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The role of tillage, fertiliser and forage species in sustaining dairying based on crops in southern Queensland 1. Winter-dominant forage systems

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Abstract. Field studies were conducted over 5 years on two dairy farms in southern Queensland to evaluate the impacts of zero-tillage, nitrogen (N) fertiliser and legumes on a winter-dominant forage system based on raingrown oats. Oats was able to be successfully established using zero-tillage methods, with no yield penalties and potential benefits in stubble retention over the summer fallow. N fertiliser, applied at above industry-standard rates (140 *vs.* 55 kg/ha.crop) in the first 3 years, increased forage N concentration significantly and had residual effects on soil nitrate-N at both sites. At one site, crop yield was increased by 10 kg DM/ha.kg fertiliser N applied above industry-standard rates. The difference between sites in fertiliser response reflected contrasting soil and fertiliser history. There was no evidence that modifications to oats cropping practices (zero-tillage and increased N fertiliser) increased surface soil organic carbon (0–10 cm) in the time frame of the present study. When oats was substituted with annual legumes, there were benefits in improved forage N content of the oat crop immediately following, but legume yield was significantly inferior to oats. In contrast, the perennial legume *Medicago sativa* was competitive in biomass production and forage quality with oats at both sites and increased soil nitrate-N levels following termination. However, its contribution to winter forage was low at 10% of total production, compared with 40% for oats, and soil water reserves were significantly reduced at one site, which had an impact on the following oat production. The study demonstrated that productive grazed oat crops can be grown using zero tillage and that increased N fertiliser is more consistent in its effect on N concentration than on forage yield. A lucerne ley provides a strategy for raising soil nitrate-N concentration and increasing overall forage productivity, although winter forage production is reduced.

Additional keywords: farming systems, forage quality, livestock, lucerne ley, oats, raingrown, soil nitrate-N, soil organic carbon, zero-till.

Introduction

Within the Australian dairy industry, the cropping-based farms of southern Queensland are unique in their high dependence on forage crops rather than pastures. These farms, mostly located in the Darling Downs and Inland Southern Burnett agricultural zones (Webb *et al*. 1997), typically devote over 80% of the improved pasture/crop area to annual crops (Chataway *et al*. 2003). Farms grow both winter and summer crops, to provide a continuous supply of feed (Kerr *et al*. 1996). The dominant winter crop is forage oats (*Avena sativa*), while in summer *Sorghum* spp. crops predominate. The focus on forage crops rather than pasture is due to several reasons, including limited or no access to irrigation (Kerr *et al*. 1996), the capacity of the regions dominant soils (Vertosols) to accumulate water over fallows and thus enable crops to be grown with relative confidence (Webb *et al*. 1997) and the high potential biomass of crops (Garcia *et al*. 2008). Within this subtropical cereal belt, both summer and winter crops are also grown to provide strategic grazing for prime lamb and beef cattle. In the central Darling Downs region alone, ~180 000 ha of forage crops are planted annually (Harris *et al*. 1999). Second, for the national dairy industry, there is increasing interest in forage-crop production across regions to improve water-use efficiencies, increase biomass yields and reduce exposure to climatic variability (Chapman *et al*. 2008; Garcia *et al*. 2008; Chataway *et al*. 2010).

However, dairy farming based on annual crops in the subtropical region faces threats to long-term productivity from soil erosion, general soil-fertility decline and suboptimal productivity. Soil erosion is particularly problematic because farms tend to be located on the shallower, sloping soils of the earliest settled upland areas (Harris *et al*. 1999; Marshall *et al*. 1988), and over the summer period, when rainfall can be intense (Webb *et al*. 1997), paddocks used for winter production have little or no plant cover (Marshall *et al*. 1988). Conventional farming practices that use tillage to maintain a weed-free fallow, and prepare a fine seedbed for the following winter crop, are inimical to long-term productivity (Freebairn and Wockner 1986; Thomas *et al*. 2007). The routine use of tillage

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also hastens the decline in soil organic matter (Dalal and Mayer 1986). Reductions in soil organic matter levels have been associated with both declining soil chemical and physical fertility (Blanco-Canqui and Lal 2009; Dalal *et al*. 1991). In the dairy industry, declining chemical fertility has been noted through plant response to increased rates of nitrogen (N) fertiliser (Thompson and Bywater 1987). While the physical fertility of Vertosols, the main soils used for forage cropping, are relatively resilient to declines in organic matter, other soils used for forage cropping such as Ferrosols and lighter-textured soils are more dependent on organic matter for preserving physical fertility (Bridge and Bell 1994; Chan and Hulugalle 1999). With respect to farm productivity, Kerr *et al*. (2000) determined that cropping-based dairy farmers in southern Queensland were falling well short of their achievable milk production. This was in part due to a failure to reach achievable milk production from home-grown forage (Ashwood *et al*. 1993). Improved forage production would also have additional benefits in better protecting the soil from erosion through a relative increase in crop residues (Strong and Holford 1997) and potential gains to the soil organic matter pool (Paustian *et al*. 1997).

In the subtropical grains industry, strategies have been developed that have the potential, when incorporated into farming systems, to improve sustainability of the resource base through reducing the risk of erosion, arresting soil organic matter decline and increasing plant-available N. These strategies include the use of ley pastures (Lloyd *et al*. 1991), annual forage legumes (Armstrong *et al*. 1997; Weston *et al*. 2002), increased cropping frequency (Wylie 1997), zero-tillage (Freebairn and Wockner 1986) and improved use of both inorganic fertilisers and manure (Strong and Holford 1997). It was hypothesised that these same strategies could be used by the dairy industry to better manage the soil resource base, while maintaining or improving productivity of the forage base. However, a previous study by Chataway *et al*. (2003) showed that dairy farmers have reservations about some of these strategies. These include concern that an increased emphasis on perennial forages will result in lower and less reliable production, that double-cropping is not necessarily a feasible or a desirable way to farm, and that zero-tillage may not be successful on clay soils that have been trafficked by cattle. Farmers also expressed a desire to make greater use of annual legumes in future farming systems (Chataway *et al*. 2003).

To investigate these issues, field trials were conducted on two dairy farms located on contrasting soil types on the eastern Darling Downs. On each of these farms, a range of forage systems were evaluated for their productivity and impact on the soil resource base. In the present paper, we report specifically on the productivity of winter-dominant forage systems based on sole-cropped oats and the impact changes to tillage, N-fertiliser rate and the replacement of oats with legumes has on forage productivity and soil parameters.

Materials and methods

Site details

Following consultation with regional farmers, dairy advisors and soil conservationists, two sites on the central Darling Downs (Harris *et al*. 1999) were chosen as test sites. Both had been cultivated for at least 40 years. The first site at Kulpi (27°11′S, 151°41′E; alt. 450 m) was located on a pediment below a basalt ridge (2% slope) on a haplic self-mulching black Vertosol (Isbell 1996). The soil was characterised by a very fine granular surface, overlying dark, cracking clay down to ~0.3–0.6 m, with soil colour changing to red–brown below this depth. The site was protected from run-on water through a newly constructed contour bank located between the experimental site and elevated pasture land to the south. The farming community considered this soil to be well suited to forage cropping (Chataway 2006). Until 1990, very little fertiliser had been used. Since then, urea and mono-ammonium phosphate had been applied at rates of 75 and 20 kg/ha.crop. The site had been fallowed over the winter before the study commenced. Mean site nitrate-N concentrations at the beginning of the study in the 0–10-, 10–30-, 30–60-cm soil layers was 6.0, 1.9 and 0.6 mg/kg, respectively.

