Meinke H, Bange M (2000) The potential value of seasonal climate forecasting in managing cropping systems. In 'Applications of seasonal climate forecasting in agricultural and natural ecosystems: the Australian experience'. (Eds GL Hammer, N Nicholls, C Mitchell) pp. 167–181. (Kluwer Academic Publishers: the Netherlands)

Chapman DF, Kenny SN, Beca D, Johnson IR (2008) Pasture and forage crop systems for non-irrigated dairy farms in southern Australia. 1. Physical production and economic performance. *Agricultural Systems* **97**, 108–125. doi:10.1016/j.agsy.2008.02.001

Chataway RG, Orr WN, Cowan RT, Franz AJ, Buchanan IK, Long PL (1994) Milk responses to nitrogen fertiliser applied to dryland forage crops in south east Queensland. Final Report Project DAQ066. Dairy Research and Development Corporation, Melbourne.

Chataway RG, Doogan VJ, Strong WM (2003) A survey of dairy farmers' practices and attitudes to some aspects of arable land management in the Darling Downs and South Burnett regions off Queensland. *Australian Journal of Experimental Agriculture* **43**, 449–457. doi:10.1071/EA01179

Chataway RG, Orr WN, Cooper JE, Cowan RT (2011) The role of tillage, fertiliser and forage species in sustaining dairying based on crops in southern Queensland 1. Winter-dominant forage systems. *Animal Production Science* **51**, 890–903. doi:10.1071/AN11028

Clarke AL, Greenland DJ, Quirk JP (1967) Changes in some physical properties of the surface of an impoverished red-brown earth under pasture. *Australian Journal of Soil Research* **5**, 59–68. doi:10.1071/SR9670059

Clewett JF, Clarkson NM, George DA, Ooi SH, Owens DT, Partridge IJ, Simpson GB (2003) Rainman StreamFlow, version 4.3: a comprehensive climate and streamflow analysis package on CD to assess seasonal forecasts and manage climate risk. QI03040, Department of Primary Industries, Brisbane, Queensland.

Cowan RT, Lowe KF, Ehrlich W, Upton PC, Bowdler TM (1995) Nitrogen-fertilised grass in a subtropical dairy system. 1. Effect of level of nitrogen fertiliser on pasture yield and soil chemical characteristics. *Australian Journal of Experimental Agriculture* **35**, 125–135. doi:10.1071/EA9950125

Craswell ET, Martin AE (1974) Effect of moisture content on denitrification in a clay soil. *Soil Biology & Biochemistry* **6**, 127–129. doi:10.1016/0038-0717(74)90072-8

Crooke WM, Simpson WE (1971) Determination of ammonium in Kjeldahl digests of crops by an automated procedure. *Journal of the Science of Food and Agriculture* **22**, 9–10. doi:10.1002/jsfa.2740220104

Dalal RC, Mayer RJ (1986) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. *Australian Journal of Soil Research* **24**, 281–292. doi:10.1071/SR9860281

Doughton JA, Holford ICR (1997) Legumes. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. (Eds AL Clarke, PB Wylie) pp. 235–257. (Department of Primary Industries, Queensland: Brisbane)

Freebairn DM, Wockner GH (1986) A study of soil erosion on Vertisols of the eastern Darling Downs, Queensland 1. Effect of surface conditions on soil movement with contour bay catchments. *Australian Journal of Soil Research* **24**, 135–158. doi:10.1071/SR9860135

Freebairn DM, Connolly RD, Dimes J, Wylie PB (1997) Crop sequencing. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. (Eds AL Clarke, PB Wylie) pp. 289–305. (Department of Primary Industries, Queensland: Brisbane)

French AV (1981) Forage sorghums. In 'Forage crops and regional forage systems in Queensland'. Toowoomba Workshop 20–22 May 1980. (Queensland Department of Primary Industries: Brisbane)

Garcia SC, Fulkerson WJ, Brookes SU (2008) Dry matter production, nutritive value and efficiency of nutrient utilisation of a complementary forage rotation compared to a grass pasture system. *Grass and Forage Science* **63**, 284–300. doi:10.1111/j.1365-2494.2008.00636.x

Harris PS, Biggs AJW, Coutts AJ (1999) 'Central Darling Downs land management manual.' (Department of Natural Resources, Queensland: Brisbane)

Haynes RJ, Naidu R (1998) Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems* **51**, 123–137. doi:10.1023/A:1009738307837

Hendricksen RE (1980) The agronomy, yield, composition and nutritional value of *Lablab purpureus* and *Vigna unguiculata*. In 'Forage crops and regional forage systems in Queensland workshop'. Toowoomba, pp. 2–1 to 2–21. (Queensland Department of Primary Industries: Brisbane)

