Nitrogen-fertilised grass in a subtropical dairy system 3. Effect of stocking rate on the response to nitrogen fertiliser

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Summary. Two stocking rates, one as practised on farms (2 cows/ha) and the other 50% higher, were assessed for effect on pasture and milk yield response to applied nitrogen (N) fertiliser (0–600 kg N/ha.year) for Holstein–Friesian cows grazing Rhodes grass (*Chloris gayana*) cv. Callide pastures. Pastures were grazed in combination with grazing oats for winter, with overall farm stocking rates of 1.17 and 1.37 cows/ha for the 2 treatments. Cows were maintained on these areas for 3 years. Cracked grain was given at 0.8 t/cow.year, and hay or silage supplements were given when green grass yield was <0.5 t dry matter (DM)/ha.

The incremental response (P<0.05) in milk yield to each kg increase in level of applied N was 4.93 kg/ha at 1.17 cows/ha and 1.64 kg/ha at 1.37 cows/ha. The amount of conserved forage fed at the high stocking rate increased (530 and 970 kg/ha.year at 1.17 and 1.37 cows/ha), and financial margins over costs were reduced at the high stocking rate.

The low milk response at the high stocking rate was associated with a low response in pasture growth. At <2 t pasture DM/ha on offer, incremental response to applied N declined, and there may have been an excessive loss of N through volatilisation in heavily grazed pastures.

Milk yield per cow was closely related to total pasture yield on offer (P<0.01), and to leaf and stem yields (P<0.05). Relationships were stronger in summer and autumn than in spring. Over the full year, milk yield increased by 1.24 kg/kg leaf DM or 0.24 kg/kg total pasture DM on offer. At the higher stocking rate, surface soil (0–10 cm) concentrations of phosphorus and nitrate were higher than at the lower stocking rate.

We conclude that in areas of moderate rainfall (<1000 mm/year) in the subtropics, high stocking rates resulting in low pasture yields and exposed ground surface will be associated with low efficiency of use of applied N.

Introduction

Milk production response to level of nitrogen (N) fertiliser is influenced by the stocking rate at which the comparison is made. Gordon (1973) showed that on temperate grass pastures fertilised with high rates of N, a milk response to additional N occurred only at very high stocking rates. With tropical grass and legume mixed pastures, Cowan and Stobbs (1976) measured an increase in both pasture and milk yield with application of N at a high stocking rate, and no increase at a lower stocking rate. The response was influenced by a reduction in legume content of the pasture as stocking rate was increased. With tropical grass pastures, Davison *et al.* (1985) measured a stocking rate x level of N fertiliser interaction in the third year of a 3-year experiment. The milk response to N was also greater in that year than in the previous 2 years.

Cowan *et al.* (1995*a*, 1995*b*) described the animal, pasture, and soil responses to level of N fertiliser at a stocking rate chosen to be representative of industry practice. This paper describes how these responses change when stocking rate on a Rhodes grass (*Chloris gayana*) cv. Callide pasture was increased by 50%.

Materials and methods

The experiment was conducted over 3 years at the Mutdapilly Research Station in south-eastern Queensland (27°45'S, 152°40'E; alt. 40 m). Details of rainfall, experimental site, and pastures are presented in Cowan *et al.* (1995*a*). Over the first 3 years there were 2 stocking rates on Rhodes grass pasture: 2 and 3 cows/ha, the former as used on farms. In addition to the summer-growing pasture, each treatment group was allocated a separate area of 0.4 ha/cow of grazing oats (*Avena sativa*), giving overall stocking rates of 1.17 and 1.37 cows/ha (these rates will be referred to throughout this paper). Rhodes grass areas were subdivided to receive applied N at 0, 150, 300, 450, and 600 kg/ha (1.17 cows/ha) or 150, 300, and 600 kg/ha (1.37 cows/ha). Nitrogen was applied as urea in 3 equal-sized dressings in October, December, and February each year; date of fertiliser application was not changed in response to weather conditions. The 8 pasture treatments and 8 areas of grazing oats were laid out as an incomplete, randomised block with 2 site replications. Cows grazed the 2 site replicates on a 2-week grazing, 2-week spelling rotation throughout the year. Oats were grazed during the day in winter and early spring, and cows returned to the Rhodes grass area each night.