The second site at Acland (27°40′S, 151°40′E; alt. 400 m) was located on a relict alluvial plain of material derived primarily from fine-grained sandstones and still subject to some overland flow. The soil fitted within the description of a eutrophic, mottled-subnatric, brown Sodosol (Isbell 1996), commonly known as Downfall (Harris *et al*. 1999). In an undisturbed situation, Downfall is a texture contrast soil with a thin, hardsetting surface. The soil was sodic in the mid- to lower B horizons (below ~0.5 m). Very little, if any, fertiliser had been used until 1989 when urea was applied at 150–200 kg/ha.crop, which was higher than the industry standard of 125 kg/ha.crop (Anon 1988). A summer crop had been grown on the site in the preceding two summers (1993–95). This higher fertiliser regime was reflected in initial nitrate-N concentrations in the 0–10-, 10–30-, 30–60-cm soil layers of 23.0, 7.4 and 5.2 mg/kg, respectively. In contrast to Kulpi, this site represented a structurally difficult soil that was representative of a smaller, but significant, portion of cropping soils found in the region. Surface soil (0–10 cm) properties for both sites are listed in Table 1.

Long-term mean annual rainfall at Oakey, the nearest recording centre, 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 (Table 2), 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. The exception to the general

Table 1. Properties of the surface soil (0–10 cm) at Kulpi and Acland experimental sites before the commencement of the study

Parameter	Kulpi	Acland
pH (1 : 5, soil : water)	8.5	7.3
Coarse sand (%)	4	12
Fine sand (%)	16	41
Silt (%)	20	12
Clay (%)	60	35
Total nitrogen (%)	0.133	0.07
Organic carbon (%)	1.43	0.82
Cation exchange capacity (meq %)	41	19
Nitrate-nitrogen (mg/kg)	6	23
Bicarbonate phosphorus (mg/kg)	80	24
Exchangeable potassium (meq/100 g)	1.10	0.4
SO_4-sulfur (mg/kg)	4	6
Exchangeable sodium (%)	1	4.3

Table 2. Rainfall summary for the sites at Kulpi and Acland (1996–2002)
WY, water year from 1 October to 30 September

Year	Rainfall (mm)					
	Kulpi			Acland		
	WY	Oct.–Mar.	Apr.–Sep.	WY	Oct.–Mar.	Apr.–Sep.
1996–1997	445	290	155	484	301	183
1997–1998	926	435	491	1124	674	450
1998–1999	596	439	157	665	506	159
1999–2000	508	424	84	544	453	91
2000–2001	554	424	130	474	339	135
2001–2002	543	418	125	711	590	121
Long-term mean (102 years)	661	452	210	661	452	210

rainfall pattern was in 1997–1998, when very high rainfall was recorded at both sites. Overall, rainfall was higher at Acland than Kulpi due primarily to three major events that caused flooding (November 1997, February 1998, October–November 2001).

The mean maximum (January) and minimum (July) temperatures recorded between 1997 and 2002 were 31.0 and 3.6°C at Kulpi and 31.2 and 3.8°C for Acland. Long-term mean annual pan evaporation for Oakey is 1900 mm (Clewett *et al.* 2003).

Site advisory groups

Industry discussion groups from both Kulpi and Acland were asked to act in an advisory capacity for the field studies. The host farmers were members of both groups. These advisory groups met twice a year with scientific staff to review findings from the previous season and discuss general operational plans (variety selection and planting, grazing and fallow management) for the coming season. Members of these groups also critiqued the proposed forage systems (Chataway 2006). Contact with the host farmer was more frequent (once or twice a month) to discuss the timing of grazing, tillage events and planting operations. There was general agreement on how and when to carry out these operations, although the final decision was left with project staff.

Treatments

The different management strategies under evaluation (rate of N fertiliser, tillage regime, cropping frequency, annual and perennial legumes and feedlot manure) were incorporated into 11 different forage systems (treatments). Five of these systems had a focus on winter production, three on both winter and summer (double-crop) and three on summer (sole-crop). In the present paper, the five systems with a focus on winter production are reviewed and only these systems are detailed in Table 3. System 1 (S1) was considered the ‘industry standard’.

The 11 forage systems were established in a randomised block design, with three replications in plots 30 by 9 m in size. The final forage systems selected were developed through an iterative process among scientists, extension officer and farmers (Chataway 2006). The objective of the 11 chosen systems was that they captured the diversity of views held by scientists and farmers on strategies to better sustain the soil resource base while maintaining or increasing forage productivity.

Techniques

Fallow management

The forage plots were either cultivated (CT) two or three times to control fallow weeds and prepare a seedbed or sprayed (ZT) two to four times with glyphosate herbicide (450 g active ingredient (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.

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-

Table 3. The five winter-dominant forage systems and their associated cropping sequences at Kulpi and Acland
CT, conventionally tilled; ZT, zero-tillage; low N, 50 kg N/ha as urea; high N, as described in Table 4. Variations at Acland: no sorghum crop was grown in Year 1 but a sorghum crop (unfertilised) was grown across all systems in an additional sixth year; vetch rather than medic was grown in S4; and the lucerne ley was extended one further year in S5

Forage system	Year 1 (1996–1997)		Year 2 (1997–1998)	Year 3 (1998–1999)	Year 4 (1999–2000)	Year 5 (2000–2001)
S1: oats, CT, low N	Sorg	Oats	Oats	Oats	Oats	Oats
S2: oats, CT, high N	Sorg	Oats	Oats	Oats	Oats	Oats
S3: oats, ZT, high N	Sorg	Oats	Oats	Oats	Oats	Oats
S4: medic (Years 1, 2), oats (Years 3–5), ZT, low N	Sorg	Medic	Medic	Oats	Oats	Oats
S5: lucerne (Years 1–3), oats (Years 4, 5), ZT, low N	Lucerne		Lucerne	Lucerne	Oats	Oats

engaging tools and press wheels, making it suitable for zero-tillage planting. Inter-row cultivating tines were also fitted to the planter, but were used only when stubble levels were low.

Crop types, planting rates and time of planting

Crops used were oats (*Avena sativa* L. cv. Graza 50 in Years 1 and 2 and Nugene in Years 3, 4 and 5 at 40 kg/ha, medic (*Medicago scutellata* L. cv. Sava and Kelson mix) at 10 kg/ha lime-coated seed, vetch (*Vicia benghalensis* cv. Popany) at 20 kg/ha and lucerne (*Medicago sativa* L. cv. Sceptre) at 7 kg/ha lime-coated seed. Transition crops of the sorghum sudan grass hybrid cv. Nectar at 8 kg/ha were also grown at the commencement of the cropping program at Kulpi and at the completion of the program at Acland and reflect a typical industry double-cropping intensity of 1 in 5 years (Chataway *et al*. 2003). Both these crops were grazed just once and the crop at Kulpi was fertilised with 55 kg N/ha. Crops 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, medic and vetch were planted between April and July inclusive, with May being the most frequent planting month. Lucerne was planted in February at Kulpi and in May at Acland.

