The effect of phosphorus as fertiliser or supplement on pasture and cattle productivity in the semi-arid tropics of north Queensland

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Abstract

Pastures of *Urochloa mosambicensis* (Sabi grass), *Stylosanthes hamata* cv. Verano and *S. scabra* cv. Seca were established on a low phosphorus (P) soil. The P status of the soil and pasture was manipulated by applying superphosphate at different frequencies, *viz*: an unfertilised control; fertilised once-only 12 months after sowing; fertilised biennially; and fertilised annually. The pastures were set-stocked annually with yearling Droughtmaster heifers. Soil and pasture responses to fertiliser, and animal responses to soil and supplementary P, were determined over 9 years following sowing.

Sabi grass became the dominant species in all fertilised pastures whereas unfertilised pasture became progressively more stylo-dominant during the first 7 years. Subsequently, there was an increase in Sabi grass in unfertilised pasture. Fertiliser P increased dry matter yields and P concentration of pasture and diet but had no effect on the nitrogen concentration or digestibility of forage.

Liveweight gain responses to fertiliser were large (60–80 kg/heifer/annum) in the early years, irrespective of the amount of applied P. In later years, liveweight gain on once-only fertilised pasture declined relative to annually and biennially fertilised pasture, but liveweight gain on unfertilised pasture increased relative to fertilised treatments. These changes were considered to be due to differences in the quantities of Sabi grass on different treatments. Differences in total pasture yield were not an important determinant of animal performance except in a drought year. A dietary P supplement was able to substitute for fertiliser P in improving liveweight gain except in the drought year when there was an increasing dry matter limitation with decreasing amount of applied fertiliser. Liveweight gain responses to both fertiliser and supplementary P were mainly confined to the wet season and early dry season when dietary nitrogen and energy levels were sufficient to sustain growth.

Levels of plasma inorganic phosphate, faecal P concentration, thickness and chemical composition of cortical rib-bone were assessed as indicators of responsiveness to P supplementation. Plasma inorganic phosphate level during the autumn was the most reliable indicator of P deficiency with levels of 50 mg/L or less being indicative of a P-responsive situation.

Liveweight gains were much higher than predicted for such low-P diets indicating that the published P requirements for growing cattle overestimate the requirements of growing heifers grazing stylo-based pastures on low-P soils in north Queensland.

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Introduction

The productivity of cattle grazing native grass pastures in northern Australia is usually limited by poor forage quality. Large increases in cattle growth have been achieved by sowing legume-based pastures fertilised regularly with superphosphate (e.g. Norman 1974; Winks *et al.* 1974; Gillard *et al.* 1980; Winter *et al.* 1985; Mannetje and Jones 1990).

The high cost of fertiliser is a deterrent to the widespread adoption of this technology and there is a need for systems of pasture improvement which require less fertiliser. Winks *et al.* (1977)

demonstrated positive growth responses to supplementary phosphorus (P) in cattle grazing unfertilised Townsville stylo (*S. humilis*) pastures but gains were lower than those of cattle grazing Townsville stylo pasture fertilised annually with superphosphate at 125 kg/ha. Subsequently, a number of grazing experiments were established to study the effects of different levels of fertiliser and supplementary P on pasture and cattle productivity. These experiments, established in the late 1970s and early 1980s on soils with low available P, were located near Katherine in the Northern Territory, Mareeba and Townsville in north Queensland and Mundubbera in south-east Queensland. The combined results to 1987 for these 4 sites were presented at a workshop in 1988 and subsequently published (Winter *et al.* 1990; Wadsworth *et al.* 1990; McLean *et al.* 1990; Coates *et al.* 1990; Kerridge *et al.* 1990).

This paper presents, in detail, the results to 1989 for the study near Townsville, on the effect on pasture and animal productivity of different ways of supplying additional P. The value of P concentration in blood plasma and faeces and of bone thickness as indicators of P deficiency is discussed. The reliability of currently recommended levels of dietary P for growth of cattle is also considered.

Materials and methods

Site details

The experiment was established at the CSIRO Lansdown Pasture Research Station (19°41 'S, 146°51 'E), 48 km south of Townsville, Queensland. The experimental area was originally open eucalypt woodland with a native grass understory comprised mainly of *Heteropogon contortus*, *Themeda triandra*, *Chrysopogon fallax* and *Bothriochloa* spp. Trees were cleared prior to sowing the pastures used in the study.

The soils of the area have been described by Murtha and Crack (1966) and comprised a mixture of yellow earth (Gn2.64, Northcote 1971), solodic (Dy3.43) and solodic/solonized-solonetz (Dy3.43) types. The bicarbonate extractable phosphorus (P_B, Colwell 1963) in the surface 10 cm was 4–5 ppm.

The experiment encompassed years of above- and below-average rainfall, including a drought in 1987. Rainfall recorded on site is shown in Table 1.

Experimental design and management

In December 1980, a mixture of *Stylosanthes hamata* cv. Verano (Verano)(3.6 kg/ha), *S. scabra* cv. Seca (Seca)(1 kg/ha) and *Urochloa mosambicensis* cv. Nixon (Sabi grass) (2.4 kg/ha) was broadcast into the native pasture following a single pass with an offset disc plough. The area was divided into 16 paddocks, each of 4 ha, to accommodate a factorial combination of 4 fertiliser rates × 2 levels of P supplement × 2 replicates.

The fertiliser treatments were:

- F0 — nil P fertiliser (control)
- F10/0 — 10 kg/ha P applied only once in November 1981
- F10/BI — 10 kg/ha P applied biennially
- F10/AN — 10 kg/ha P applied annually.

Table 1. Rainfall (mm) recorded at the experimental site during the study with the 78-year mean data.

Year	Jan–Mar	Apr–Jun	Jul–Sep	Oct–Dec	Annual
1981	793	124	18	172	1107
1982	150	37	0	29	216
1983	212	394	0	83	689
1984	322	10	133	190	655
1985	292	98	50	289	729
1986	291	54	37	130	512
1987	249	45	11	246	551
1988	230	100	38	373	741
1989	349	301	54	183	887
1990	355	364	11	279	1009
Mean[1]	587	93	33	153	866

[1] 78-year data (Cook and Russell 1983).

Single superphosphate (9% P; 11% S) was applied in November 1981 and as the maintenance dressings at the end of 1985 and 1989. Triple superphosphate (21% P; 1.3% S) was used at all other times. Paddocks not fertilised in 1981, 1985 and 1989 received gypsum to provide the equivalent amount of sulphur.

P supplements were provided at nil (S0) and 5–7 gP/hd/day (SP) all-year-round as sodium orthophosphate in the drinking water. Until December 1987, sodium carbonate was added to the drinking water of the S0 treatments to provide a similar amount of sodium as that fed to animals receiving sodium orthophosphate. Subsequently, salt blocks were provided in all paddocks. During the 1988 grazing year in both replicates of F0 paddocks, previous supplementation regimes were reversed to test if there was a paddock effect in the results. In 1989, one replicate remained as for 1988 and one reverted to the previous regime.

Grazing commenced in December 1981 with 12-month-old Droughtmaster heifers (c. 50% Brahman), and groups were replaced annually in mid-December. Mean initial liveweights of annual drafts varied between 151 and 195 kg (± 10 S.D.) liveweight. A common stocking rate, designed to ensure forage in excess of animal requirements in all treatments in all but severe drought years, was applied across the experiment from December 1981–December 1982 (1 heifer/ha) and December 1982–December 1987 (0.75 heifers/ha). Following a drought in 1987, stocking rate was reduced in F0 paddocks to 0.5 heifers/ha (January–December 1988) and 0.75 heifers/ha (December 1988–December 1989). All fertilised treatments were stocked at 1 heifer/ha from January–May 1988 and 0.75 heifers/ha from May–December 1988. The F10/0 paddocks remained at 0.75 heifers/ha during 1989 while F10/BI and F10/AN were increased again to 1 heifer/ha.

Measurements

Soil. The bicarbonate extractable P in the surface 10 cm of soil was measured annually towards the end of each year from 1982–1989. Four 25 mm diameter soil core samples were collected from 16 sites in each paddock, prior to the annual application of fertiliser.

Pasture. The botanical composition and yield of pasture were determined annually in April–June using BOTANAL (Tothill *et al.* 1978). Samples of sown species were plucked for chemical analysis from all paddocks every second month from 1984–1987. Shoots of Verano and Seca were harvested down to the fourth or fifth node and Sabi grass was plucked to simulate material harvested by the grazing animal. Samples of grazed forage were collected from one replicate every 2 months using 4 oesophageal fistulated steers injected subcutaneously with ^{32}P to measure dietary P concentration (Little *et al.* 1977) and to estimate digestibility by the pepsin-cellulase method (McLeod and Minson 1978).

Animals. Heifers were weighed every 4 weeks after an overnight fast. Faecal N and P concentrations were determined on faecal grab samples collected monthly. Plasma inorganic phosphate (PiP) levels were determined on jugular blood samples collected at 2–3 month intervals. Phosphorus concentration and compact bone thickness were determined on samples of bone obtained by rib-bone biopsy (Little 1984) from at least half the heifers from each draft at the end of each grazing year (1985–1987) and in August 1985.