Twenty-four Holstein–Friesian cows and 8 Holstein–Friesian heifers were grouped on parity and calving date into 4 blocks of 8, and allocated to treatment and managed as described by Cowan *et al.* (1995*a*). Measurements of milk yield, liveweight, pasture yield, and botanical and chemical composition of pasture were as described by Cowan *et al.* (1995*a*, 1995*b*). When green dry matter (DM) on offer in Rhodes grass pastures was visually assessed at <0.5 t/ha, second-quality lucerne (*Medicago sativa*) hay or maize silage supplements were given at about 9 kg DM/cow.day. Feeding ceased when green DM on offer was assessed at >1 t/ha. Dry cows were given 1 kg rolled sorghum or barley grain once daily; during lactation this was increased to 3 kg once daily.

Soil samples were taken before the imposition of treatments in September 1983, and again in September 1984, 1985, and 1986. On each occasion 20 soil cores were taken to a depth of 10 cm from each paddock, bulked, and subsampled for analyses of nitrate-N (1 : 5 soil : water); pH (1 : 5 soil : water); electrical conductivity (EC, 1 : 5 soil : water); water-soluble chloride (Cl, 1 : 5 soil : water); phosphorus (bicarbonate-extractable P, Colwell 1963); and potassium (K), sodium (Na), magnesium (Mg), and calcium (Ca) (all exchangeable, 1 : 20 soil : 1 mol NH_4Cl/L). In spring 1984 and 1985, samples were weighed before and after drying to determine DM content, and in 1985 this weight was used to determine bulk density of surface soil.

Data were analysed by least squares regression using yearly treatment means, including years as a factor and level of applied N as a variable. Where predictive equations are presented, reduction in the residual mean square (P<0.05) was used as the criterion for acceptance of a quadratic equation.

Table 1. Effect of stocking rate on the relationship of milk yield and milk constituents (kg/year) to level of applied nitrogen (kg/ha.year)

Stocking rate	Constant (*a*)		Regression coefficient (*b* ± s.e.)		r.s.d.	
(cows/ha)	Per cow	Per ha	Per cow	Per ha	Per cow	Per ha
			Milk yield			
1.17	2319	2713	4.21 ± 0.77	4.93 ± 0.90	144	168
1.37	2645	3623	1.20 ± 0.27	1.64 ± 0.36	48	66
			Milkfat			
1.17	92	107	0.153 ± 0.029	0.179 ± 0.034	5	6
1.37	94	129	0.081 ± 0.007	0.110 ± 0.009	1	2
			Protein			
1.17	79	92	0.106 ± 0.016	0.125 ± 0.020	3	4
1.37	83	114	0.050 ± 0.012	0.065 ± 0.015	2	3
			Lactose			
1.17	109	125	0.215 ± 0.059	0.256 ± 0.073	11	13
1.37	123	167	0.070 ± 0.009	0.098 ± 0.012	2	2

Table 2. Effects of stocking rate and level of nitrogen fertiliser (kg/ha.year) on inputs of conserved forage (kg DM/ha.year)

	1.17 cows/ha					1.37 cows/ha		
N applied:	0	150	300	450	600	150	300	600
Year 1	774	735	735	735	735	904	904	904
Year 2	1211	755	739	739	739	1486	1486	907
Year 3	766	350	0	0	0	894	826	410
Mean	917	613	491	491	491	1095	1072	740

Results

The incremental response in milk yield to an increase in level of N fertiliser application was less at the higher than the lower stocking rate (Table 1). The response in milk yield per cow was 4.21 kg/kg N at 1.17 cows/ha, compared with 1.20 kg/kg N at 1.37 cows/ha ($P<0.05$). Responses in yields of milk constituents were consistent with those for milk yield. There was no effect of stocking rate on constituent concentration in milk or on lactation length, and mean values (± s.e.) were 3.75 ± 0.05% milkfat, 3.13 ± 0.06% protein, 4.69 ± 0.02% lactose, and 258 ± 7 days of lactation. Inputs of conserved forage were consistently higher at the high stocking rate, and the effect was greater at lower levels of applied N (Table 2).