Fertiliser

All the fertiliser requirements for the industry-standard (low-N) plots were applied at planting. N fertiliser as urea was applied at 50 kg N/ha.crop between every second crop row via an inter-row tine. In addition, 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. Plots' receiving what was considered optimum rates of N fertiliser (high N) received the same rate of mixed fertiliser. For these plots, however, it was proposed that urea would be applied at planting to supply 100 kg N/ha, with further urea applied as topdressing (50 kg N/ha) after the 1st and 2nd grazings if further grazings were anticipated. A maximum of 200 kg N/ha, as urea, was applied to each crop. As Table 4 shows the mean annual rates applied were less and higher N rates were applied only during Years 1–3 inclusive. The lucerne ley system received an annual broadcast application of 100 kg/ha of Granulock ST-Z and the oats crops grown following this the lucerne ley were fertilised at the same rate as industry-standard oat crops. Chosen fertiliser rates were based on multiple sources. Survey data were used to determine current industry practice (Kerr *et al*. 1996), while the high N level was based on the expert opinion of project scientists from the grain and dairy industries. The application of a mixed fertiliser, and the rate applied, was to ensure that other nutrients, particularly P and Zn, did not limit plant growth at the higher rates of N application; the decision to apply the same rate across all systems was based on conventional agronomic research protocol. With respect to N fertiliser, at the completion of Year 3, a decision was made to reduce the planting application rate of urea to 'high N' plots from 100 to 50 kg N/ha. This was made due to forage yield at first grazing being lower than anticipated and forage N concentration being well in excess of animal requirements (NRC 2001).

Grazing

Forage plots were grazed by a herd of adult dairy cows following sampling for yield and quality analysis. Sites were grazed 1 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, depending on the level of forage on offer. 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. Animals typically grazed for 2–4 h per day before being moved to another paddock for watering and lounging. The time to first grazing varied according to climatic conditions, but was typically 8–10 weeks for *Avena sativa* and 10–12 weeks for *Medic* and *Vetch* spp. The timing of subsequent grazings was dependent on the incidence and extent of in-crop rainfall and associated growing conditions. The target height for grazing was 40 cm for oats.

In-crop herbicides

In two of the five winters, 2, 4-DB (400 g a.i./L) was sprayed on winter forage crops at 3 L/ha before the first grazing to control broadleaf weeds.

Lucerne-dominant system

At Kulpi, grass weeds in the pure lucerne leys were controlled with the use of fluzifop-p (212 g a.i./L) applied at 500 mL/ha, 1 and 8 months after planting. Then at 18 months after planting, lucerne leys at both sites were sprayed with imazethapyr (240 g a.i./L) at 400 mL/ha to control both broadleaf and grass weeds. Two strategies were used to terminate the lucerne leys. At Kulpi, a series of herbicide applications using glyphosate (450 g a.i./L) at 3, 2 and 1 L/ha were applied on 24 November 1999, 19 January 2000 and 21 February 2000 respectively. On the

Table 4. The annual rate of nitrogen fertiliser (kg N/ha) applied to winter-forage crops and lucerne at Kulpi and Acland
Explanation for the forage systems is given in Table 3

Forage system	Year 1 (1996–1997)	Year 2 (1997–1998)	Year 3 (1998–1999)	Year 4 (1999–2000)	Year 5 (2000–2001)	Annual mean
S1	55	55	55	55	55	55
S2	105	205	105	55	55	105
S3	105	205	105	55	55	105
S4	5	5	55	55	55	35
S5	11	11	11	55 (11)[A]	55	29 (20)

[A] Acland data are given in parentheses.

final spraying 2,4-D as IPA salt (225 g a.i/L) at 2 L/ha was combined with the glyphosate. At Acland, rather than herbicides, tillage was used, with four operations conducted between 16 June 2000 and 14 March 2001. A blade plough was used for the initial tillage event.

Plant measurements and analysis

Harvestable forage

Prior to each grazing, five 1-m^2 samples were cut from within the two central planter runs. Winter-forage crops were harvested at a mean height of 7.5 cm above ground level. For repeat samplings, only new growth was harvested. In the lucerne ley treatment, swards were harvested at 7.5 cm above ground level. For this forage, where distinguishing new from old growth would have been more difficult, fixed sampling points were used to avoid sampling any residue left from the previous grazing. These points were relocated each year to minimise the effect of repeated cutting.

The fresh forage cut from each plot was weighed and a representative subsample of ~0.5 kg was placed into a sealed plastic bag and returned to the laboratory. On the same day as sampling, these were weighed and placed in a forced-draft oven at 80°C for drying. After drying for 48 h, they were reweighed to determine dry matter content and two subsamples were removed for chemical analysis. One subsample was ground (1-mm sieve) and analysed for total N and phosphorus content using Kjeldahl digestion followed by automated continuous flow methods (Crooke and Simpson 1971; Technicon 1976). The other subsample (whole plant) was pooled on the basis of species, maturity and N-fertiliser rate. These pooled samples were then analysed for neutral detergent fibre (NDF) using a modified version of the method of Van Soest *et al*. (1991).

An estimate of harvestable forage (measured forage yield) 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 was 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 during the fallow period were conducted over two fallow periods before crops being sown in Years 4 and 5. 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). A photograph of soil cover within a quadrat at one sampling site for each treatment was taken and retained.

Soil sampling and analysis

Nitrate-N and available soil water

A soil sample was taken before planting all crops and a second sample was taken after the final grazing. Plots were stratified into 14 potential sampling positions within the central two planter runs. Sampling positions were 3 m apart and located between 6 and 24 m along each planter run. At each sampling, a new position was chosen randomly. Within this position, five soil cores, each 10 cm apart, were taken along a transect placed at random across the planted rows and fertiliser application bands with a 50-mm-diameter tube sampler. Cores were collected from each plot to a depth of 30 cm, then two cores to 150-cm depth in a shallow–deep–shallow–deep–shallow pattern by using a self-propelled hydraulic soil-sampling rig. The core samples were subdivided into 10-cm layers down to 30-cm depth and into 30-cm layers below that. The soil cores for each plot were bulked by depth, sealed in plastic bags and stored at 4°C, usually overnight, until drying.

Soil was dried at 35 ± 5°C in a forced-draught oven and then ground to <2 mm for colourimetric determination of nitrate-N (Best 1976) after extraction of 10 g of soil in 100 mL of 2 M KCl. Gravimetric soil water (g/g) was determined by drying the ground soil samples at 105°C for 48 h and calculating the total water content. Volumetric water content (mm/layer) was calculated using a bulk density adjusted for the soil moisture of the layer at sampling. Plant-available water was derived by subtracting the soil water content at the estimated lower limit of availability (wilting point) for each soil layer from the measured volumetric water content. The lower limits of availability were 22, 24, 25, 79, 86, 94 and 96 mm for soil layers 0–10, 10–20, 20–30, 30–60, 60–90, 90–120 and 120–150 cm for the Acland site and 28, 29, 29, 91, 100, 106 and 109, respectively, for the Kulpi site. Lower limits for 0–120 cm were 330 and 380 mm for Acland and Kulpi respectively.

Organic carbon

Six soil core samples were collected from each plot with a 50-mm-diameter foot sampler down to 20 cm in the early phase of the field experiments. A further two sampling operations were completed in mid-project and a fourth at the end of the main experimental phase, using the rig described above. Where possible, the samples were taken without oil; however, a small quantity of silicon-based oil was used when soil moisture levels were high. The samples were subdivided into 10-cm layers, bulked, sealed in plastic bags and stored at 4°C until drying. After removing visible pieces of plant material and stones, the soil was dried at 35 ± 5°C in a forced-draught oven and then ground to <2 mm initially, and then to <0.25 mm for determination of total N by a micro-Kjeldahl method (Bremner 1965) and organic carbon by the Walkley–Black method adapted for spectrophotometric determination (Sims and Haby 1971).

Calculations

Weighted mean N and NDF %

Where total crop yield comprised more than one harvest (grazing), N and NDF% for each harvest were weighted according to the contribution that harvest made to the total yield for the assessment period.