Data analysis

All data were analysed with the GENSTAT 5 computer package using the analysis of variance appropriate for a standard randomised block design. Separate analyses were performed for each sampling occasion. Unless otherwise stated, differences were considered significant at $P < 0.05$.

Data on animal performance are not included for the first 2 years of grazing (December 1981–December 1983) when pastures were developing in response to the imposed fertiliser treatments. In the analysis of animal gains, each year was divided into 4 periods:

- period 1 from early to mid-wet season when the growth rates of cattle were highest (mean 109 days);
- period 2 from the mid-wet season to the early dry season when the cattle continued to make good gains but at a slower rate than in period 1 (mean 91 days);
- period 3 from the mid- to late dry season when weight gains varied between small gains

and small losses in different years (mean 82 days); and
— period 4 including the end of the dry season and the beginning of the new wet season when large weight losses followed by rapid weight gains were commonly encountered (mean 75 days).

Weight gains for each period and each full year were analysed separately.

Results

Soil P

Changes in soil P_B from 1980–1989 are shown in Figure 1. The mean P_B of unfertilised soil was 4.9 ppm while the average increase 1 year after the first application of 10 kg/ha P was 1.25 ppm. Soil P_B in treatment F10/0 remained significantly higher than in the unfertilised control for 4 years after the 1 application of fertiliser, but from 1986, mean levels were not significantly different. Differences between the F0 treatment and the F10/BI and F10/AN treatments increased with successive fertiliser applications, reaching 2–3 ppm and 6–7 ppm, respectively, after 9 years. Feeding supplement had no measurable effect on soil P levels.

Botanical composition

Both stylos established well (mean content of 40% legume in April 1982) and persisted for the duration of the experiment (Figure 2). Seca formed the minor legume component of the pastures in the first few years but was the dominant legume in all treatments in 1989 and

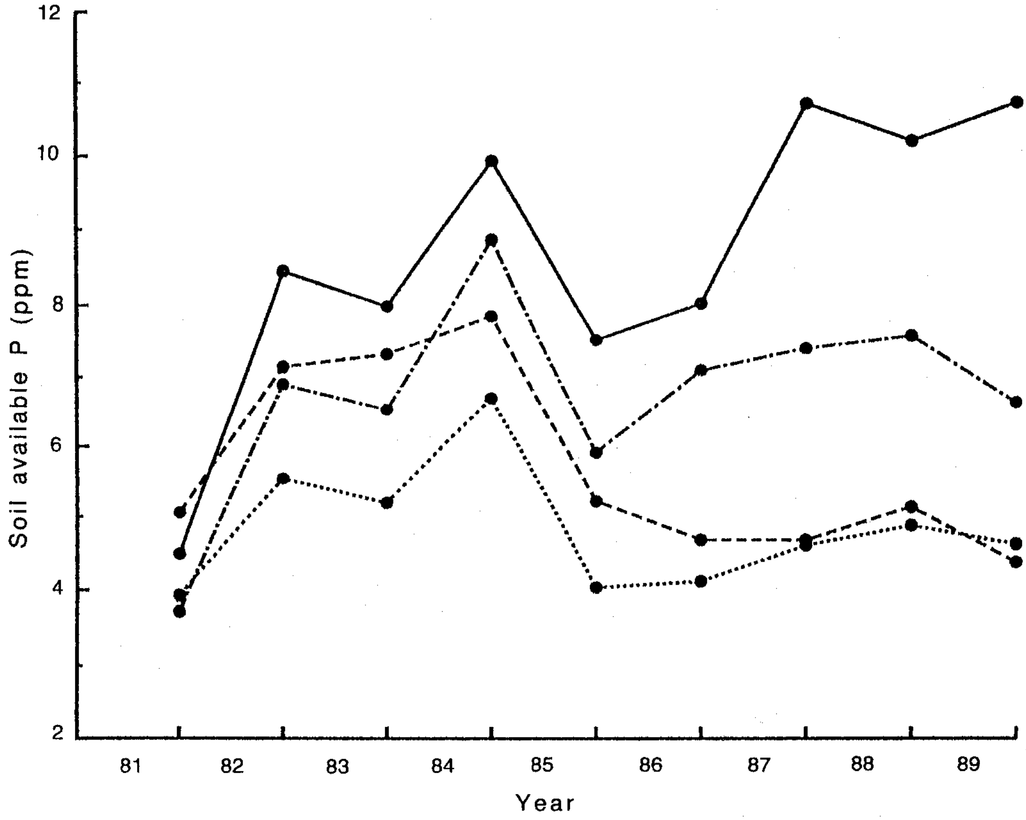

Figure 1. Changes in bicarbonate extracted soil P (P_B) of grazed, stylo-based pastures with different rates of fertiliser: ...... nil fertiliser (F0); ------ 10 kg/ha P applied in November 1981 (F10/0); –·–·–·– 10 kg/ha P applied biennially (F10/BI); —— 10 kg/ha P applied annually (F10/AN).

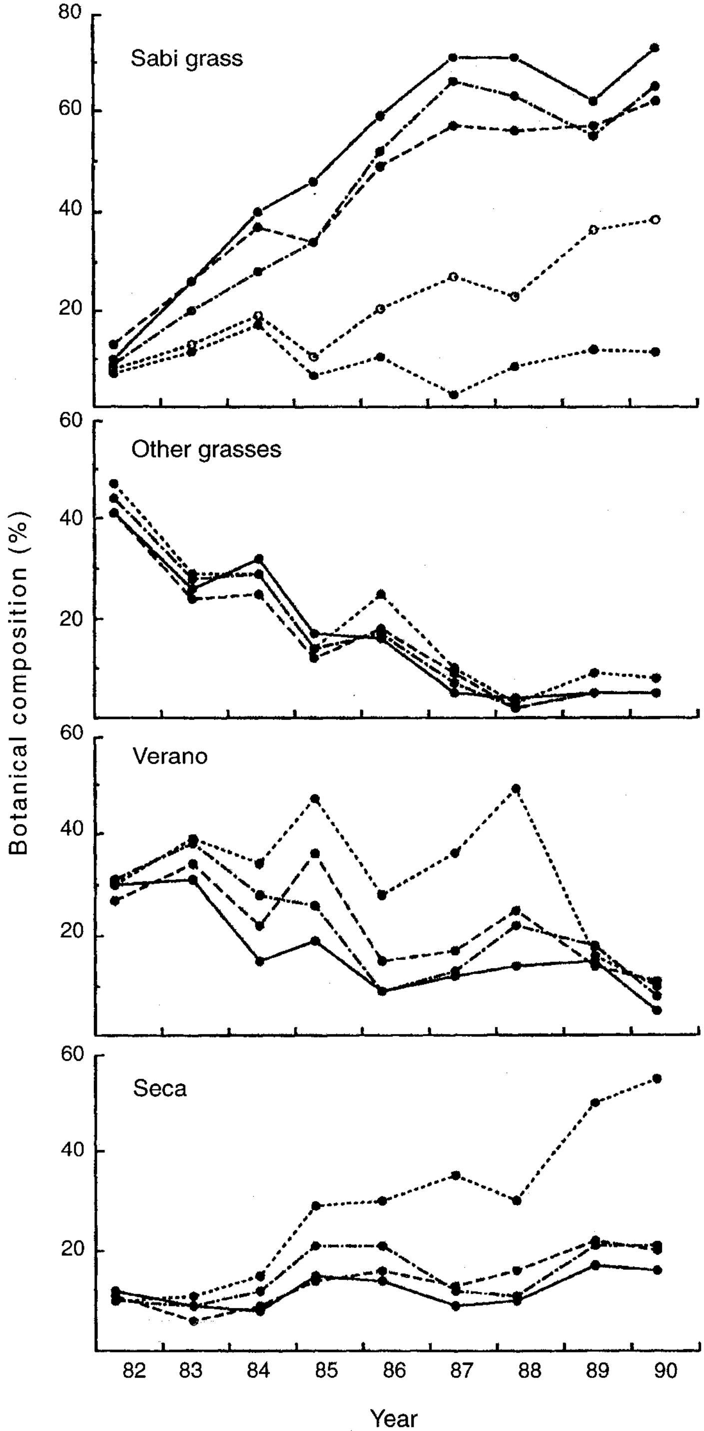

Figure 2. The effect of P fertiliser on the botanical composition of stylo-based pasture: ...... nil fertiliser (F0); ------ 10 kg/ha P applied in November 1981 (F10/0); –·–·– 10 kg/ha P applied biennially (F10/BI); —— 10 kg/ha P applied annually (F10/AN). For Sabi grass at the F0 level, o······o paddocks where supplement was fed 1984–1987, and ●······● paddocks where supplement was not fed.

1990. Overall, Verano content declined, especially in fertilised treatments, as Sabi grass or Seca strengthened. By 1985, unfertilised pastures had become strongly stylo-dominant whereas there was a gradual decline in the stylo content of fertilised treatments, especially in F10/AN.