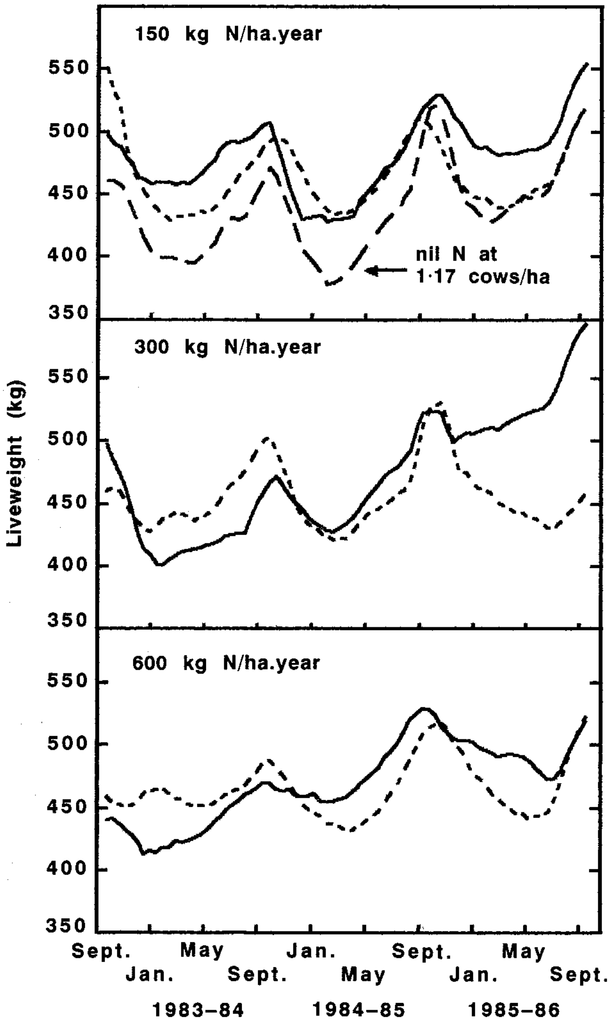

Figure 1. Effect of stocking rate (—— 1.17, - - - 1.37 cows/ha) on seasonal variation in liveweight of cows grazing nitrogen-fertilised (150, 300, or 600 kg N/ha.year) tropical grass pastures.

Cows lost more liveweight during summer and autumn at the high than the low stocking rate (Fig. 1). The effect was consistent at the different levels of applied N, although the extent of liveweight loss was less at higher levels of applied N. During late lactation and the dry period, cows at the high stocking rate and lower levels of applied N gained liveweight rapidly, and precalving liveweights were not different for the various treatment groups (Fig. 1). Liveweight gain in year 3 by cows at the lower stocking rate at 300 kg N/ha.year was abnormally high, although not at the expense of milk yield. Milk yield for this group averaged 3560 kg/cow, compared with 3300 and 3400 kg/cow for cows at 150 and 450 kg N/ha.year, respectively.

Mean pasture DM on offer to cows was less at the high than the low stocking rate, and the difference was greatest at intermediate levels of applied N (Fig. 2). Greatest differences occurred during autumn, with similar pasture yields at the 2 stocking rates during summer. At the low stocking rate, the depression in pasture yield at the highest level of applied N was entirely due to a substantial reduction in pasture yield during spring. These effects were generally consistent across the 3 years, although in year 1 the pasture yield on offer at 600 kg N/ha was similar at both stocking rates, and the yield at the high stocking rate was reduced substantially in years 2 and 3.

An increase in stocking rate was associated with more leaf in the pasture and less standing dead material, but

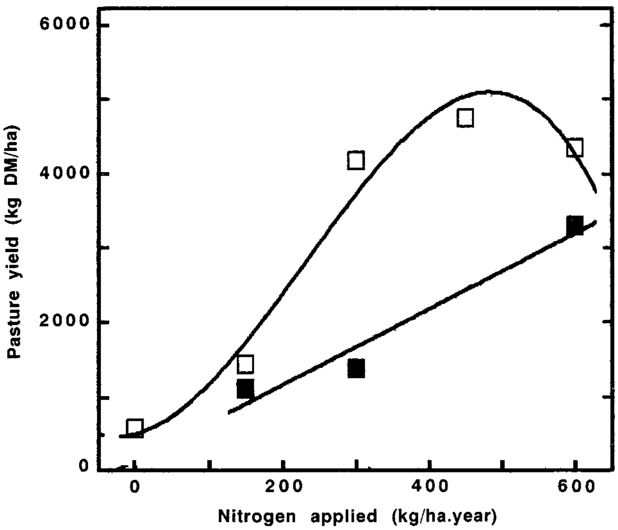

Figure 2. Effect of stocking rate (□ 1.17, ■ 1.37 cows/ha) on the relationship between level of nitrogen applied to a Rhodes grass pasture and pasture yield on offer to cows. Equations for the annual relationships are