Apparent recovery of fertiliser N

The apparent recovery of N fertiliser applied above the industry-standard rate was calculated using the same principles as described by Whitehead (1995). That is, N recovered in forage fertilised at the high N rate, less the N recovered in the herbage fertilised at industry-standard rate (low N), was expressed as a percentage of the additional fertiliser N applied.

Fallow water storage efficiency

This was calculated by expressing, as a percentage, the change in plant-available water (PAW) over the fallow (mm) (0–1.2 m) compared with rainfall over the fallow (mm), where change in PAW (mm) is calculated by taking PAW at the start of the fallow (mm) from PAW at the end of the fallow (mm).

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 a subset of the five winter-focussed forage systems for forage dry matter yield, forage N concentration, soil nitrate-N, soil water and soil cover. Significant differences among 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 yield

Within sites, mean annual production over 5 years was similar for all continuous oat-based systems (S1, 2, 3) regardless of differences in tillage or N fertiliser practices (Tables 5, 6). On a yearly basis, fertilising oats with additional N fertiliser increased production ($P < 0.05$) only in Year 2 at Kulpi when high in-crop rainfall (500 mm) was received; the production difference was measured at the second and subsequent grazings (Fig. 1). While not significant ($P > 0.05$), there was some indication that additional N fertiliser may have been beneficial to production in Year 1 at Kulpi and in Year 2 at Acland (Tables 5, 6). In contrast, the industry-standard system (S1) outperformed other continuous oat systems in Year 4 at Kulpi. Annual yields for zero-tilled (ZT) and cultivated systems (CT) was similar in all years except Year 5 at Acland when production under ZT was lower (Table 6). Site differences and rainfall were important determinants of yield. The mean annual yield of oats was consistently higher at Kulpi than at Acland, 4.04 and 2.68 t DM/ha, respectively, and for both sites there was a

Table 5. Annual harvestable forage yield (DM, t/ha) for five forage systems based around oats at Kulpi over 5 years

Rainfall is given for each year and is based on water-year from 1 October 1 to 30 September. Explanation for the forage systems is given in Table 3. The total yield of S1, S2, S3 and S4 in Year 1 comprises yield from a transition summer crop as well as the winter crop; winter crop yield only is given in parentheses. Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined

Forage system	Year 1 (1996–1997)	Year 2 (1997–1998)	Year 3 (1998–1999)	Year 4 (1999–2000)	Year 5 (2000–2001)	Mean (1996–2001)	Utilisation (Years 1–5)
Year rainfall (mm)	445	926	596	508	554	606	
S1	6.16b (3.15b)	4.81b	2.89a	2.92d	5.07c	4.38bc	77
S2	6.46b (3.66bc)	7.02cd	3.29a	2.47bc	4.36b	4.76c	74
S3	6.75b (3.75c)	7.38d	3.24a	2.07b	4.43bc	4.78c	75
S4	4.42a (1.65a)	2.98a	3.11a	2.17bc	4.45bc	3.43a	72
S5	4.97a	6.25c	4.22b	0.810a	3.63a	3.98b	70
l.s.d. ($P = 0.05$)	0.78 (0.53)	0.83	0.64	0.36	0.68	0.43	n.d.

Table 6. Annual harvestable forage yield (DM, t/ha) for five forage systems based around oats evaluated at Acland over 6 years

Rainfall is given for each year and is based on water-year from 1 October 1 to 30 September. Explanation for the forage systems is given in Table 3. Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined

Forage system	Year 1 (1996–1997)	Year 2 (1997–1998)	Year 3 (1998–1999)	Year 4 (1999–2000)	Year 5 (2000–2001)	Mean (1996–2001)	Utilisation (Years 1–5)	Year 6[A] (2001–2002)
Year rainfall (mm)	484	1124	665	544	474	658		711
S1	3.30bc	3.95ab	2.35a	0.95a	1.93b	2.50ab	88	6.48a
S2	3.48c	5.00bc	2.44ab	1.06ab	1.90b	2.78b	87	7.05ab
S3	3.58c	5.06bc	2.56ab	1.45bc	1.12a	2.75b	85	7.66b
S4	1.80a	3.04a	2.76b	1.81c	1.28a	2.14a	71	7.63b
S5	2.61ab	6.09cd	3.18c	2.40d	3.06c	3.47c	75	7.84b
l.s.d. ($P = 0.05$)	0.87	1.48	0.36	0.50	0.50	0.50	n.d.	0.87

[A] Assay crop of forage sorghum planted across all systems (no N fertiliser applied, ZT).