Applying superphosphate increased the proportion of Sabi grass in the sward ($P < 0.001$) (Figure 2). Early establishment of Sabi grass was poor with a mean contribution of only 10% to pasture yield in April 1982, 16 months after sowing. Thereafter, there was a linear increase in the proportion of Sabi grass in all fertilised pastures to a mean of >60% in 1987. From 1983, the percentage was always highest in the annually fertilised and lowest in unfertilised pasture, especially the original F0.S0 paddocks. During the 1989 wet season, there was an appreciable increase in the percentage of Sabi grass in unfertilised pasture but the mean content remained less than half that of fertilised pasture.

There was no main effect of supplement on botanical composition but there was a fertiliser x supplement interaction (Figure 2) where higher proportions of Sabi grass developed in the 2 unfertilised paddocks in which supplement was fed from 1983–1987 than in the remaining 2 unfertilised paddocks. Conversely, stylo dominance in unfertilised pasture was more pronounced in the unsupplemented pair of paddocks. These effects, which were significant from 1987, were aligned with the original regime for supplementation and were not negated by the changes in supplementation treatment that occurred after 1987.

There was a linear decline in native perennial grasses in all treatments from 40% in 1982 to less than 3% in 1988.

Pasture yield

From 1983, there was a significant ($P < 0.01$) effect of fertiliser on yield of pasture DM due mainly to the higher yield of Sabi grass in all fertilised treatments (Figure 3). Sabi grass yields remained low in the unfertilised pasture until the 1988–1989 wet season when there was a sharp increase. Higher yields of Sabi grass in unfertilised pasture were associated with feeding a P supplement in the earlier years (fertiliser x supplement interaction significant from 1987). Despite the reversal of the supplementation regime in F0 paddocks in 1988, the effect established in the previous years persisted and increased (Figure 3). Feeding P supplement had no effect on any component of pasture yield in fertilised paddocks.

Other grasses, comprised of native grasses and Indian couch (*Bothriochloa pertusa*), contributed 1.15 t/ha, or 40% of total pasture on offer, in April 1982. End-of-wet season yield of other grasses for the years 1984–1986 was fairly stable at about 0.8 t/ha averaged over all treatments, but this represented a declining proportion of total pasture on offer (Figure 3). In 1987, other grasses contributed very little to total pasture yield. The rise in yield of other grasses in 1989 was due primarily to an increase in Indian couch which was most prominent in unfertilised paddocks. Differences between fertiliser treatments in the yield of other grasses were not significant.

The yield of Verano, Seca and native grass was unaffected by fertiliser treatment in most years, but there was a sharp rise in the amount of Seca in unfertilised pasture during the 1988–1989 wet season when yields soared to over 6 t/ha, nearly 3 times that of other treatments (Figure 3). The effect was maintained throughout the following season, but with some reduction in yield. Verano yields rarely exceeded 2 t/ha.

Pasture quality

Phosphorus. The concentration of P in plucked forage was increased by the more frequent application of superphosphate (Figure 4). Differences between treatment F10/0 and the unfertilised control were small and rarely significant whereas P concentrations were consistently and appreciably higher in annually and biennially fertilised pasture ($P < 0.001$). Responses in the P concentration of plucked forage to P fertiliser were greatest during periods of active growth but differences were maintained through the dry season. Applied P had a greater effect on the P concentration in Sabi grass than in stylo. Annual fertiliser applications almost doubled the wet season P concentration of Sabi grass compared with about a 30% increase for the stylos (Table 2). In unfertilised pasture, Sabi grass had a similar mean P concentration to the stylos; in annually fertilised pasture, P concentration in Sabi grass was substantially higher than that in the stylos.

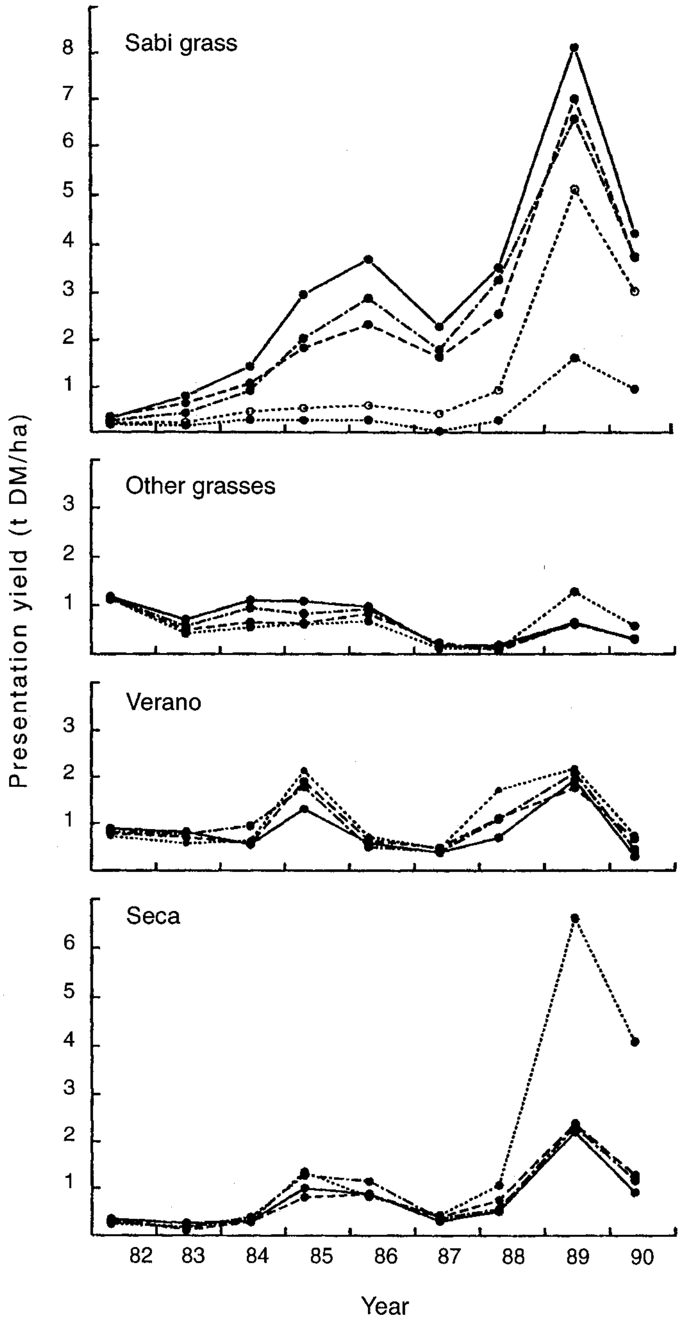

Figure 3. The effect of P fertiliser on the presentation yields of Sabi grass, other grasses, Verano and Seca in stylo-based pasture: ...... nil fertiliser (F0); ------ 10 kg/ha P applied in November 1981 (F10/0); -·-·-·- 10 kg/ha P applied biennially (F10/BI); ——— 10 kg/ha P applied annually (F10/AN). For Sabi grass at the F0 level, o······o paddocks where supplement was fed 1984–1987, and ●······● paddocks where supplement was not fed.

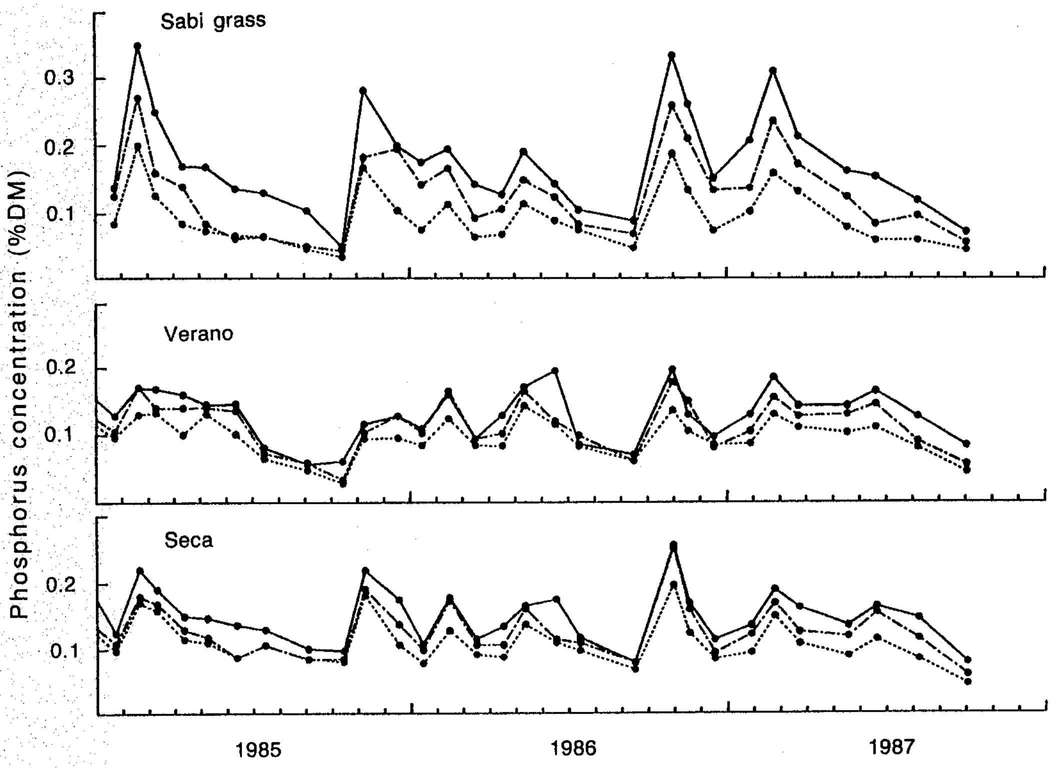

Figure 4. Effect of P fertiliser on the phosphorus (P) concentrations of plucked samples of Sabi grass, Verano and Seca in stylo-based pasture: ...... low soil P status (mean of treatments F0 and F10/0); -·-·-·- medium soil P status (treatment F10/BI — fertilised biennially); —— high soil P status (treatment F10/AN — fertilised annually).