2 cows/ha: $Y = 470 + 5.15X + 0.0313X^2 - 0.0000467X^3$ ($P<0.01$; $R^2 = 0.88$; r.s.d. = 202)

3 cows/ha: $Y = 133 + 5.11X$ ($P<0.15$; $R^2 = 0.95$; r.s.d. = 213)

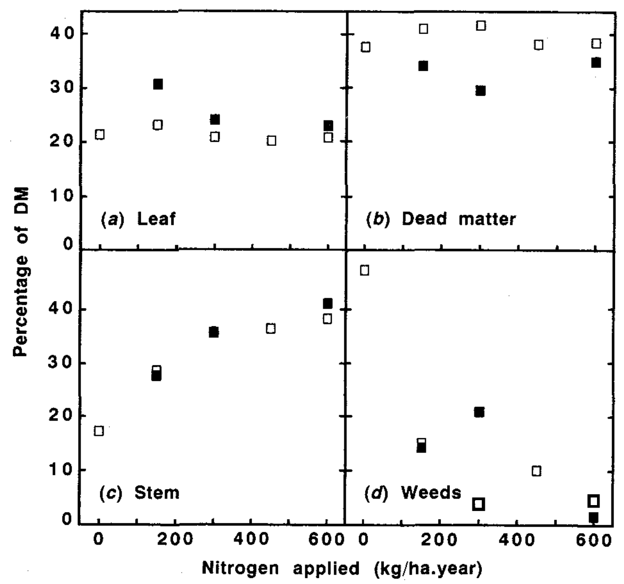

Figure 3. Effect of stocking rate (□ 1.17, ■ 1.37 cows/ha) on the relationship between proportions of botanical components of a Rhodes grass pasture and level of applied nitrogen.

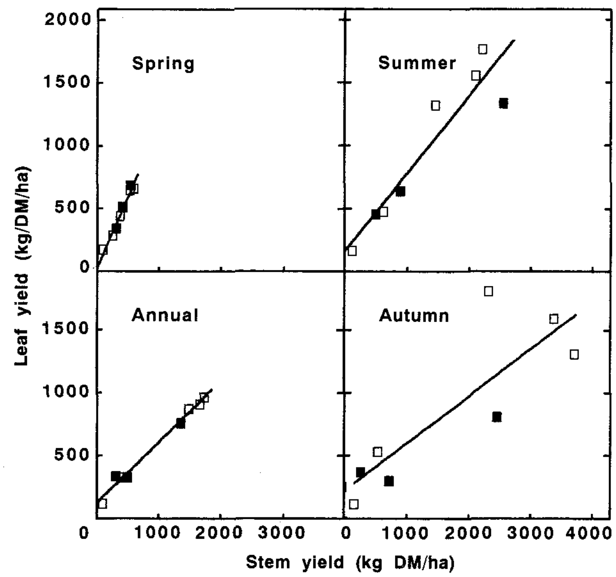

Figure 5. Effect of stocking rate (□ 1.17, ■ 1.37 cows/ha) on the seasonal relationship between leaf and stem yields of a grazed Rhodes grass pasture.

there was no effect on the proportion of stem or weeds (Fig. 3). The proportion of stem in the pasture increased with level of applied N in a similar way at both stocking rates, with a rapid increase up to 300 kg N/ha and much smaller increases at higher levels. The proportion of weeds in the pasture decreased markedly from 0 to 150 kg N/ha at the lower stocking rate.

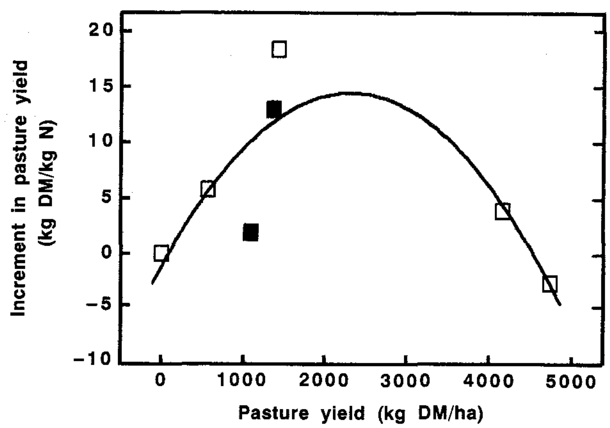

Figure 4. Relationship of incremental response in yield on offer of a grazed Rhodes grass pasture (□ 1.17, ■ 1.37 cows/ha) given an additional 150 kg N/ha to level of pasture yield on offer to cows. A zero value is included at 2 cows/ha. The equation of the curve is

$$Y = -1.2152 + 0.013539X - 0.00000293X^2$$
$$(P<0.16, R^2 = 0.67; \text{r.s.d.} = 5.2)$$

Figure 4 shows that increases in pasture yield on offer were at a maximum when N was applied to pastures with DM yields in the range 1000–3000 kg DM/ha. At yields <1000 kg DM/ha, the reduction in apparent response was rapid, while at yields >3000 kg DM/ha, the reduction was more gradual.