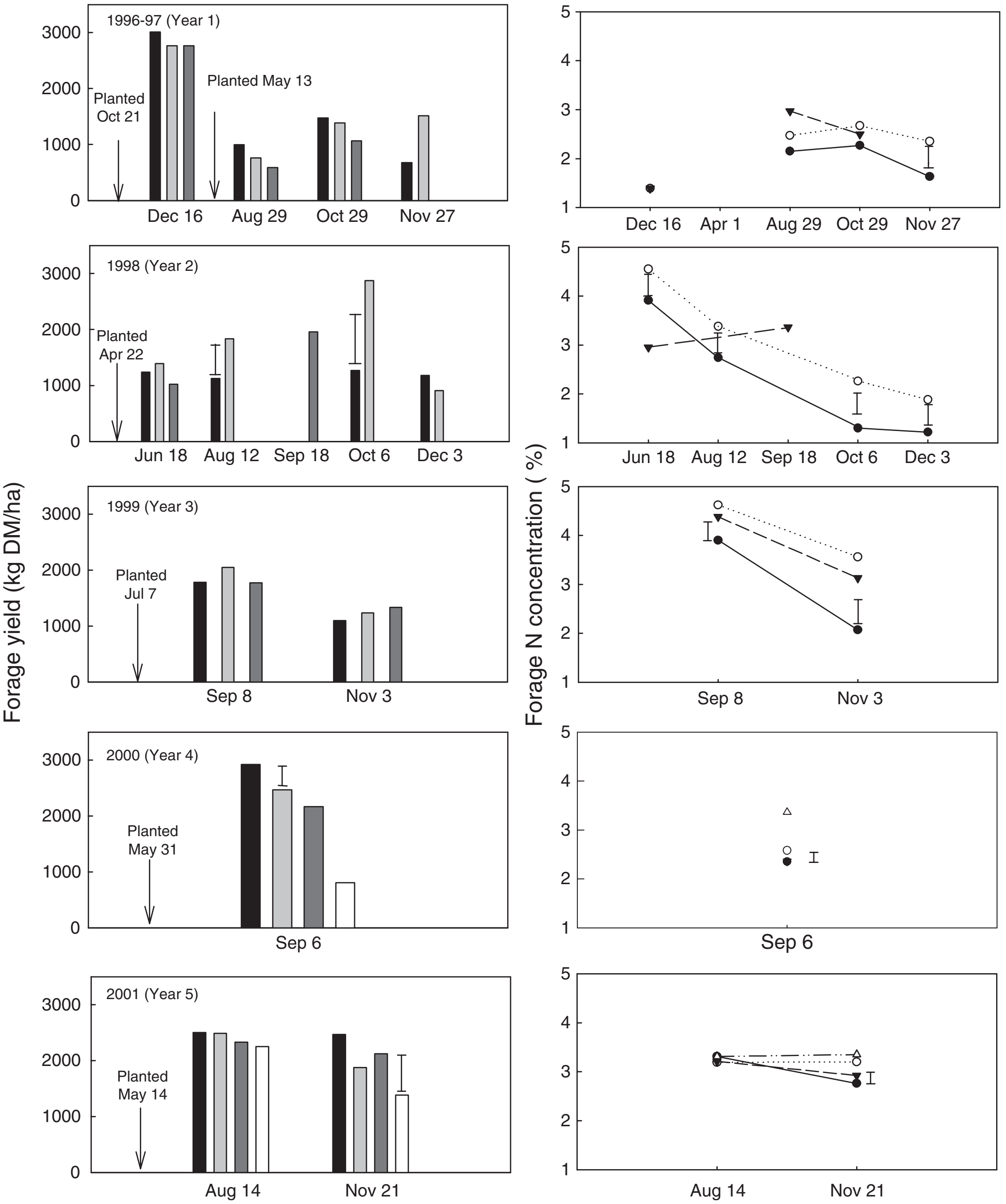

Fig. 1. Dry matter yield (t DM/ha) and nitrogen (N) content (%) of individual grazings for the following four forage systems at Kulpi: S1 (solid bar, solid circle); S2 (lightly shaded bar, open circle); S4 (heavily shaded bar, solid triangle); S5 (open bar, open triangle). Vertical bars show l.s.d. ($P = 0.05$) among oats crops at specific grazings. See Table 3 for an explanation of the forage systems.

relationship between total rainfall during fallow and crop growth, where N was not limiting (high N systems), as follows:

$$\text{Forage yield (kg DM/ha)} = -1469 + 9.84 \times \text{rainfall (mm)}$$
$$(R^2 = 0.84,\ P < 0.05)\ \text{(Kulpi)};$$

$$\text{Forage yield (kg DM/ha)} = -690 + 5.87 \times \text{rainfall (mm)}$$
$$(R^2 = 0.78, P <, 0.05)\ \text{(Acland)}.$$

Replacing oats with an annual legume in Years 1 and 2 (S4) reduced production ($P < 0.05$) in those years at both sites and reduced production overall at Kulpi (Table 5). When oats was replaced by lucerne (S5) at Kulpi (Years 1–3), it out-yielded industry-standard oats (S1) and medic oats (S4) and was competitive with other oat systems (S3, S4). However in Years 4 and 5, oat crops following lucerne (S5) yielded less than oats following oats (Table 5), reducing the overall yield. At Acland, the lucerne–oats system was more productive overall than all other systems (Table 6) and, in contrast to Kulpi, the oat crop grown in Year 5, following termination of the lucerne ley (S5), out-yielded ($P < 0.05$) oats following oats in all other systems. An assay crop of sorghum grown following the last oats crop also showed yield benefits from the lucerne ley in comparison to the industry-standard oats system (S1) (Table 6).

Forage N concentration

All alternative management practices (S2, S3, S4, S5) at both sites raised mean forage N concentration ($P < 0.05$) above those achieved using industry-standard practices (S1) (Tables 7, 8). At Kulpi, overall mean N concentration was lower for ZT than CT (S2 *vs.* S3) ($P < 0.05$). Higher rates of N fertiliser increased N content of oats during Years 1–3 at Kulpi (Table 7), whereas at Acland there was a difference only in the year of high rainfall (Year 2) (Table 8). N concentration of oats at first grazing was frequently between 3% and 4% at both sites (Fig. 2), and at times exceeded 4% when fertilised at higher rates (S2, S3) or grown following a legume phase (S4). Additional N fertiliser at Kulpi reduced the decline in N content of forage at the second and subsequent grazings (Fig. 1). At Acland, a significant ($P < 0.05$) difference was noted only in Year 2 (data not presented). Replacing oats with a legume crop in Years 1 and 2 (S4) resulted in a significant increase in forage N concentration in the following oats crop (Year 3) relative to industry-standard oats (S1) at both sites, but these differences did not continue into Years 4 and 5 (Tables 7, 8). The two oat crops following lucerne at Kulpi (S5) had higher N concentration ($P < 0.05$) than industry-standard oats (S1), while at Acland the N concentration of the oats and sorghum crop following lucerne (S5) was not different from that of the industry-standard crops (S1). NDF concentration was consistently lower in lucerne than in oats grown in the same years.

Time of harvest and utilisation of forage

For the oats crops, the predominant period of harvest (grazing) was in spring (September, October, November) (~65% of the annual forage yield), with the remainder harvested in winter (June, July and August) (~35% of annual yield). Harvestable yield at each grazing event was typically between 1.0 and 2.0 t DM/ha (Fig. 1). Similarly, spring was the most productive period for lucerne (~45%), but winter yield was only 10%, with the balance being provided over summer (December, January, February) (~25%) and autumn (~20%). For lucerne, harvestable yield at each grazing ranged from 0.5 to 1.5 t DM/ha, with up to seven grazing events per annum. The utilisation of oats was generally higher at Acland than at Kulpi, at 85% and 75%, respectively (Tables 5, 6), and was utilised more highly than other forage types. Lucerne was more highly utilised than the annual legumes, but still less utilised than oats, with overall utilisation of 75% and 65% at Acland and Kulpi respectively.

Soil water

Plant available water (PAW down to 1.2 m) before sowing the first winter crops (S1–S4) was 47 and 50 mm at Kulpi and Acland respectively. Over the course of the study, pre-sowing water did

Table 7. Annual weighted nitrogen (N) and neutral detergent fibre (NDF) content (% DM) for five forage systems based around oats at Kulpi over 5 years

Rainfall was as given in Table 5. Explanation for the forage systems is given in Table 3. S1, S2, S3 and S4 in Year 1 comprise a sorghum crop (1.39% N, 52.3% NDF); values for the winter crop are given in parentheses. Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined

Forage system	Year 1 (1996–1997)		Year 2 (1997–1998)		Year 3 (1998–1999)		Year 4 (1999–2000)		Year 5 (2000–2001)		Mean (1996–2001)	
	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF
S1	1.75a (2.10a)	46.2 (40.0)	2.30a	46.7	3.22a	39.2	2.36a	40.0	3.04ab	43.8	2.45a	43.9
S2	2.06cd (2.50b)	46.2 (41.9)	3.00b	44.9	4.23d	39.2	2.58a	40.0	3.20bc	42.7	2.91c	43.5
S3	1.97bc (2.43ab)	45.4 (39.6)	2.79b	47.3	3.82c	39.4	2.52a	38.4	2.89a	43.5	2.69b	44.2
S4	1.88ab (2.70b)	46.4 (35.6)	3.27c	39.1	3.87c	39.3	2.36a	38.0	3.07ab	43.0	2.84c	41.9
S5	3.11e	33.1	3.65d	34.1	3.51b	34.2	3.36b	38.0	3.33c	42.0	3.42d	35.5
l.s.d. ($P = 0.05$)	0.15 (0.39)	n.d.	0.25	n.d	0.26	n.d	0.30	n.d.	0.22	n.d.	0.13	n.d.