Seasonal influences on plant P concentration were large and related to plant maturity and soil moisture (Figure 4). Concentrations in plucked samples reached maximum levels in new growth at the beginning of the wet season but declined with progressive plant maturity or with the onset of water stress even in physiologically immature forage (e.g. December 1986). Rapid rises occurred with subsequent improvement in soil moisture (e.g. February 1987). These seasonal fluctuations were more pronounced in Sabi grass than in the stylos.

Nitrogen. There was no effect of fertiliser or supplement on the N content of Verano or Seca but the N content of plucked Sabi grass from unfertilised pasture was generally higher than that from the other treatments. Mean N concentrations (%DM) of Sabi grass from 1985–1987 (n = 16) were 1.53, 1.11, 1.11 and 1.05% for treatments F0, F10/0, F10/BI and F10/AN, respectively. The N content of plucked Verano and Seca rarely fell below 2%, while that of Sabi grass rarely reached 2% and on average was less than half that of the stylos. Seasonal changes in plant N concentration were similar to those in P concentration.

Calcium and other minerals. Fertiliser had no effect on plant calcium concentration but because P concentration increased with fertiliser rate, Ca:P ratios narrowed with increasing level of fertiliser (Table 3). Stylos were high in calcium (1.1–1.6%) with wide Ca:P ratios, especially for the unfertilised pasture and during the dry season.

The concentrations of other minerals were above the levels required by cattle except for Na which was low in Verano and native grasses (0.01–0.03%).

Table 2. Effect of P fertiliser on mean concentration of P (%DM) in plucked samples of Sabi grass and stylo for wet (n = 12) and dry (n = 6) seasons over the period January 1985–October 1987.

		Treatment				
		F0[1]	F10/0	F10/BI	F10/AN	LSD (5%)
Wet	Sabi grass	0.11	0.11	0.15	0.20	0.012
	Verano	0.11	0.11	0.12	0.14	0.010
	Seca	0.12	0.12	0.14	0.16	0.012
Dry	Sabi grass	0.06	0.06	0.07	0.10	0.012
	Verano	0.06	0.06	0.07	0.08	0.009
	Seca	0.08	0.08	0.09	0.11	0.008

[1] F0 — nil fertiliser; F10/0 — 10 kg/ha P applied in November 1981; F10/BI — 10 kg/ha P applied biennially; F10/AN — 10 kg/ha P applied annually.

Table 3. Effect of P fertiliser on mean (± s.e.) calcium (Ca) and phosphorus (P) concentrations (%) and on Ca:P ratios in plucked samples of Sabi grass, Verano and Seca in 1985.

		Wet season[1]			Dry season[2]		
Species	Fert.	Ca	P	Ca:P	Ca	P	Ca:P
Sabi grass	F10/AN[3]	0.30 (0.011)	0.24 (0.034)	1.2	0.53 (0.021)	0.11 (0.013)	5.0
	F0[4]	0.29 (0.014)	0.11 (0.013)	2.7	0.38 (0.020)	0.05 (0.008)	7.7
Verano	F10/AN	1.37 (0.052)	0.15 (0.007)	9.0	1.30 (0.050)	0.07 (0.004)	19.4
	F0	1.34 (0.058)	0.11 (0.008)	11.6	1.32 (0.028)	0.05 (0.002)	25.4
Seca	F10/AN	1.27 (0.040)	0.17 (0.013)	7.5	1.40 (0.032)	0.12 (0.003)	11.5
	F0	1.28 (0.072)	0.13 (0.009)	10.1	1.41 (0.040)	0.10 (0.006)	14.7

[1] Mean of 6 samples.
[2] Mean of 3 samples.
[3] 10 kg/ha P applied annually.
[4] Nil fertiliser.

Dietary phosphorus concentration

The effect of fertiliser treatment on dietary P concentration varied with the season and the amount and timing of fertiliser applications (Table 4). During the wet season, the increase in dietary P concentration on fertilised treatments over the unfertilised control was generally directly related to the amount of fertiliser applied. Differences during the dry season were much smaller. There was a trend for treatment F10/0 to have marginally higher wet season dietary P concentrations than the unfertilised control (non-significant except in March 1984) but there was no advantage in the dry season. Mean wet season dietary P concentration on the unfertilised treatment for years 1984–1987 was 0.110% (values ranged from 0.069–0.167% for 15 sampling occasions).

Digestibility of diet

There was no consistent effect of fertiliser treatment on the DM digestibility of extrusa samples. Season had the major effect with DM digestibility, averaged over all treatments, ranging from 66% in the early wet season to 43% in the late dry season of 1987.

Animal production

There were responses in liveweight gain (LWG) to both fertiliser and supplement with a significant interaction between fertiliser and supplement. Cattle grazing unfertilised pasture responded to P supplement while those grazing fertilised pasture generally had a lesser or nil response to supplement (Table 5). Cattle generally gained weight from the summer storms

Table 4. Effect of fertiliser on mean dietary P concentrations (%DM) during the wet and dry seasons, 1984–1987.

Season	Year	n	Treatment				
			F0[1]	F10/0	F10/BI	F10/AN	LSD (5%)
Wet	1984	2	0.148	0.157	0.200	0.207	0.023
	1984/85	4	0.091	0.108	0.122	0.158	0.044
	1985/86	4	0.091	0.093	0.128	0.158	0.032
	1986/87	5	0.109	0.130	0.156	0.205	0.042
	4-year mean		0.110	0.122	0.151	0.182	0.021
Dry	1984	3	0.072	0.082	0.100	0.091	n.s.
	1985	2	0.062	0.056	0.067	0.081	n.s.
	1986	2	0.060	0.050	0.073	0.082	0.009
	1987	2	0.049	0.045	0.060	0.080	n.s.
	4-year mean		0.061	0.058	0.075	0.083	0.018

[1] F0 — nil fertiliser; F10/0 — 10 kg/ha P applied in November 1981; F10/BI — 10 kg/ha P applied biennially; F10/AN — 10 kg/ha P applied annually.

Table 5. Effect of fertiliser and P supplement on period and annual liveweight gains (kg) of heifers grazing stylo-based pastures.

Year	Period (days)	Nil supplement				P supplement				LSD (5%)
		F0[1]	F10/0	F10/BI	F10/AN	F0	F10/0	F10/BI	F10/AN	
1984	1(98)	76	96	90	95	100	96	110	102	26.1
	2(56)	16	27	38	33	44	46	42	43	12.8
	3(84)	−17	−15	−2	−18	1	1	−1	3	16.5
	4(126)	19	67	51	70	50	52	60	48	20.5
	Annual	**94**	**175**	**177**	**180**	**195**	**195**	**211**	**196**	**40.5**
1985	1(98)	46	75	76	74	80	72	76	77	14.6
	2(112)	39	57	48	63	73	69	68	67	13.4
	3(84)	−2	−1	3	8	4	−5	5	11	8.7
	4(70)	11	27	15	15	8	15	14	11	22.5
	Annual	**94**	**158**	**142**	**160**	**165**	**151**	**163**	**166**	**33.5**
1986	1(98)	59	85	88	83	93	92	97	83	18.8
	2(112)	31	44	42	51	49	61	62	49	19.3
	3(84)	7	4	11	9	15	5	15	8	17.2
	4(70)	3	26	28	32	14	24	36	23	11.7
	Annual	**100**	**159**	**169**	**175**	**171**	**182**	**210**	**163**	**34.4**
1987	1(125)	51	81	95	112	97	111	102	113	29.1
	2(57)	23	27	29	35	35	37	38	37	19.3
	3(111)	3	5	1	4	−17	−11	−1	1	17.4
	4(72)	−28	−23	−31	−18	−40	−36	−8	−17	25.5
	Annual	**49**	**90**	**94**	**133**	**75**	**101**	**131**	**134**	**40.2**
1988	1(81)	66	64	70	72	73	79	84	81	22.8
	2(115)	41	44	56	53	77	63	60	55	20.2
	3(56)	7	9	12	5	16	11	12	7	10.5
	4(70)	11	1	8	2	−20	−1	−4	11	22.9
	Annual	**125**	**118**	**146**	**132**	**145**	**152**	**152**	**154**	**46.0**
1989	1(155)	116	112	116	133	147	137	132	140	21.4
	2(98)	41	44	50	45	46	48	47	50	11.6
	3(70)	12	4	7	13	20	10	16	9	13.2
	4(41)	−12	−1	1	1	−14	−8	−9	−4	17.7
	Annual	**157**	**159**	**174**	**192**	**199**	**187**	**187**	**195**	**21.4**

[1] F0 — nil fertiliser; F10/0 — 10 kg/ha P applied in November 1981; F10/BI — 10 kg/ha P applied biennially; F10/AN — 10 kg/ha P applied annually.

until mid-dry season (end of July) with fertilised or supplemented groups gaining more than the unfertilised, unsupplemented control group. Cattle in all treatments usually maintained weight during the late dry season while substantial weight losses associated with loss of gut-fill were recorded immediately following the first storms. The weight loss was quickly restored as cattle made rapid gains on new season pasture growth.