The yield of leaf in the pasture was positively related to the yield of stem, with a close linear relationship over the full year and in spring, summer, and autumn (Fig. 5). During spring the yield of leaf exceeded that of stem, with a coefficient of 1.14 kg leaf/kg stem; this declined to 0.62 in summer and 0.37 in autumn. Mean total yield was also linearly related to stem yield, although variation in the yield of dead material in pasture during spring meant the relationship was not as close then ($r^2 = 0.52$) as in summer and autumn ($r^2 = 0.94$).

Nitrogen, P, and K concentrations of grass leaf in year 1 were higher at the high than the low stocking rate (Table 3), in particular during autumn and early winter. Increasing the level of applied N generally increased N concentrations of grass leaf and reduced P concentration at both stocking rates. At the low stocking rate increased levels of applied N decreased K concentration of grass leaf, whereas at the high stocking rate there was an increase in K concentration. Concentrations of Ca, Mg, and S in grass leaf were not affected by treatment and averaged (% DM), respectively, 0.50, 0.24, and 0.23 in spring; 0.53, 0.30, and 0.24 in summer; and 0.61, 0.33, and 0.29 in autumn.

Table 3. Chemical analysis of Rhodes grass leaf (% DM) as affected by stocking rate and level of nitrogen fertiliser (kg N/ha.year)

	1.17 cows/ha			1.37 cows/ha	
N applied:	0	300	600	300	600
		Spring 1983			
N	1.25	1.35	2.18	0.97	2.53
P	0.23	0.18	0.13	0.17	0.17
K	1.50	0.93	1.06	1.84	2.28
		Summer 1983–84			
N	1.26	1.57	1.82	1.80	1.98
P	0.31	0.15	0.11	0.18	0.11
K	1.71	1.03	1.06	1.26	1.93
		Autumn 1984			
N	2.17	2.11	2.09	3.34	2.85
P	0.52	0.20	0.12	0.29	0.17
K	1.72	1.39	1.11	1.89	2.11
		Winter 1984			
N	1.76	1.22	1.87	2.53	2.29
P	0.24	0.11	0.11	0.26	0.19
K	1.61	1.09	0.74	1.33	1.73

Annual milk yield per cow was linearly related ($P<0.01$) to each of total yield of pasture, stem yield, and leaf yield. Both leaf and stem yields were significantly ($P<0.05$) related to milk yield during summer and autumn but not in spring. The relationships of annual milk yield per cow (Y, kg) to leaf yield, stem yield, and total pasture (kg DM/ha) are given by the equations

Leaf: $Y = 2372 + 1.24 (\pm 0.32)X$ ($R^2 = 0.71$; r.s.d. = 281)
Stem: $Y = 2518 + 0.61 (\pm 0.15)X$ ($R^2 = 0.72$; r.s.d. = 278)
Total: $Y = 2452 + 0.24 (\pm 0.06)X$ ($R^2 = 0.71$; r.s.d. = 283)

The initial soil P concentration (mean ± s.e.) was 12 ± 4 mg/L, and at the end of 3 years, there was an increase ($P<0.05$) in P concentration of soil with level of applied N at the high stocking rate but not at the low stocking rate (Fig. 6). At the low stocking rate, only pastures receiving nil applied N showed an increase in P concentration over the 3 years, from 18 to 29 mg/L; whereas, at the high stocking rate, fertilised soils increased in P concentration. Nitrate-N concentrations were higher ($P<0.05$) by 13 mg/L at the high than the low stocking rate, and increased by 0.103 ± 0.026 mg/L.kg applied N at both stocking rates. Soil pH decreased by 0.0018 ± 0.0004 unit for each kg N applied per year at both stocking rates. Soil K concentration averaged 0.36 ± 0.13 cmol/kg initially, and over 3 years increased to 0.60 cmol/kg at both stocking rates. Stocking rate did not affect changes in EC or Cl, Ca, Mg, and Na contents of soil, or soil bulk density.