Herridge DE, Holland JF (1984) No-tillage effects on nitrogen fixation, soil nitrogen and growth and yield of summer crops. In 'No-tillage crop production in northern NSW: proceedings of the project team meeting'. (Eds RJ Martin, WL Felton) pp. 47–52. (New South Wales Department of Agriculture: Tamworth, NSW)

Hossain SA, Dalal RC, Waring SA, Strong WM, Weston EJ (1996) Comparison of legume-based cropping systems at Warra, Queensland. 1. Soil nitrogen and organic carbon accretion and potentially mineralisable nitrogen. *Australian Journal of Soil Research* **34**, 273–287. doi:10.1071/SR9960273

Jacobs JL, Ward GN (2011) Effect of nitrogen application on dry matter yields, nutritive characteristics and mineral content of summer-active forage crops in southern Australia. *Animal Production Science* **51**, 77–86. doi:10.1071/AN10105

Jokela WE (1992) Nitrogen fertiliser and dairy manure effects on corn yield and soil nitrate. *Soil Science Society of America Journal* **56**, 148–154. doi:10.2136/sssaj1992.03615995005600010023x

Kerr D, Davison T, Hetherington G, Lake M, Murray A (1996) Queensland Dairy Farm Survey 1994–95. Queensland Department of Primary Industries QI96115, Brisbane.

Kerr DV, Pepper PM, Cowan RT (2000) Estimates of achievable milk production on subtropical dairy farms in Queensland. *Australian Journal of Experimental Agriculture* **40**, 805–811. doi:10.1071/EA99150

Lloveras-Vilamanya J (1987) Forage production and quality of several crop rotations and pastures in northwestern Spain. *Grass and Forage Science* **42**, 241–247. doi:10.1111/j.1365-2494.1987.tb02112.x

McCalla TM (1974) Use of animal wastes as a soil amendment. *Journal of Soil and Water Conservation* **29**, 213–216.

Minson DJ, Cowan T, Havilah E (1993) Northern dairy feedbase 2001. 1. Summer pasture and crops. *Tropical Grasslands* **27**, 131–149.

Molloy JM (1988) 'Field manual for measuring stubble cover.' (Queensland Department of Primary Industries: Brisbane)

Muldoon DK (1984) Self regenerating annual forage legumes for double cropping with irrigated wheat or sorghum. *Experimental Agriculture* **20**, 319–326. doi:10.1017/S0014479700018007

Muldoon DK (1985) Summer forage under irrigation 3. The effect of nitrogen fertiliser on the growth, mineral composition and digestibility of a sorghum x sudangrass hybrid and Japanese barnyard millet. *Australian Journal of Experimental Agriculture* **25**, 411–416. doi:10.1071/EA9850411

Muldoon DK (1985*b*) Summer forages under irrigation 4. The growth and mineral composition of forage legumes. *Australian Journal of Experimental Agriculture* **25**, 417–423. doi:10.1071/EA9850417

Mullen CL, Watson RW (1999) Summer legume forage crops: cowpeas, lablab, soybeans. NSW Agriculture AgFact P4.2.16. 2nd edn (NSW Agriculture: Dubbo)

Njarui DMG, Mureithi JG (2010) Evaluation of lablab and velvet bean fallows in a maize production system for improved livestock feed supply in semiarid tropical Kenya. *Animal Production Science* **50**, 193–202. doi:10.1071/AN09137

Paustian K, Andren O, Janzen HH, Lal R, Smith P, Tian G, Tiessen H, Van Noordwijk M, Woomer PL (1997) Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management* **13**, 230–244. doi:10.1111/j.1475-2743.1997.tb00594.x

Payne RW, Harding SA, Murray DA, Soutar DM, Baird DB, Welham SJ, Kane AF, Gilmour AR, Thompson R, Webster R, Tunnicliffe Wilson G (2007) 'The guide to GENSTAT release 10, part 2: statistics.' (VSN International: Hemel Hempstead, UK)

Peterson GA, Halvorson AD, Havlin JL, Jones OR, Lyon DJ, Tanaka DL (1998) Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. *Soil & Tillage Research* **47**, 207–218. doi:10.1016/S0167-1987(98)00107-X

Rahman M, Fukai S, Blamey FPC (2001) Forage production and nitrogen uptake of forage sorghum, grain sorghum and maize as affected by cutting under different nitrogen levels. In 'Proceedings of 10th Australian agronomy conference', Hobart. (Ed. B Rowe). Available at www.regional.org.au/au/asa/2001/1/c/rahman.htm [Verified 10 January 2011]

Russell JS, Jones PN (1996) Continuous, alternate and double crop systems on a vertisol in subtropical Australia. *Australian Journal of Experimental Agriculture* **36**, 823–830. doi:10.1071/EA9960823