The increase in annual LWG as a result of feeding P supplement to heifers grazing unfertilised pasture was as high as 101 kg/heifer in 1984 and averaged 55 kg/heifer over the 6 years. The response occurred primarily during periods 1 and 2. Smaller positive responses to supplement also occurred at the F10/0 and F10/BI fertiliser levels, where the mean responses in annual LWG were 18 and 26 kg/heifer, respectively. There was no LWG response to P supplement on the F10/AN treatment.

There was no LWG response to fertiliser where supplement was fed except in the drought year of 1987 but there were large responses when supplement was not provided (Table 5). These responses again occurred primarily in periods 1 and 2 but significant responses occurred in period 4 of 1984 and 1986. The magnitude and pattern of response to fertiliser changed as the study progressed. In 1984, 1985 and 1986, there was a significant response to fertiliser *per se* without significant differences between rates of fertiliser P, but in 1987 and 1989 the response increased in line with the amount of fertiliser applied. Concurrent with the change in response pattern to fertiliser treatment, there was a reduction in the magnitude of the LWG response to fertiliser as exemplified by the relative performance of unsupplemented heifers grazing unfertilised and annually fertilised pasture. In the 3 years 1984–1986, annual LWG of heifers on treatment F0.S0 was 56% of that on treatment F10/AN.S0 (response of 76 kg/heifer/annum). Subsequently, the relative performance of heifers on treatment F0.S0 improved so that for 1988–1989, performance was 87% of that on treatment F10/AN.S0 (response of 21 kg/heifer/annum). Similarly, heifers on treatment F10/0.S0 had a mean annual LWG advantage of 68 kg/heifer for years 1984–1986 compared with heifers on treatment F0.S0, but gains on these treatments were the same in 1988–1989.

Plasma inorganic P

Both fertiliser and supplement significantly increased the plasma inorganic phosphate (PiP) concentrations throughout the year. PiP levels in response to P supplement (Figure 5) or annual fertiliser applications (not shown in Figure 5) did not differ and averaged nearly 70 mg/L, rarely falling below 60 mg/L. PiP of heifers on treatment F0.S0 declined from starting values of 50–70 mg/L to levels around 40 mg/L and on occasions approached 30 mg/L. Levels were intermediate for heifers on treatment F10/BI.S0 (not shown in Figure 5), being higher in years following fertiliser application. PiP levels of heifers on treatment F10/0.S0, relative to other treatments, declined as the study progressed and approached those of treatment F0.S0, particularly in the second half of the year.

When the growth response in heifers due to feeding P supplement was plotted against PiP of their unsupplemented contemporaries (Figure 6), an apparently curvilinear relationship was derived for 3 of the 4 years. Although the relationship varied from year to year, PiP levels of 50 mg/L or less in the late wet season indicated a P responsive situation, while levels of 60 mg/L or more indicated a lack of response to additional P.

Faecal P and N

Faecal P concentrations in unsupplemented groups increased in response to fertiliser rate (Figure 7). Heifers grazing unfertilised pasture had an average faecal P concentration during the wet season of 0.23% (n = 20, 1984–1987) compared with an average of 0.36% for heifers grazing annually fertilised pasture. Significant differences were recorded on over half the sampling occasions and were more common during the wet season and after 1984 when treatment differences in soil P_B were more pronounced. Seasonal changes in faecal P concentration (Figure 7) followed the same pattern as did pasture and dietary P.

Fertiliser and supplementary P had no effect on faecal N concentrations. Seasonal changes in faecal N were related to seasonal changes in plant N concentrations. Faecal N concentrations of 2% or higher were measured for short periods during the wet season and concentrations as low as 1% were recorded only in the late dry season.

Bone thickness and composition

The thickness of rib cortical bone (CBT) was always lowest in unsupplemented heifers grazing unfertilised pasture with values ranging from 2.1 mm in 1987 to 2.85 mm in 1985 and an overall mean of 2.3 mm. There was a consistent trend (non-significant except for 1986) for CBT to increase with increasing fertiliser rate in unsupplemented heifers, with values for F10/0, F10/BI and F10/AN of 2.8, 3.1 and 3.3mm, respectively. Average CBT was 3 mm in all treatments where supplement was fed.

The specific gravity of fresh cortical bone varied from 1.70–1.82 g/cm^3 and was not affected by treatment. Concentrations of P and calcium were determined on only 3 occasions, December 1984 and August and December 1985. Calcium concentrations were unaffected by treatment while there were small but significant increases due to fertiliser and supplement in P concentrations of dry, fat-free bone in August 1985, and due to supplement in December 1985 (Table 6).

Discussion

The results of this experiment showed that inputs of P either as fertiliser or supplement gave rise to a substantial improvement in the annual gain of cattle grazing stylo-based pastures growing on soil low in P.

Response to supplement

P supplement was just as effective as P fertiliser in improving annual gain in all but the 1987 drought year when pasture DM on offer became an over-riding influence on cattle performance. This contrasts with the results at Swans Lagoon (Winks *et al.* 1977) and at Springmount and Narayen (Winter *et al.* 1990), where feeding P supplement to cattle grazing unfertilised pasture failed to raise LWG to the level achieved with annually fertilised pasture. In this study, it appears that the only significant determinant of animal growth rate which differed between treatments was the adequacy of dietary P, primarily during periods 1 and 2. When weight gain ceased, there was no response to feeding a P supplement, a result in agreement with previous studies with mature, low quality forages (Minson 1990).

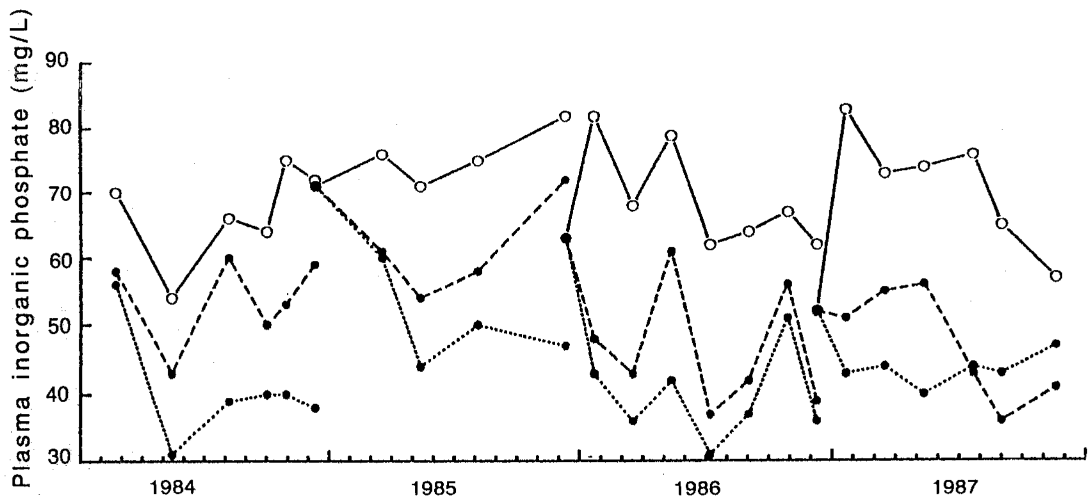

Figure 5. Effect of treatment on circulating levels of plasma inorganic phosphate (PiP) of heifers grazing stylo-based pasture. The breaks in the graph occur due to the annual replacement of heifers: ...... nil fertiliser (F0), nil P supplement; ------ 10 kg/ha P applied in November 1981 (F10/0), nil P supplement; o——o plus P supplement meaned over fertiliser levels.