Moisture content of soil in spring of years 1 and 2 averaged 15.4% at nil applied N and increased ($P<0.05$) linearly to 19.6% at 600 kg N/ha.year (1.17 cows/ha); at 1.37 cows/ha, moisture content increased from 15.8% at 150 kg N/ha.year to 17.1% at 600 kg N/ha.year.

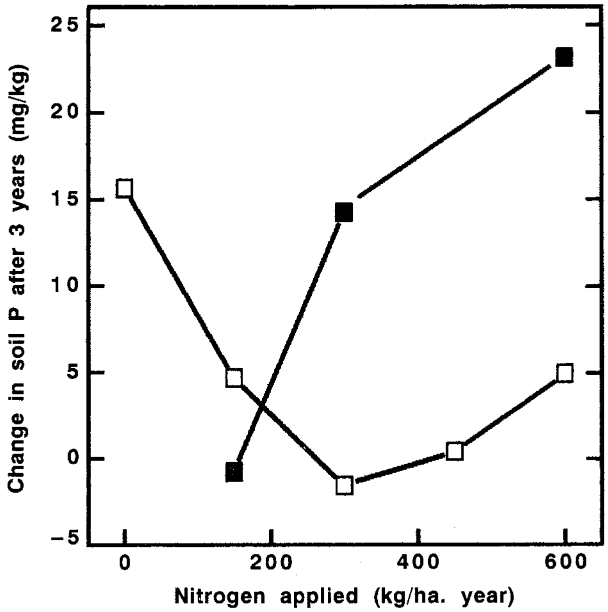

Figure 6. Effect of level of nitrogen applied to Rhodes grass pasture on the bicarbonate-soluble phosphorus concentration of soil after three years. Stocking rates were □ 1.17 and ■ 1.37 cows/ha.

Discussion

Increasing the stocking rate markedly reduced the response in milk yield to level of applied N. This is in contrast to several reports where increasing stocking rate either caused no change (King and Stockdale 1980; Davison *et al.* 1985) or enhanced the milk response to applied N (Gordon 1973; Cowan and Stobbs 1976). In a survey of farm practice, Hawkins and Rose (1979) found that increases in rate of applied N and stocking rate occurred concurrently on farms. With beef cattle, however, Mears and Humphreys (1974) and Jones (1990) found a diminution of liveweight gain response to level of applied N with increased stocking rate. Visual examination of milk yield data of Davison *et al.* (1985) also suggests a decrease in response at the highest stocking rates used. Murtagh *et al.* (1980) measured a diminution in response of estimated carrying capacity of kikuyu grass pastures with level of applied N at high stocking rates. This was attributed to increased stoloniferous growth at high levels of applied N, making the pasture more susceptible to overgrazing; this effect was consistent with changes in the mode of pasture growth in the present experiments (Cowan *et al.* 1995*a*). Hoglund (1980) also demonstrated reduced pasture response to applied N in heavily grazed, compared with leniently grazed, pastures. There is general agreement in the above literature and other reports (e.g. Bryant *et al.* 1982) that milk response to N depends on a pasture DM response, and at the high stocking rate used in our experiment, a lack of response in pasture growth was associated with the lack of response in milk yield.

An alternative explanation for the poor pasture response at the high stocking rate would be excessive losses of N through volatilisation. Under unfavourable conditions, up to 50% of surface-applied urea is lost through this route (Catchpoole *et al.* 1983; Hossner 1985; Fenn and Jarvis *et al.* 1989; Chapman *et al.* 1992; Cowan *et al.* 1995*b*), and the loss is increased with level of applied N (Fenn and Hossner 1985; Jarvis *et al.* 1989). At the high stocking rate in this experiment, losses would have been increased compared with the low stocking rate because of the reduced yields of standing pasture and trash, leading to more exposed, drier conditions at the soil surface (Hoult and McGarity 1987; Chapman *et al.* 1992). In addition, a greater proportion of the N present in the soil–plant complex was likely to be present as green herbage rather than trash (Strong *et al.* 1987) or standing mature and dead material (Jarvis *et al.* 1989). This would increase the proportion of N recycled through urine, further increasing the rate of loss by volatilisation (Jarvis *et al.* 1989). In the absence of irrigation, the maintenance of a substantial groundcover of grass may enhance the efficiency of use of surface-applied urea.