Table 8. Annual weighted nitrogen (N) and neutral detergent fibre (NDF) contents (% DM) for five forage systems based around oats evaluated at Acland over 6 years

Rainfall was as given in Table 7. Explanation for the forage systems is given in Table 3. Means followed by the same letter do not differ significantly at $P = 0.05$; n.d., not determined; n.s., not significant

Forage system	Year 1 (1996–1997)		Year 2 (1997–1998)		Year 3 (1998–1999)		Year 4 (1999–2000)		Year 5 (2000–2001)		Mean (1996–2001)		Year 6 (2001–2002)	
	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF	N	NDF
S1	2.67c	44.3	2.80a	46.3	2.79ab	49.5	1.82a	47.7	2.35ab	37.2	2.60a	45.1	1.77	60.5
S2	2.55bc	43.9	3.12b	44.0	3.13bc	49.9	1.89a	47.7	2.18a	37.2	2.76b	44.3	1.91	60.5
S3	2.19ab	38.7	3.46c	44.0	3.43c	49.8	1.80a	47.5	2.26a	37.2	2.82b	43.6	1.78	60.2
S4	3.43e	40.1	3.53c	44.7	3.27c	48.8	1.71a	48.0	2.60b	37.2	3.03c	44.6	1.72	60.3
S5	3.11de	37.3	3.34bc	35.2	3.67d	34.1	3.26b	36.2	2.20a	37.2	3.15c	35.9	1.90	63.2
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.	n.s.	n.d.

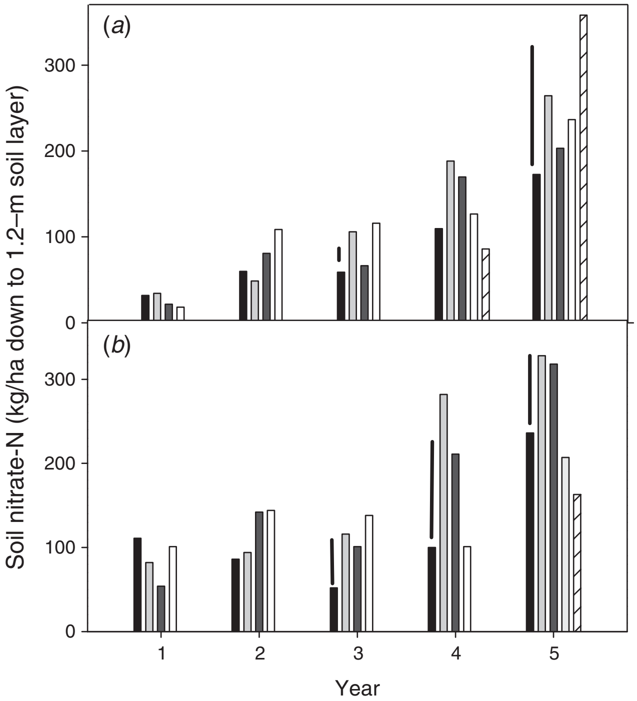

Fig. 2. Pre-sowing crop soil nitrate-nitrogen (N) (kg/ha down to 1.2-m soil layer) for the following winter-dominant forage systems at (*a*) Kulpi and (*b*) Acland. S1 (solid bar); S2 (light grey bar); S3 (dark grey bar); S4 (white bar); S5 (Years 4 and 5 only at Kulpi and Year 5 only at Acland) (marked bar). Vertical bar represents l.s.d. ($P = 0.05$) where there were significant differences. See Table 3 for an explanation of the forage systems.

not vary ($P < 0.05$) among these four systems at either site (data not presented). Pre-sowing water levels varied from year to year and at Kulpi ranged from 47 to 114 mm and at Acland from 50 to 86 mm (Table 9). When all four systems and years were included, mean PAW at Kulpi was 90.5 mm compared with 70.0 mm at Acland. For the lucerne–oats system (S5) at Kulpi, soil water before the sowing of oats crops in Years 4 and 5 was 35 and 73 mm, being lower ($P < 0.05$) than for the continuous cropping systems which had mean pre-sowing levels of 104 and 118 mm for the same years. In contrast, at Acland, pre-sowing water levels for the oats and sorghum crops following the lucerne ley were no different than for the same crops in the continuous cropping systems (S1–S4).

Table 9. Mean fallow water storage efficiency (0–1.2 m) over 4 years of the three continuous oats systems (S1, S2, S3) at Kulpi and Acland
PAW, plant-available water

Parameter	Year 2	Year 3	Year 4	Year 5	Overall mean
		Kulpi			
Fallow rainfall (mm)	230	357	335	441	340.8
Fallow length (days)	117	113	197	198	156.2
PAW, fallow start (mm)	13	49	43	16	30.2
PAW, fallow end (mm)	59	114	100	114	96.8
Change in PAW (mm)	46	65	57	98	66.5
Efficiency (%)	20	18	17	22	19.5
		Acland			
Fallow rainfall (mm)	473	404	337	410	383
Fallow length (days)	152	112	188	209	165.2
PAW, fallow start (mm)	44	20	18	0	23.8
PAW, fallow end (mm)	86	85	63	70	74.8
Change in PAW (mm)	42	65	45	70	51
Efficiency (%)	9	16	13	17	14

Fallow moisture storage efficiency

Mean fallow water storage efficiency for the three continuous oats forage systems (S1–S3) ranged from 17% to 22% at Kulpi and 9% to 17% at Acland (Table 9). Overall, water storage efficiency at Kulpi and Acland was 19.5 and 14% respectively.

Soil nitrate-N

Soil nitrate-N (kg/ha down to 1.2 m) measured before sowing increased over time for all systems at both sites (Fig. 2). Initial mean soil nitrate-N was higher at Acland than at Kulpi (87 *vs.* 26 kg N/ha) but the relative change from Year 1 to Year 5 was ~200 kg/ha for both sites. Significant ($P < 0.05$) within-site differences in pre-sowing nitrate-N between industry-standard oats (S1) and oats fertilised with a higher rate of N (S2) were measured in Year 3 only at Kulpi and in Years 3, 4 and 5 at Acland. When industry-standard oats (S1) was replaced with legumes in Years 1 and 2 (S3), soil nitrate-N was higher ($P < 0.05$), an increase of 40–60 kg nitrate-N, before the Year 3 oats crop being sown. However, there were no apparent further benefits of these legumes in subsequent years (Fig. 2). With the lucerne–oats systems (S5), immediately before termination of the lucerne ley, mean available nitrate-N was low (20–30 kg N/ha down to 1.2 m) at both sites. Nitrate-N rose over the first fallow to 86 kg/ha at Kulpi and 160 kg N/ha down to 1.2 m at Acland, and then to 360 kg N/ha down to 1.2 m following the second fallow at Kulpi (Fig. 2).

Post-crop nitrate-N

There was a general tendency for post-crop nitrate-N to also increase over time at both sites, and particularly so at Acland under the higher rate of N fertiliser (Fig. 3). Of interest was that after Year 3 when N fertiliser rates were constant across systems (55 kg N/ha), the difference between the high and low N treatments continued to be evident for the following 2 years (Fig. 3), indicating general retention of this N in the system.

Apparent N recovery from fertiliser

The apparent recovery of N fertiliser applied above the industry-standard rate (S1 *vs.* S2) over Years 1–5 was 55% and 23% at Kulpi and Acland respectively.

Soil cover over the fallow

At Kulpi, stubble cover was consistently higher ($P < 0.05$) under ZT (S3) than under CT (S2) in the 2 years assessed. Under ZT, following Year 3 crop, it remained above 30% (range 55–35%) over the fallow but fell below this level following Year 4 crop (range 20–15%). Under CT, cover in both years ranged from 15% to 0%. At Acland, there was no significant ($P > 0.05$) difference between CT and ZT, with cover at less than 20% in both years.