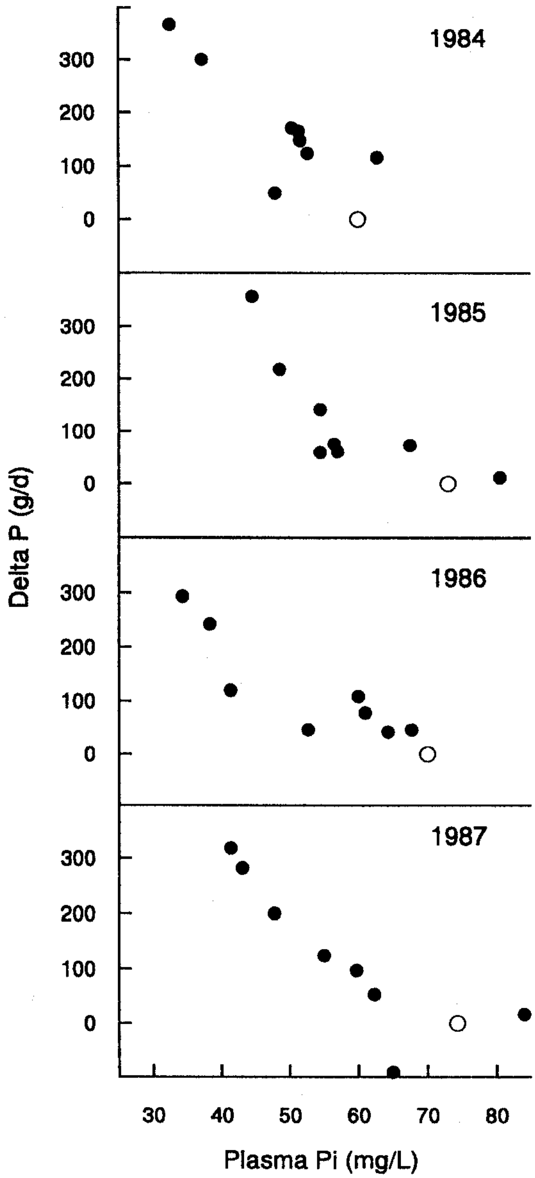

Figure 6. The relationship between Delta P (difference between the average daily gain of unsupplemented and supplemented heifers over the main growing period (210–224 days)) and plasma inorganic phosphate (PiP) levels of unsupplemented heifers. PiP values are the mean of 2 samplings (May and August) for years 1984 and 1985, and the mean of 3 samplings (March, May and July) for years 1986 and 1987. Each point (●) represents a paddock mean. PiP of supplemented heifers is shown as o.

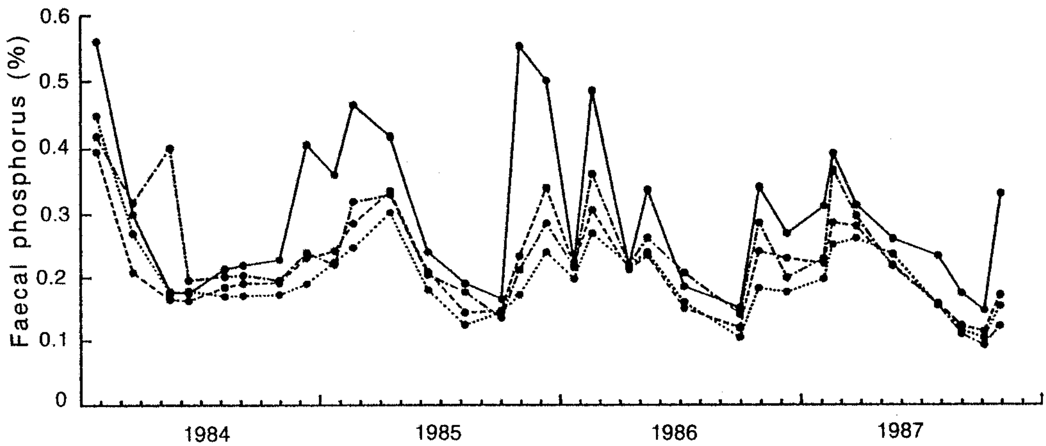

Figure 7. Effect of fertiliser level and season on the faecal phosphorus concentration of heifers grazing stylo-based pasture. Values are for nil supplement treatments: ...... nil fertiliser (F0); ------ 10 kg/ha P applied in November 1981 (F10/0); -·-·-·- 10 kg/ha P applied biennially (F10/BI); —— 10 kg/ha P applied annually (F10/AN).

Table 6. Effect of fertiliser and phosphorus supplement on the phosphorus concentration (g/kg dry, fat-free bone) of rib cortical bone of heifers grazing stylo-based pasture.

	Fertiliser rate					Supplement		
	F0[1]	F10/0	F10/BI	F10/AN	LSD (5%)	−P	+P	LSD (5%)
Dec 1984	111	111	113	113	4.1	112	113	2.9
Aug 1985	107	109	109	110	1.4	108	110	1.0
Dec 1985	109	111	110	110	2.1	109	111	1.5

[1] F0 — nil fertiliser; F10/0 — 10 kg/ha P applied in November 1981; F10/BI — 10 kg/ha P applied biennially; F10/AN — 10 kg/ha P applied annually.

The magnitude of the LWG response was moderated not only by the level of soil P but by other influences that emerged as the study progressed. The largest responses were in the earlier years (1984–1986) at the lowest fertility when the mean annual response was 80 kg/heifer compared with only 30 kg/heifer in 1988 and 1989. The smaller response in the later years was not due to any reduction in the growth of supplemented heifers, but to an improved performance of unsupplemented heifers grazing unfertilised pasture. Possible reasons for this improvement are discussed later.

Response to fertiliser

Applying P fertiliser had significant effects on the yield, botanical composition and P concentration of the pasture, all of which can contribute to improved growth rates of cattle. However, owing to the lenient stocking rates imposed, pasture productivity was unlikely to have had any effect on LWG in this experiment. The only exception was in 1987, when pasture DM on offer in May accounted for *c.* 70% and 40% of the variation in annual LWG for unsupplemented and supplemented heifers, respectively. In commercial practice, the improved pasture production from applying P fertiliser would be captured by increasing the stocking rate.

Since feeding supplementary P eliminated all LWG differences between fertiliser treatments, it might be concluded that the LWG responses to fertiliser in this study resulted from an increased dietary P concentration on fertilised treatments. However, the performance of the unsupplemented heifers on the pasture fertilised only once initially, questions the validity of this simple hypothesis. The increase in annual LWG on this treatment over the unfertilised treatment was 68 kg/heifer from 1984–1986, with only minimal effect on P content of both plucked forage and feed selected by OF animals (Table 4). Differences in species composition or species yield in the different paddocks seemed to play a significant role. While unfertilised paddocks were dominated by stylos with little Sabi grass, Sabi grass was a major component of once-only fertilised pasture. P concentration was similar in both stylos and Sabi grass, but Sabi grass had much lower calcium concentration and hence Ca:P ratio. It is well documented (Theiler *et al.* 1927; Field *et al.* 1975; Minson 1990; Ternouth and Sevilla 1990a, 1990b) that the adverse effects of low dietary P are exacerbated by high dietary calcium. It is possible that high dietary calcium and low dietary P levels in heifers on unfertilised pasture limited their performance relative to those on once-only fertilised pasture. The improved performance of heifers on the unsupplemented, unfertilised treatment in 1988 and 1989, when the amount of Sabi grass in the pasture increased, relative to the once-only fertilised pasture, lends further weight to this hypothesis.

Native grasses did not seem to be as effective as Sabi grass in improving LWG under conditions of low soil P. From 1984–1986, one replicate of treatment F0.S0 contained much more native grass than the other (920 vs. 140 kg/ha at the end of the wet season). The heifers grazing the replicate with more native grass had higher mean annual LWGs than those in the other replicate (107 vs. 84 kg/heifer) but the response was much less than that attributed to Sabi grass. The difference between Sabi grass and native grass could not be attributed to a difference in calcium concentration but may have been associated with differences in other attributes, such as P concentration, digestibility or rate of passage, not detected by the OF animals. Regardless of the underlying causes, the results indicated that better gains were achieved on stylo-Sabi grass pastures than on either pure stylo or stylo-native grass pastures growing on soils low in P. This could have important economic implications, especially in the long term.

Native perennial grasses, which accounted for about 40% of pastures throughout the experiment one year after sowing the introduced species, failed to persist in any of the treatments. The inability of native perennial grasses to tolerate heavy grazing pressure is well recognised in the semi-arid tropics of north Australia (Gillard and Winter 1984) and stylo dominance is a likely consequence of high stocking rate on stylo-native grass pastures in the absence of an adapted, grazing-tolerant grass. In terms of pasture stability, the potential for invasion by undesirable weeds, and the risk of soil loss from water erosion, high stylo dominance is considered undesirable. The inclusion of Sabi grass in this experiment provided a productive and persistent perennial grass component in all but the unfertilised treatment where its development was restricted by inadequate soil P. However, in treatment F10/0, one application of fertiliser P resulted in the development of a strong component of Sabi grass which was able to persist at low soil P without applying more fertiliser. Annual fertiliser applications favoured the Sabi grass at the expense of stylo and could eventually have undesirable consequences on dietary N levels due to lack of legume. However, the botanical changes recorded in this study in response to fertiliser treatment suggest that a desirable mixture of stylo and Sabi grass may be maintained by manipulating soil P levels.