The suggestion of an accelerated rate of loss of N from heavily stocked pastures is further supported by comparisons of the response curves of pasture on offer against level of applied N. When the incremental response in pasture yield on offer is plotted against yield of pasture on offer (Fig. 4), there is a common relationship for the 2 stocking rates. Nitrogen applied to pastures of low yield will not result in a large DM response. These comparisons are complicated by differences in pasture consumption between stocking rates, although previous work has shown a reasonable correlation between pasture yield on offer under grazing and in enclosures (Cowan and Stobbs 1976; Cowan *et al.* 1995*a*). Murtagh *et al.* (1980) concluded that an autumn decline in kikuyu response to N level was related to a heavy defoliation of the pasture during summer.

At the high stocking rate and at low levels of applied N, cows dried off prematurely and gained liveweight rapidly on the winter oats. At calving, liveweights of cows in all treatments were not very different, but during the following summer and autumn, cows at the higher stocking rate generally lost more liveweight than those at the low stocking rate. This transfer of body energy to milk is consistent with previous reports for cows grazing under Queensland conditions and producing 12–14 kg milk/cow.day (Cowan 1982).

Increases in soil P and nitrate contents at the high stocking rate were consistent with previous reports for soils of high cation exchange capacity (Barrow 1967; Rouquette *et al.* 1973; Bromfield and Simpson 1974; Simpson *et al.* 1974). These changes suggest a faster recycling of nutrients at the high stocking rate (Rouquette *et al.* 1973) and the transport of nutrients from the soil profile to the top 10 cm (Simpson *et al.* 1974). Unlike Langlands and Bennett (1973), we did not measure an increase in bulk density of the soil with stocking rate, and this may reflect the cracking and self-mulching characteristics of the soils we used (Powell *et al.* 1985).

The relative economic values of the 2 stocking rates can be calculated using local prices for milk, additional cows, and grain, hay, and fertiliser inputs. At an applied N level of 300 kg/ha.year, total milk output will be $A883 and $1007/ha.year at 1.17 and 1.37 cows/ha, respectively. Total costs for fertiliser, hay, and grain, and an additional cost for 0.2 cows, were $611 and $910, giving margins over costs of $272 and $97, respectively. These values demonstrate the advantages of maintaining a modest stocking rate on tropical grass pastures in areas of moderate rainfall (<1000 mm/year).

We conclude that the effects of stocking rate on milk response to level of applied N will be affected through changes in pasture growth, and for pasture growth to be increased there must be a substantial groundcover of grass during, and following, fertilisation. Stocking rates that result in low pasture yields and exposed ground surface will be associated with low efficiency of use of applied N.

Acknowledgments

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References

Barrow, N. J. (1967). Some aspects of the effects of grazing on the nutrition of pastures. *Journal of the Australian Institute of Agricultural Science* **33**, 254–62.

Bromfield, S. M., and Simpson, J. R. (1974). Effects of management on soil fertility under pasture. 2. Changes in nutrient availability. *Australian Journal of Experimental Agriculture and Animal Husbandry* **14**, 479–86.

Bryant, A. M., MacDonald, K. A., and Clayton, D. G. (1982). Effects of nitrogen fertiliser on production of milk solids from grazed pasture. *Proceedings of the New Zealand Grassland Association* **43**, 58–63.

Catchpoole, V. R., Oxenham, D. J., and Harper, L. A. (1983). Transformation and recovery of urea applied to a grass pasture in south-eastern Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* **23**, 80–6.

Chapman, L. S., Freney, J. R., Denmead, O. T., Wood, A. W. and Saffigna, P. G. (1992). Improving the efficiency of nitrogen fertilisation of sugarcane under minimum till and trash conservation cultural conditions. Final Report, Project BS375. Sugar Research and Development Corporation, Brisbane.

Colwell, J. D. (1963). The estimation of the phosphorus fertiliser requirements of wheat in southern New South Wales by soil analysis. *Australian Journal of Experimental Agriculture and Animal Husbandry* **3**, 190–7.

Cowan, R. T. (1982). An interpretation of responses in milk yield of dairy cows to increased levels of feeding during late pregnancy. *Proceedings of the Australian Society of Animal Production* **14**, 409–12.

Cowan, R. T., Lowe, K. F., Ehrlich, W., Upton, P. C., and Bowdler, T. M. (1995*a*). 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**, 125–35.