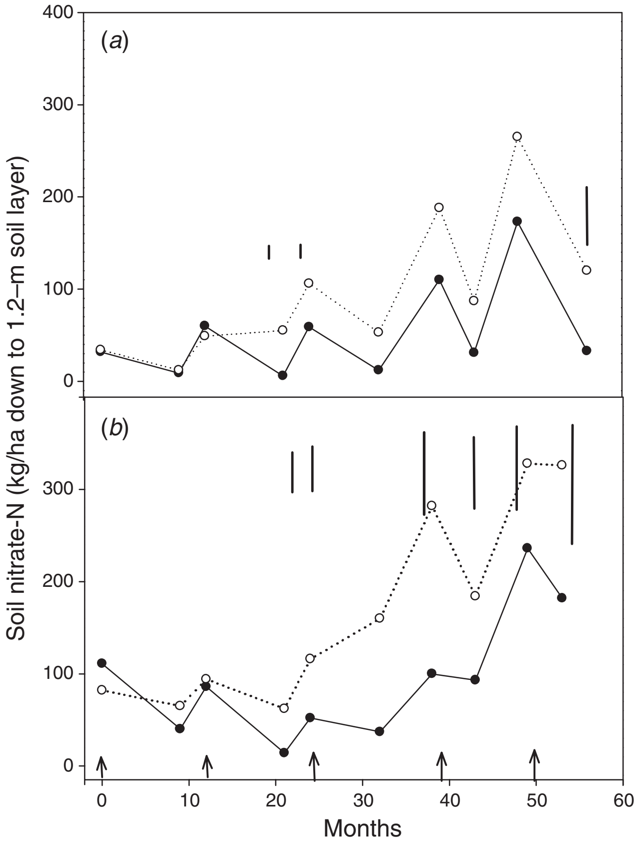

Fig. 3. Pre-sowing and post-crop soil nitrate-nitrogen (N) (kg/ha down to 1.2-m soil layer) for S1 (solid line) and for S2 (broken line) at (*a*) Kulpi and (*b*) Acland. Arrows indicate when crops were planted. Vertical bar represents l.s.d. ($P = 0.05$) where there were significant differences. See Table 3 for an explanation of the forage systems.

Soil organic carbon (SOC)

Mean SOC concentration (0–10 cm) in the first year of the study was 1.44% and 0.81% at Kulpi and Acland. Apart from the third sampling at Kulpi, where there was a general rise in SOC across all systems, values remained relatively unchanged over the study period. While there were some significant differences between the systems at the end of the study period (Table 10), any change from the first to the last sampling was small and ranged between –0.05 and 0.05 percentage points of the original values. There was a suggestion that winter systems that incorporated a medic or lucerne ley were more likely to maintain SOC than were continuous oats systems (S1, S2, S3); however, any difference was small.

Discussion

In the present 5-year study, modifying the industry-standard winter-dominant forage production system by increasing N fertiliser inputs, reducing tillage or replacing oats with a legume phase had only modest or no impact on mean annual forage production, soil organic carbon levels and fallow storage moisture efficiency. More influenced by interventions were forage quality and soil nitrate-N. Background factors had an important influence on the response to interventions and these were the inherent site differences (Harris *et al.* 1999), past N fertiliser inputs and the consistently low rainfall received over the winter period (Bureau of Meteorology 2006).

Nitrogen fertiliser

The mean annual production of industry-standard raingrown oats, 3.78 t DM/ha at Kulpi and 2.50 t DM/ha at Acland, was similar to yields recorded in multi-site 2-year studies conducted by both Kemp (1974) near Taree in northern New South Wales and McClement and Howard (1980) on the eastern Darling Downs. In the latter study, with a fertiliser application of 50 kg N/ha.crop, a mean yield of 3.05 t DM/ha (range 1.38–4.98 t DM/ha) was recorded across sites. A feature of this and other on-farm studies conducted on the Darling Downs has been a wide variation in oats forage yields across sites and years, and in response to additional N fertiliser (McClement and Howard 1980; Thompson and Bywater 1987; Chataway *et al.* 1994).

With respect to N fertiliser, McClement and Howard (1980), reporting on studies conducted in the late 1960s, measured no response to additional N fertiliser applied above 25 kg/ha. In a

Table 10. 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 final samplings

Explanation for the forage systems is given in Table 3. Means followed by the same letter do not differ significantly at $P = 0.05$; n.s., not significant

Forage system	Kulpi					Acland				
	May 1997	May 1999	December 1999	December 2001	Difference (1st and 4th sampling)	May 1997	May 1999	December 1999	May 2002	Difference (1st and 4th sampling)
S1	1.42	1.37a	1.48abc	1.42ab	0.00abc	0.81	0.81	0.78	0.78ab	–0.03ab
S2	1.38	1.41a	1.44a	1.35a	–0.03a	0.79	0.74	0.72	0.74a	–0.05a
S3	1.45	1.38a	1.57bcd	1.44ab	–0.01ab	0.78	0.77	0.78	0.79abc	0.01bcd
S4	1.48	1.57b	1.64d	1.52b	0.04bc	0.80	0.83	0.77	0.81abcd	0.01bc
S5	1.47	1.50ab	1.53abcd	1.51b	0.05c	0.85	0.81	(0.96)[A]	0.88cde	0.03cde
Mean	1.44	1.45	1.53	1.45	0.01	0.81	0.79	0.77	0.80	–0.006
l.s.d. ($P = 0.05$)	n.s.	0.150	0.126	0.148	0.053	n.s.	n.s.	n.s.	0.099	0.049

[A] Sample was taken in October 2000 at the completion of the lucerne ley, before cultivation. This value is not included in the 1999 analysis.

latter study, that involved five sites on the eastern Darling Downs, J. Collingwood (1984, unpubl. data) recorded a mean forage yield for oats, fertilised with 50 kg N/ha, of 4.65 t DM/ha (range 3.25–6.60 t DM/ha) and a response of 10 kg DM (range 0–20) per kg of N applied up to 100 kg/ha. At some sites, yield responses were recorded at up to 200 kg N/ha applied (Thompson and Bywater 1987). In the context of these findings, the variable, but overall limited forage yield response to N fertiliser applied at above the industry-standard rate (55 kg N/ha) was not surprising given the combination of unseasonal low winter rainfall (Bureau of Meteorology 2006) and the presence of moderate levels of pre-existing nitrate-N in the structurally impaired Sodosol soil at Acland.

Additional N fertiliser was more consistent in its effect on the concentration of N in forage rather than DM yield. This result is consistent with those of other studies in forage production (Rahman *et al*. 2001) and subtropical wheat production where a higher N application has had a more consistent impact on grain protein than on yield (Holford *et al*. 1992; Strong *et al*. 1996*b*). For first grazing of 1–2 t DM/ha, 55 kg N/ha applied at or before planting generally provided sufficient or excess N to meet the requirements of high production cows (NRC 2001) but was not necessarily sufficient for second and later grazings (Fig. 1). Our approach (high N) of doubling the application rate at planting, combined with further topdressing, was not appropriate as a routine fertiliser regime. In fact, some reduction of the current 55 kg N/ha applied at or before planting could be made with more emphasis on applying the balance of fertiliser later in the crop cycle.

An important finding was the general build-up under all forage systems of soil nitrate-N (0–1.2 m) (Fig. 2), indicating that all systems had moved into a positive N balance over the course of the study and that fertiliser N, unutilised in the season of application, could be available to crops in subsequent seasons. Supporting this was the continued relative difference between high and low N input systems (Years 1–3) into Years 4 and 5 when fertiliser rates were the same (Fig. 3). The residual benefits of fertiliser N to subsequent crops has also been noted in the subtropical grain industry (Strong *et al*. 1996*a*) and the present study gives confidence that fertiliser not used in the immediate year of application to forage crops can contribute to production in the subsequent year. This knowledge allows for simpler, rather than complex, approaches to N management, which are favoured by farmers (Cox 1996).

