Phosphorus nutrition and management – overcoming constraints to wider adoption

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Abstract. The importance of phosphorus nutrition for cattle grazing northern Australian rangelands has been well documented and demonstrated. Phosphorus is clearly one of the most important nutritional deficiencies, within the limitations of potential metabolizable energy intakes, of grazing cattle in the seasonally dry tropics. Nevertheless it appears that only a small proportion of cattle grazing phosphorus deficient pastures are supplemented or otherwise managed to alleviate phosphorus deficiency. Estimated requirements for dietary phosphorus by various classes of cattle grazing tropical pastures have recently been revised (CSIRO 2007). The development of faecal near infrared spectroscopy (F.NIRS) allows the routine estimation of metabolizable energy and nitrogen concentrations in the diet, and thus the potential productivity, of cattle grazing northern rangelands. The concentration of phosphorus in the diet of grazing cattle can be estimated from the concentration of phosphorus in the faeces, at least in cattle not fed phosphorus supplements. Combining estimates of diet metabolizable energy, nitrogen and phosphorus allows estimation whether current needs of the animal are supplied by the diet. Phosphorus-replete cattle have substantial body reserves of phosphorus which can be mobilized, especially in late pregnancy and lactation, to alleviate a dietary deficiency. However, these body reserves need to be replenished in late lactation or post-lactation if mobilization occurs each year. Diagnosis of subclinical phosphorus deficiency in grazing cattle, and prediction of animal responses to phosphorus supplements is difficult. In growing cattle the concentration of inorganic phosphorus in blood (Pi), in the late wet or early dry season, combined with information on diet metabolizable energy and nitrogen concentrations obtained by F.NIRS, provides the most reliable test. In pregnant or lactating cows measurements of faecal phosphorus concentration and F.NIRS provide the best estimate of whether phosphorus intake meets the current needs of the animal. However, estimates of adequacy of phosphorus supply need to also consider possible mobilization of body phosphorus reserves. Indicative responses to provision of phosphorus supplements by cattle grazing pastures ranging from marginal to acute deficiency are summarized. Economic evaluation of benchmark enterprises where cattle are expected to be phosphorus deficient indicate that phosphorus supplementation is highly cost-effective. Major obstacles to more widespread adoption of phosphorus supplementation appear to be lack of knowledge and appreciation by managers of the phosphorus status of their cattle, lack of appreciation of the cost-effectiveness of a phosphorus supplementation particularly for some classes of cattle, and the practical difficulties in implementing phosphorus supplementation during the wet season.

Introduction

The importance of phosphorus as a limiting nutrient for cattle grazing the rangelands of northern Australia has been recognized for many decades. Against the background of the generally low metabolizable energy concentration and intake of tropical forages in the seasonally dry tropics, intake of phosphorus is arguably the single most important nutritional constraint for increased productivity in a large proportion of the northern beef herd. Phosphorus is seldom a major nutritional constraint for cattle production in temperate or intensive systems since extensive use of phosphorus fertilizers and availability of high phosphorus feedstuffs usually ensure adequacy. Indeed the focus of phosphorus nutrition in such systems has changed to reduction of phosphorus usage to address environmental concerns. Knowledge of phosphorus as a nutrient limiting for grazing cattle is primarily from research and experience in northern Australia and South Africa.

Proceedings of a phosphorus workshop (Tropical Grasslands 1990) and McCosker and Winks (1994) provide excellent overviews of knowledge, and practical perspectives, of phosphorus in the nutrition of cattle in northern Australia at that time. Major studies in northern Australia since then are those of Ternouth *et al.* (1996), Ternouth and Coates (1997) and Miller *et al.* (1998). The principal pathways of digestion, absorption and excretion of phosphorus are known. Usually about 75% phosphorus in forages is digested and absorbed from the gastrointestinal tract, while the availability of phosphorus in supplements may vary depending on the source. Absorbed phosphorus passes to the blood inorganic phosphate pool. A large amount of inorganic phosphorus in the blood is transferred (recycled) to the rumen in saliva, and in grazing ruminants this recycling is usually much greater than the phosphorus intake. At low to moderate phosphorus intakes almost all excretion of phosphorus is via faeces.