Phosphorus requirements of cattle

Forage P concentrations of once-only fertilised pasture during the wet season were low as were the dietary P levels selected by OF animals during this period (mean 0.12%; Table 4). Wet season weight gains of unsupplemented heifers grazing these pastures (mean 0.66 kg/d, 1984–1987) were appreciably higher than might be expected from the published P requirements for growth in cattle (ARC 1980; NRC 1984; AFRC 1991). Rib-bone CBT values (2.8 mm) in these heifers were only marginally below the 3 mm considered normal by Little (1984) indicating that heifers were not suffering significant bone demineralisation. Even the dietary P concentrations of heifers grazing biennially and annually fertilised pasture were calculated to be only slightly over 40% and 50%, respectively, of those recommended in the revised estimates of AFRC (1991). Minson (1990) suggested that animals on low-P diets may require up to 40% less P than those recommended by ARC (1980). The disparity would be even greater in relation to the revised requirements of AFRC (1991). The results from this experiment support the view that ARC (1980), NRC (1984) and AFRC (1991) overestimate the P requirements of animals on low-P diets; the results of a one-year study of the P kinetics of heifers on these pastures (Coates and Ternouth 1992) lend further evidence for this conclusion. A revision of the supplementary P requirements of animals grazing P-deficient pastures in northern Australia seems warranted.

Pasture P status

The results of this study support the notion that measuring pasture P concentration is an unsatisfactory method for determining the capacity of a pasture to meet the dietary P requirements of the grazing animal in the variable north Queensland environment. The problem lies not only in the large shift in plant P concentration from peak wet season levels to minimum dry season levels, but also in the large and rapid fluctuations that occur, especially in the growing season, in response to fluctuations in soil moisture and other factors affecting plant growth (see Figure 4). Whereas single or intermittent sampling for plant or dietary P levels can reliably detect differences between pastures in P status, only regular, frequent monitoring can reliably quantify these parameters over a given period. An additional problem arises from the fact that the level of pasture or dietary P required to meet animal requirements is highly variable, being dependent on other quality attributes which determine the productive potential of the diet (e.g. N content, digestibility, other minerals). Therefore, measures to determine or predict the capacity of a pasture to satisfy animal P requirements have been directed towards soil P status (Kerridge *et al.* 1990) or indicators of animal P status.

Indicators of P status

Despite reported limitations of plasma or blood Pi as a predictor of responsiveness to additional dietary P (Cohen 1974), data from experiments in northern Australia indicate this parameter to be a useful aid in the diagnosis of P deficiency provided measurements are made during or at the end of the animal growth phase (Winter 1988) and preferably at the end of the wet season (Wadsworth *et al.* 1990). The results of this study support this view and highlight some of the dangers associated with inappropriate sampling times. After the heifers entered the experiment in December each year, there was a rapid decline in PiP of unsupplemented heifers grazing unfertilised pasture, but the time taken to reach minimum values varied from as little as 6 weeks in 1987 to over 12 weeks in 1985 (Figure 5). Thus, measuring PiP too early in the growing season, when pasture P concentrations are highest, may give false estimates of the ability of the forage to supply sufficient P. Misleading, elevated levels of PiP in P-deficient cattle can also occur for short periods when rain induces a flush of pasture growth following a dry spell. This effect was most noticeable in 1986 (Figure 5) when temporary increases were observed in May and October. The effect may be more pronounced where deficiency is marginal rather than acute (cf. treatments F10/0.S0 and F0.S0). These results suggest that measuring PiP for determining the likely responsiveness of cattle to supplementary P should be avoided immediately following pronounced flushes of pasture growth.

Published lower limits of PiP for determining responsiveness of growing cattle to additional dietary P vary, but most lie in the range of 40–50 mg/L (e.g. Underwood 1966; Cohen 1973a; Preston 1977; Gartner *et al.* 1980,1982). Since the Pi concentration of whole blood is about 75% of that in plasma (Little *et al.* 1971; Teleni *et al.* 1976), it is important to be aware whether published values refer to whole blood or plasma. The results from this study support these levels with PiP of 50 mg/L or less at the end of the summer growing season indicating a P-responsive situation while levels greater than 60 mg/L indicate the absence of any likely response to additional P.

When the increase in growth rate due to feeding P supplement was plotted against the mean P concentration in faeces sampled during the growing season (1984–1987), the lack of a consistent relationship indicated that faecal P concentration was of lesser value than PiP in predicting responsiveness to P supplement, a conclusion in agreement with earlier reports (Winter 1988; Wadsworth *et al.* 1990).

While there were treatment differences in rib CBT, the results did not foster confidence in this measure as a reliable diagnostic tool for determining responsiveness to P supplement in growing cattle. The within-treatment variation from year to year showed that factors other than the adequacy of dietary P influence rib CBT so that it is not possible to define specific values for P deficiency or sufficiency that are universally applicable. At the end of each grazing year, the mean CBT of heifers in treatment F0.S0 always remained above the 2 mm proposed by Little (1984) as indicative of P deficiency, even though the response to supplement showed that inadequate dietary P depressed annual LWG by as much as 100 kg/heifer. The results from this experiment suggest that critical values for rib CBT of <2.5 mm for P deficiency, and >3.0 mm for P adequacy, are appropriate for 24-month-old Droughtmaster heifers grazing stylo-based pasture.

Although the P concentration of rib cortical bone (w/v of fresh bone, w/w of dry, fat-free bone) in F0.S0 heifers was less than that in all other treatments, these measurements showed no promise as diagnostic aids in detecting P deficiency. Little and Shaw (1979) quoted levels over 150 mg/cm^3 fresh bone as indicating adequacy but P-deficient heifers in treatment F0.S0 averaged 158 and 153 mg/cm^3 fresh bone in 1984 and 1985. Hoey *et al.* (1982) also measured P concentrations of well over 150 mg/cm^3 in rib biopsy samples from P-deficient heifers. There was little difference between treatments in the P content of dry, fat-free bone and the mean value of 111 g/kg for supplemented heifers fell below the values suggested by McDowell *et al.* (1983) and Cohen (1973 a; 1973b) as being deficient. These differences again indicate that the chemical composition of rib cortical bone is an unreliable indicator of P deficiency or adequacy.

Conclusions

The following section outlines some conclusions of practical significance based on the results of this study.

The liveweight gain of cattle grazing stylo-based pasture growing on low-P soil may be severely limited by inadequate dietary P, but the limitation can be remedied by inputs of P either as fertiliser, or supplement fed direct to the animal. Provided the pasture has a productive stylo component, and provided mineral nutrients other than P are not limiting (e.g. sulphur), P supplement can substitute for fertiliser in maximising per head liveweight gains. Supplement need only be fed during the growing season (e.g. during the wet season to mid-dry season) because cattle are responsive to additional P only when gaining weight. Large responses in animal gains can be achieved from relatively small inputs of P fertiliser and there is a strong residual effect of applied fertiliser. The amount of fertiliser needed to overcome the dietary P deficiency depends on the initial soil fertility but since fertiliser increases pasture production as well as the P status of the forage, it provides the opportunity for higher stocking rates. The good responses to both fertiliser and supplementary P indicate that producers have flexibility in choosing P input options (fertiliser, supplement or a combination of both) as well as the ability to modify the strategy in response to changing circumstances.

At low soil P, unsupplemented cattle perform better on a stylo-Sabi grass mixture than on either stylo-native grass or highly stylo-dominant pasture. As well as the obvious economic advantage (reduced need for P inputs), the presence of Sabi grass (or other grazing-tolerant grass compatible with stylo) as a major component of the pasture is considered desirable for pasture stability and the protection of the soil. Fertiliser may be required to establish Sabi grass but once established it will persist well at low soil P. Sabi grass-stylo proportions in the pasture may be influenced by manipulating soil P levels: stylo is favoured at low soil P; Sabi grass is encouraged by increasing soil P.

Measuring PiP in growing cattle during the late wet or early dry season provides a simple and reliable test for determining whether liveweight gain is being limited by inadequate dietary P. Levels of 60 mg/L or higher indicate a low probability of responsiveness to additional P while levels of 50 mg/L or less indicate a high probability of responsiveness to additional P.

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References

AGRICULTURAL AND FOOD RESEARCH COUNCIL (AFRC) (1991) AFRC Technical Committee on Responses to Nutrients, Report 6. A reappraisal of the calcium and phosphorus requirements of sheep and cattle. *Nutrition Abstracts and Reviews* (Series B), **61**, 573-612.

AGRICULTURAL RESEARCH COUNCIL (ARC) (1980) *The Nutrient Requirements of Ruminant Livestock.* (Commonwealth Agricultural Bureau: Farnham Royal, GB).

COATES, D.B., KERRIDGE, P.C., MILLER, C.P. and WINTER, W.H. (1990) Phosphorus and beef production in northern Australia. 7. The effect of phosphorus on the composition, yield and quality of legume-based pasture and their relation to animal production. *Tropical Grasslands,* **24**, 209-220.