Zero-tillage (ZT)

The success of systems using ZT to grow winter-forage crops with no reduction in yield was an important finding. While dairy farmers are in general agreement that ZT has lower labour requirements, reduces machinery costs and is generally beneficial in reducing erosion, they are concerned about its effectiveness on clay soils under grazed conditions (Chataway *et al*. 2003). The present study has demonstrated that yield is maintained under ZT. Although ground cover was improved with ZT, there were still periods where there was insufficient stubble to protect the soil from water erosion over the fallow period. We noted in particular at the Acland site, that the combination of lower-yielding crops, high summer rainfall and flooding events, that provided conditions favouring organic matter decomposition (Jenkinson 1988), often led to very low stubble levels (<10% cover) by the end of the fallow. This low residue cover could also have contributed to the lack of difference in fallow moisture accumulation between CT and ZT systems. In a review of no-tillage and conservation farming practices in southern and central Queensland, Thomas *et al*. (2007) found that there was a general decline in fallow moisture storage efficiency as tillage practices became more aggressive and incorporated stubble rather than retaining it on the soil surface. However, in systems where stubble is removed or is sparse (Radford *et al*. 1992), ZT systems have been found to store less water than cultivated systems. As the Sodosol soil, that comprised the Acland site, is more disposed to hard-setting and crusting than Vertosols (McGarry 1993), stubble cover was probably more important for enhancing infiltration. Also of interest was that forage oats yields from ZT plots were lower ($P < 0.05$) than those from CT plots only in Year 5 at Acland. This year was preceded by one that achieved very low forage yields (<2 t DM/ha), providing little stubble cover for ZT plots over the subsequent fallow. At the Kulpi site, the higher fallow efficiencies recorded were more in line with efficiencies measured in the grains industry; Thomas *et al*. (2007) reported mean efficiencies of 18–21% across a range of tillage systems in southern and central Queensland.

Thomas *et al*. (2007) noted that grain protein content is generally lower in systems using less tillage than that in conventionally tilled systems and our results in some years at Kulpi reflected this, with forage grown under ZT having a lower N concentration than forage grown under CT where the same amount of fertiliser N was applied (Table 7). Where the supply of plant-available N is limited, plants grown under ZT conditions may experience N deficiencies earlier than plants grown under CT (Thomas *et al*. 2007).

That changes to tillage practices and N fertiliser rates in the continuous oats systems made no measurable difference to SOC concentration (0–10- and 10–20-cm soil layers) is not surprising, given the short study time frame and limited difference between systems in potential carbon inputs and the rate of organic matter decomposition (Paustian *et al*. 1997). In winter cereal (grain)–summer fallow systems of southern Queensland, significant differences in SOC (0–10 cm) have generally been measured only between strongly contrasting management practices that involved multiple, rather than sole, management practice changes. For example, significant effects of zero-tillage, N fertiliser and stubble retention on SOC (0–10-cm layer) were noted only when they were practiced together, rather than individually, in a 33-year study at Warwick on the southern Darling Downs (Wang *et al*. 2004). Second, the practices were strongly contrasted against alternatives; tillage (nil *vs*. 4 or 5 tillage operations), N fertiliser (50–90 kg/ha.crop *vs*. 0 kg/ha.crop), stubble management (retained *vs*. burnt shortly after harvest).

Legumes

The replacement of oats with annual legumes (S4) in Years 1 and 2 resulted in a substantial reduction in production, further exacerbated by lower utilisation of available forage. Also tempering the benefits of annual legumes over oats was the cost to control broad-leaf weeds which requires the use of more expensive herbicides (Thompson and Bywater 1987). Of the two legumes used, snail medic demonstrated a greater potential value than did vetch, due to its ability to regenerate from seed in future years (Lloyd *et al*. 1991). In our study, we believe the snail medic was somewhat disadvantaged by its establishment year coinciding with low winter rainfall and a reduced fallow period; other experiments with medics in the region, conducted over multiple seasons, have achieved higher maximum and mean annual yields (Clarkson *et al*. 1987; Weston *et al*. 2002). A weakness of medic is its senescence in late September/early October compared with November/early December for oats (Fig. 1; Weston *et al*. 2002). This feature may make it more suited to a double- rather than sole-cropping program. While medic increased soil nitrate-N concentrations as expected, it was not considered that the inclusion of a legume phase in the winter-cropping system would have a positive impact on SOC, given the relatively low biomass production of legumes and the rapid rate of turnover of legume C (Dalal *et al*. 1995). On this basis, it is difficult to explain the positive difference in SOC following medic at Kulpi. One contributing factor may have been the absence of soil disturbance through tillage which hastens organic matter decomposition (Balesdent *et al*. 2000).

The findings from the present study, with respect to ease of establishment, productivity and forage quality of lucerne (*Medicago sativa*), support the views of Lloyd *et al.* (1991) and Minson *et al.*(1993) that lucerne is a high-quality temperate legume well adapted to the colder inland dairy regions. It fixed substantial quantities of N, was easily removed by ploughing (Lloyd *et al*. 1991) and once established, lucerne provides protection against erosion through the provision of soil cover and the maintenance of soil water deficits. Limitations of lucerne include the increased risk of water stress on crops immediately following, due to the greater ability of lucerne to exploit subsoil moisture than that of the cereals (McCallum *et al*. 2001; Strong *et al*. 2006), and the lower productivity of lucerne over winter than that of oats means that it cannot be considered a direct replacement. Water stress on following crops was clearly an issue at Kulpi but not at Acland. At Kulpi, the decision to terminate the lucerne with herbicides was more difficult than anticipated, as noted by other authors (Davies *et al*. 2005), and was a contributing factor. It took 4 months from when the spraying program commenced in spring to kill all the plants and this was then followed by a shorter than planned fallow. This scenario was not repeated at Acland where a blade plough was very effective in terminating growth quickly; this is a practice we would recommend until more reliable herbicide strategies can be developed. This was then followed by a longer fallow period and higher fallow rainfall than had been recorded in the previous year at Kulpi. While we were unsure of the suitability of the Acland site for lucerne because of the species vulnerability to water-logging (Bullen 2002), our results indicated that lucerne may have wider application in dairy forage systems than is generally perceived (Chataway *et al*. 2003).

Because lucerne exhausts the soil water from the whole profile within 1–2 years (McCallum *et al*. 2001; Strong *et al*. 2006), further growth is dependent on episodic rainfall events, making production less reliable. This is an issue that deters dairy farmers from making greater use of lucerne (Chataway *et al*. 2003). In our study, above average rainfall in Year 2 probably prolonged the period of reliable production and diminished this issue in the 3-year (Kulpi) and 4-year (Acland) stands. A practical response to this issue, when lucerne is grown under more typical seasonal conditions, would be to routinely terminate leys 24 months after planting to minimise this period of lower and less reliable production. This would also have minimal impact on N fixation because the amount of N fixed is closely associated with the total amount of dry matter produced, rather than the duration of the ley (Peoples and Baldock 2001).

Conclusion

Zero-tillage and lucerne can be successfully integrated into the current winter-dominant forage system, without penalties to forage yield, and the changes will be beneficial to long-term productivity. Additional N fertiliser can also be used to build up soil nitrate-N and forage quality as required. However, these strategies do not negate the risk of low forage yields due to low rainfall, and when low stubble levels are combined with summer fallows, the system will remain vulnerable to erosion and soil organic matter decline.

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