Deficiency of dietary phosphorus can have large effects on animal health and productivity. Clinical symptoms of phosphorus deficiency such as abnormalities associated with skeletal structure and abnormal ingestive behaviour (pica, bone chewing) are well known (McCosker and Winks 1994). In acutely phosphorus-deficient land systems the productivity of cattle is usually reduced severely and the problems obvious. Often the more difficult situation to evaluate is that of subclinical phosphorus deficiency where cattle growth and reproduction are lower than expected, but symptoms of deficiency are not obvious. Phosphorus deficiency in cattle is typically associated with reduced voluntary intake of forage (e.g. by up to 50%) and poor productivity. Reduced fertility is due primarily to consequent poor body condition. Botulism as a consequence of bone-chewing may cause high mortality in cattle which have not been vaccinated. The effects of phosphorus deficiency on the animal seem to be mediated primarily at the metabolic level rather than through direct effects on rumen digestion. There are interactions between the metabolism of phosphorus and calcium. Phosphorus in bones can provide a reserve for animals through intervals of dietary phosphorus shortage comparable to the role of fat reserves for the energy requirements of the animal.

Adoption of management to alleviate phosphorus deficiencies across northern Australia

The most obvious approach to addressing phosphorus deficiency is to provide phosphorus supplements, although other management such as earlier weaning and lower stocking rate are also important. It appears that phosphorus as a nutritional constraint is not effectively addressed in many northern cattle herds.

The reasons for the generally low adoption of management options to effectively alleviate phosphorus deficiency across northern Australia have not been documented. Based on the opinion of experienced extension officers, technical staff in the stockfeed industry and property managers, and a small survey in the Kimberley region (P. Smith, unpublished results) the most important reasons appear to be:

(i) a lack of knowledge by property managers of the phosphorus status of their land systems and their cattle, and often a perception that phosphorus is not a serious constraint in their circumstances and during the wet season when cattle are already growing. This results from the lack of a simple and effective diagnostic tool to measure the severity of phosphorus deficiency,

(ii) a lack of knowledge of the economics of phosphorus supplementation, and confidence that the animal responses to phosphorus supplementation would be economically worthwhile. Key concerns include the amounts of phosphorus required, animal growth and reproduction responses in specific situations, the input costs and the delays before the production benefits can be captured. This is often exacerbated by lack of adequate herd records,

(iii) the practical difficulties in implementing phosphorus supplementation during the wet season (e.g. access, achieving satisfactory supplement intakes, labour).

Economic benefit of phosphorus supplementation

A major difficulty with costs and benefits analysis for commercial properties is that introduction of a phosphorus supplementation program is usually accompanied by other management changes (e.g. improved vaccination, culling, weaning). It is usually difficult to identify the contribution of phosphorus supplementation versus other management changes to improved productivity and economic performance of the enterprise. Thus estimation of the effects of phosphorus supplementation on performance of commercial cattle herds has to depend primarily on subjective 'best estimates' of experienced people.

Table 1. The cost-benefit of wet season phosphorus (P) supplementation for a benchmark cattle property (Croydon, north Qld) in a phosphorus deficient region.

Variable	With dry season P supplementation	With wet season + dry season P supplementation
Animal Equivalents (AE)	4000	3600
Total cattle	6,032	4,828
Breeders mated	2,944	2,411
Female/total turnoff (%)	37	46
Gross margin per AE ($)	57	103
Herd gross margin ($)	228,000	372,000
Herd advantage to WS P supplement ($)		144,000

The economic benefit of phosphorus supplementation on a commercial cattle property has recently been evaluated for a 'typical' benchmark cattle property in the Croydon area of north Queensland where very low soil phosphorus leads to extensive and acute phosphorus deficiency of cattle given no phosphorus supplements. 'Best estimates' by experienced extension officers with knowledge of the region were used to estimate the required inputs and the changes in the herd structure and herd outputs from introduction of wet season phosphorus supplementation. The evaluation was done using the using the Breedcow / Dynama Herd Budgeting software program.

Assumptions for an established 'dry season phosphorus supplement' situation included: (i) a herd of 4,000 adult equivalents (AE) or 6,032 head including weaners, (ii) 2,944 breeders mated and a 43% weaning rate, (iii) annual breeder mortality of 7.9%, (iv) dry season supplements fed providing N and also 3 g P/breeder/day ($19 per breeder and $16 per heifer or steer), (v) steers sold at 42 months at 350 kg liveweight, and (vi) cull cows sold at 400 kg liveweight. Assumptions for a 'wet season plus dry season phosphorus supplement' situation included: (i) 10% less AE (3,600) to allow for the increased pasture intake of phosphorus supplemented cattle. Also a higher AE rating was used to account for the greater liveweight of cattle; the new herd comprised 4,828 head including weaners, (ii) 2,411 females mated and 53% weaning rate (i.e. a 10 percentage units or a 23% increase), (ii) annual breeder mortality of 4.2% (i.e. a 3.7 percentage units or 47% reduction in mortality rate), (iv) no change in the dry season supplement fed, (v) steers sold at 30 months at 360 kg liveweight, (v) cull cows sold at 420 kg liveweight. Additional input costs for wet season phosphorus supplementation included: (i) lick sheds and shipping containers for storage (capital cost $22,000), (ii) ongoing labour and vehicle costs ($3,970 per annum), and (iii) ongoing costs for the wet season phosphorus supplement at $13 per breeder and $9 per heifer or steer.