COATES, D.B. and TERNOUTH, J.H. (1992) Phosphorus kinetics of cattle grazing tropical pastures and implications for the estimation of their phosphorus requirements. *Journal of Agricultural Science, Cambridge,* **119**, 401-409.

COHEN, R.D.H. (1973a) Phosphorus nutrition of beef cattle. 2. Relation of pasture phosphorus to phosphorus content of blood, hair and bone of grazing steers. *Australian Journal of Experimental Agriculture and Animal Husbandry,* **13**, 5-8.

COHEN, R.D.H. (1973b) Phosphorus nutrition of beef cattle. 3. Effect of supplementation on the phosphorus content of blood and on the phosphorus and calcium contents of hair and bone of grazing steers. *Journal of Experimental Agriculture and Animal Husbandry,* **13**, 625-629.

COHEN, R.D.H. (1974) Phosphorus nutrition of beef cattle. 4. The use of faecal and blood phosphorus for the estimation of phosphorus intake. *Australian Journal of Experimental Agriculture and Animal Husbandry,* **14**, 709-714.

COLWELL, J.D. (1963) The estimation of phosphorus fertilizer requirements of wheat in southern New South Wales by soil analyses. *Australian Journal of Experimental Agriculture and Animal Husbandry,* **3**, 190-197.

COOK, S.J. and RUSSELL, J.S. (1983) The climate of seven CSIRO field stations in northern Australia. *Technical Paper No. 25. Division of Tropical Crops and Pastures, CSIRO, Australia.*

FIELD, A.C., SUTTLE, N.F. and NISBET, D.I. (1975) Effects of diets low in calcium and phosphorus on the development of growing lambs. *Journal of Agricultural Science, Cambridge,* **85**, 435-442.

GARTNER, R.J.W., MCLEAN, R.W., LITTLE, D.A. and WINKS, L. (1980) Mineral deficiencies limiting production of ruminants grazing tropical pastures in Australia. *Tropical Grasslands,* **14**, 266-272.

GARTNER, R.J.W., MURPHY, G.M. and HOEY, W.A. (1982) Effects of induced, subclinical phosphorus deficiency on feed intake and growth of beef heifers. *Journal of Agricultural Science, Cambridge,* **98**, 23-29.

GILLARD, P., EDYE, L.A. and HALL, R.L. (1980) Comparison of *Stylosanthes humilis* with *S. hamata* and *S. subsericea* in the Queensland dry tropics: Effect on pasture composition and cattle liveweight gain. *Australian Journal of Agricultural Research,* **31**, 205-220.

GILLARD, P. and WINTER, W.H. (1984) Animal production from *Stylosanthes* based pastures in Australia. In: Stace, Helen M. and Edye, L.A. (eds) *The Biology and Agronomy of* Stylosanthes. (Academic Press: Australia).

HOEY, W.A., MURPHY, G.M. and GARTNER, R.J.W. (1982) Whole body composition of heifers in relation to phosphorus status with particular reference to the skeleton. *Journal of Agricultural Science, Cambridge,* **98**, 31-37.

KERRIDGE, P.C., GILBERT, M.A. and COATES, D.B. (1990) Phosphorus and beef production in northern Australia. 8. The status and management of soil phosphorus in relation to beef production. *Tropical Grasslands,* **24**, 221-230.

LITTLE, D.A. (1984) Definition of an objective criterion of body phosphorus reserves in cattle and its evaluation *in vivo*. *Canadian Journal of Animal Science,* **64** (Supplement), 229-231.

LITTLE, D.A., ROBINSON, P.J., PLAYNE, M.J. and HAYDOCK, K.P. (1971) Factors affecting blood inorganic phosphorus determination in cattle. *Australian Veterinary Journal,* **47**, 153-156.

LITTLE, D.A., MCLEAN, R.W. and WINTER, W.H. (1977) Prediction of the phosphorus content of herbage consumed by grazing cattle. *Journal of Agricultural Science, Cambridge,* **88**, 533-538.

LITTLE, D.A. and SHAW, N.H. (1979) Superphosphate and stocking rate effects on a native pasture oversown with *Stylosanthes humilis* in central coastal Queensland. 5. Bone phosphorus levels in grazing cattle. *Australian Journal of Experimental Agriculture and Animal Husbandry,* **19**, 645-651.

MANNETJE, L. 't and JONES, R.M. (1990) Pasture and animal productivity of buffel grass with Siratro, lucerne or nitrogen fertiliser. *Tropical Grasslands,* **24**, 269-281.

MCDOWELL, L.R., CONRAD, J.H., ELLIS, G.L. and LOOSLI, J.K. (1983) *Minerals for Grazing Ruminants in Tropical Regions.* University of Florida Bulletin. (University of Florida: Gainesville).

MCLEAN, R.W., HENDRICKSEN, R.E., COATES, D.B. and WINTER, W.H. (1990) Phosphorus and beef production in northern Australia. 6. Dietary attributes and their relation to cattle growth. *Tropical Grasslands,* **24**, 197-208.

MCLEOD, M.N. and MINSON, D.J. (1978) The accuracy of the pepsin-cellulase technique for estimating the dry matter digestibility *in vivo* of grasses and legumes. *Animal Feed Science and Technology,* **3**, 277-287.

MINSON, D.J. (1990) *Forage in Ruminant Nutrition.* (Academic Press: New York).

MURTHA, G.G. and CRACK, B.J. (1966) Soils of the CSIRO Pasture Research Station 'Lansdown', Townsville, Queensland. Divisional Report 1/66. Division of Soils, CSIRO, Australia.

NATIONAL RESEARCH COUNCIL (NRC) (1984) *Nutrient Requirements of Beef Cattle.* (National Research Council, National Academy of Science: Washington D.C.).

NORMAN, M.J.T. (1974) Beef production from tropical pastures: Part 1. *Australian Meat Research Committee Review No. 16, pp. 1-24.*

NORTHCOTE, K.H. (1971) *A Factual Key for the Recognition of Australian Soils.* 3rd Edn. (Rellim Technical Publications: Glenside, SA).

PRESTON, R.L. (1977) Phosphorus in beef cattle and sheep nutrition. In: *NFIA Literature Review on Phosphorus in Ruminant Nutrition.* (National Feeds Ingredients Association: West Des Moines, Iowa, USA).

TELENI, E., DEAN, H. and MURRAY, R.M. (1976) Some factors affecting the measurement of blood inorganic phosphorus in cattle. *Australian Veterinary Journal,* **52**, 529-533.

TERNOUTH, J.H. and SEVILLA, C.C. (1990a) The effects of low levels of dietary phosphorus upon the dry matter intake and metabolism of lambs. *Australian Journal of Agricultural Research,* **41**, 175-184.

TERNOUTH, J.H. and SEVILLA, C.C. (1990b) Dietary calcium and phosphorus repletion of lambs. *Australian Journal of Agricultural Research,* **41**, 413-420.

THEILER, A., GREEN, H.H. and DU TOIT, P.J. (1927) Minimum mineral requirements in cattle. *Journal of Agricultural Science, Cambridge,* **7**, 291-314.

TOTHILL, J.C., HARGREAVES, J.N.C. and JONES, R.M. (1978) BOTANAL — A comprehensive sampling and computer procedure for estimating pasture yield and composition. 1. Field sampling. *Technical Memorandum No. 8. Division of Tropical Crops and Pastures, CSIRO, Australia.*

UNDERWOOD, E.J. (1966) *The Mineral Nutrition of Livestock.* (Commonwealth Agricultural Bureau: Farnham Royal, UK).

WADSWORTH, J.C., MCLEAN, R.W., COATES, D.B. and WINTER, W.H. (1990) Phosphorus and beef production in northern Australia. 5. Animal phosphorus status and diagnosis. *Tropical Grasslands*, **24**, 185–196.

WINKS, L., LAMBERTH, F.C., MOIR, K.W. and PEPPER, PATRICIA M. (1974) Effect of stocking rate and fertilizer on the performance of steers grazing Townsville stylo-based pasture in north Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry*, **14**, 146–154.

WINKS, L., LAMBERTH, F.C. and O'ROURKE, P.K. (1977) The effect of phosphorus supplement on the performance of steers grazing Townsville stylo-based pasture in north Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry*, **17**, 357–366.

WINTER, W.H. (1988) Supplementation of steers grazing *Stylosanthes hamata* pastures at Katherine, Northern Territory. *Australian Journal of Experimental Agriculture*, **28**, 669–682.

WINTER, W.H., MCCOSKER, T.H., PRATCHETT, D. and AUSTIN, J.D.A. (1985) Intensification of beef production. In: Muchow, R.C. (ed.) *Agro-Research for the Semi-Arid Tropics: North-west Australia.* pp. 395–418. (University of Queensland Press: Brisbane).

WINTER, W.H., COATES, D.B., KERRIDGE, P.C., MCLEAN, R.W. and MILLER, C.P. (1990) Phosphorus and beef production in northern Australia. 4. The response of cattle to fertilizer and supplementary phosphorus. *Tropical Grasslands*, **24**, 170–184.

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