Singh DK, Strahan R, Christodoulou N, Cawley S (2009*a*) Validating economic and environmental sustainability of a short-term summer forage legume in dryland wheat cropping systems in south-west Queensland. *Animal Production Science* **49**, 816–825. doi:10.1071/AN09016

Singh DK, McGuckian N, Routley RA, Thomas GA, Dalal RC, Dang YP, Hall TJ, Strahan R, Christodoulou N, Cawley S, Ward L (2009*b*) Poor adoption of ley-pastures in south-west Queensland: biophysical, economic and social constraints. *Animal Production Science* **49**, 894–906. doi:10.1071/AN09015

Sommerfeldt TE, Chang C, Entz T (1988) Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. *Soil Science Society of America Journal* **52**, 1668–1672. doi:10.2136/sssaj1988.03615995005200060030x

Stevenson FC, Johnston AM, Beckie HJ, Brandt SA, Townley-Smith L (1998) Cattle manure as a nutrient source for barley and oilseed crops in zero and conventional tillage systems. *Canadian Journal of Plant Science* **78**, 409–416. doi:10.4141/P97-094

Strong WM, Holford ICR (1997) Fertilisers and manures. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. (Eds AL Clarke, PB Wylie) pp. 214–235. (Department of Primary Industries, Queensland: Brisbane)

Strong WM, Saffigna PG, Cooper JE, Cogle AL (1992) Application of anhydrous ammonia or urea during the fallow period for winter cereals on the Darling Downs, Queensland. 2. The recovery of ^{15}N by wheat and sorghum in soil and plant at harvest. *Australian Journal of Soil Research* **30**, 711–721. doi:10.1071/SR9920711

Strong WM, Dalal RC, Weston EJ, Lehane KJ, Cooper JE, King AJ, Holmes CJ (2006) Sustaining productivity of a Vertosol at Warra, Queensland, with fertilisers, no-tillage or legumes. 9. Production and nitrogen benefits from mixed grass and legume pastures in rotation with wheat. *Australian Journal of Experimental Agriculture* **46**, 375–385. doi:10.1071/EA05007

Stuart PN (2002) 'The forage book.' (Pacific Seeds: Toowoomba, Qld)

Technicon (1976) Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Industrial method no. 329-74 W/A. Technicon Industrial Systems, Tarrytown, New York.

Thomas GA, Titmarsh GW, Freebairn DM, Radford BJ (2007) No-tillage and conservation farming practices in grain growing areas of Queensland: a review of 40 years of development. *Australian Journal of Experimental Agriculture* **47**, 887–898. doi:10.1071/EA06204

Thompson P (1988) 'Improving livestock profitability with pasture and forage crops.' (Bowdler, English and Wehl Seed and Grain and Annand, Robinson and Co.: Toowoomba, Qld)

Unger PW, Stewart BA, Parr JF, Singh RP (1991) Crop residue management and tillage methods for conserving soil and water in semi-arid regions. *Soil & Tillage Research* **20**, 219–240. doi:10.1016/0167-1987(91)90041-U

Van Soest PJ, Robertson JB, Lewis BA (1991) Methods for dietary fibre, neutral detergent fibre and non starch polysaccharides in relation to animal nutrition. *Journal of Dairy Science* **74**, 3583–3597. doi:10.3168/jds.S0022-0302(91)78551-2

Wang JR, Dalal RC, Moody PW (2004) Soil carbon sequestration and density distribution in a Vertosol under different farming practices. *Australian Journal of Soil Research* **42**, 875–882. doi:10.1071/SR04023

Webb AA, Grundy MJ, Powell B, Littleboy M (1997) The Australian sub-tropical cereal belt: soils, climate and agriculture. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. (Eds AL Clarke, PB Wylie) pp. 8–23. (Department of Primary Industries, Queensland: Brisbane)

Wockner GH, Freebairn DM (1990) Water balance and erosion studies on the eastern Darling Downs – an update. *Australian Journal of Soil and Water Conservation* **4**, 41–47.

Wylie P (1993) Conservation farming systems for the summer rainfall cereal belt. *Australian Journal of Soil and Water Conservation* **6**, 28–33.

Wylie PB (1997) Practical and economic considerations. In 'Sustainable crop production in the sub-tropics: an Australian perspective'. (Eds AL Clarke, PB Wylie) pp. 329–338. (Department of Primary Industries, Queensland: Brisbane)

Yan D-Z, Wang D-J, Sun R-J, Lin J-H (2006) N mineralization as affected by long-term N fertilization and its relationship with crop N uptake. *Pedosphere* **16**, 125–130. doi:10.1016/S1002-0160(06)60034-9

Manuscript received 3 March 2011, accepted 25 July 2011