Cowan, R. T., Lowe, K. F., Ehrlich, W., Upton, P. C., and Bowdler, T. (1995*b*). Nitrogen-fertilised grass in a subtropical dairy system. 2. Effect of level of nitrogen fertiliser on animal production. *Australian Journal of Experimental Agriculture* **35**, 137–43.

Cowan, R. T., and Stobbs, T. H. (1976). Effects of nitrogen fertiliser applied in autumn and winter on milk production from a tropical grass–legume pasture grazed at four stocking rates. *Australian Journal of Experimental Agriculture and Animal Husbandry* **16**, 829–37.

Davison, T. M., Cowan, R. T., and Shepherd, R. K. (1985). Milk production from cows grazing on tropical grass pastures. 2. Effects of stocking rate and level of nitrogen fertiliser on milk yield and pasture–milk yield relationships. *Australian Journal of Experimental Agriculture* **25**, 515–23.

Fenn, L. B., and Hossner, L. R. (1985). Ammonia volatilisation from ammonium or ammonium-forming nitrogen fertilisers. *Advances in Soil Science* **1**, 123–69.

Gordon, F. J. (1973). The effect of high nitrogen levels and stocking rates on milk output from pasture. *Journal of the British Grassland Society* **28**, 193–201.

Hawkins, S. W., and Rose, P. H. (1979). The relationship between the rate of fertiliser nitrogen applied to grassland and milk production; an analysis of recorded farm data. *Grass and Forage Science* **34**, 203–8.

Hoglund, J. H. (1980). Nitrogen use on South Island dairy farms. *Proceedings of Lincoln College Farmers Conference* **30**, 420–8.

Hoult, E. H., and McGarity, J. W. (1987). The influence of sward mass, defoliation and watering on ammonia volatilisation losses from an Italian ryegrass sward topdressed with urea. *Fertiliser Research* **13**, 199–207.

Jarvis, S. C., Hatch, D. J., and Lockyer, D. R. (1989). Ammonia fluxes from grazed grassland: annual losses from cattle production systems and their relation to nitrogen inputs. *Journal of Agricultural Science, Cambridge* **113**, 99–108.

Jones, R. J. (1990). Nitrogen rate and stocking rate effects on steer gains from grazed irrigated pangola grass in the Ord Valley, Western Australia. *Australian Journal of Experimental Agriculture* **30**, 599–605.

King, K. R., and Stockdale, C. R. (1980). The effects of stocking rate and nitrogen fertiliser on the productivity of irrigated perennial pasture grazed by dairy cows. 2. Animal production. *Australian Journal of Experimental Agriculture* **20**, 537–42.

Langlands, J. P., and Bennett, I. L. (1973). Stocking intensity and pastoral production. 1. Changes in the soil and vegetation of a sown pasture grazed by sheep at different stocking rates. *Journal of Agricultural Science, Cambridge* **81**, 193–204.

Mears, P. T., and Humphreys, L. R. (1974). Nitrogen response and stocking rate of *Pennisetum clandestinum* pastures. 2. Cattle growth. *Journal of Agricultural Science, Cambridge* **83**, 469–78.

Murtagh, G. J., Kaiser, A. G., Huett, D. O., and Hughes, R. M. (1980). Summer growing components of a pasture system in a subtropical environment. 1. Pasture growth, carrying capacity and milk production. *Journal of Agricultural Science, Cambridge* **94**, 645–63.

Powell, B., Baker, D. E., and Christianos, N. G. (1985). Soils of the Mutdapilly Research Station. Queensland Department of Primary Industries, QR85001.

Rouquette, F. M., Matocha, J. E., and Duble, R. L. (1973). Recycling and recovery of nitrogen, phosphorus, and potassium by coastal bermuda grass: 2. Under grazing conditions with two stocking rates. *Journal of Environmental Quality* **2**, 129–32.

Simpson, J. R., Bromfield, S. M., and Jones, O. L. (1974). Effects of management on soil fertility under pasture. 3. Changes in total soil nitrogen, carbon, phosphorus and exchangeable cations. *Australian Journal of Experimental Agriculture and Animal Husbandry* **14**, 487–94.

Strong, W. M., Dalal, R. C., Cooper, J. E., and Saffigna, P. G. (1987). Availability of residual fertiliser nitrogen in a Darling Downs black earth in the presence and absence of wheat straw. *Australian Journal of Experimental Agriculture* **27**, 295–302.

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