The economic analyses (Table 1) indicated that the wet season phosphorus supplementation in this situation was highly cost effective with an advantage (net of the new fixed costs) of $144,000 per annum for the property or $36 per AE of the herd before the management change. Other advantages would accrue if the wet season phosphorus supplementation allowed reduced dry season supplementation and easier handling of quieter cattle.

Another analysis of the economic benefits of phosphorus supplementation in the context of Central Queensland (Donaghy *et al.* 2010) also found very favorable economic benefits to phosphorus supplementation, comparable with those described above. Evaluation of the benefits from phosphorus supplementation in regions of marginal phosphorus status is more difficult. The increases in herd performance are likely to be lower, but so also the input costs since lesser amounts of phosphorus supplement will be required. Overall, these evaluations suggest that phosphorus supplementation is highly cost-effective where cattle are deficient in phosphorus.

A new approach to the estimation of requirements for phosphorus supplement

The calculated requirements of dietary phosphorus by various classes of cattle grazing tropical pastures have recently been revised (CSIRO 2007) based on studies of Ternouth *et al.* (1996) and Ternouth and Coates (1997). The estimated requirements are generally lower than those previously adopted. However, a difficulty with this approach is that the DM intake must be estimated for each specific situation. We have used F.NIRS data sets to estimate the diet DM digestibility corresponding to various rates of liveweight change of young growing cattle in the northern rangelands, and then based on CSIRO (2007) and QuikIntake estimated pasture intakes for both growing and breeder cattle. The phosphorus required for cattle in various rates of liveweight gain or loss, and for the pregnant and lactating cow, was calculated (Table 2).

Table 2. The estimated phosphorus (P) requirements of 400 kg steers and lactating cows calculated following CSIRO (2007) and likely threshold values for adequacy of dietary P requirements. Any net mobilization of P from body reserves will reduce these required amounts.

Liveweight gain (kg/day)	Estimated DM intake (kg/day)	Diet P required (g/day)	Diet P required (g/kg DM)	Faecal P required (g/kg DM)[A]	Faecal P/DietME required [B]	Faecal P/diet DMD required [C]
Steers						
-0.3	6.1	4	0.6	1.5	220	30
0	6.8	7	1.0	2.1	290	40
0.3	8.6	10	1.2	2.5	330	46
0.6	10.3	14	1.4	2.7	340	49
0.9	11.6	18	1.5	3.0	360	51
1.2	12.8	21	1.6	3.2	370	53
Lactating breeders[D]						
-0.3	8.2	13	1.6	3.1	430	60
0	9.5	17	1.7	3.3	420	60
0.3	10.7	20	1.9	3.5	410	59
0.6	12.0	23	1.9	3.6	400	57
0.9	13.3	27	2.0	3.7	380	55

Notes: [A], the concentration of P in faeces at which dietary P requirements are expected to be met. [B], the ratio of the concentration of P in faeces (mg P per kg faecal DM) to ME content of the diet (MJ ME per kg diet DM) at which dietary P requirements are expected to be met. [C], the concentration of P in faeces (mg P/kg DM) to the DM digestibility (%) of the diet at which dietary P requirements are expected to be met. [D], calculations assume 5 kg milk per day and 2 months pregnancy.

A second aspect to the new approach is to use the concentration of phosphorus in faeces to estimate the concentration of phosphorus in the diet. In cattle grazing tropical pastures there is a close relationship between diet and faecal phosphorus concentrations in cattle not fed phosphorus supplements, with faecal concentration about twice that in the diet. Estimation of DM intake and diet phosphorus concentration allows estimation of the phosphorus intake by grazing cattle (Table 2). Furthermore, the concentration of phosphorus in faeces, or the ratios of faecal phosphorus concentration to diet DM digestibility or diet metabolizable energy content provide 'threshold' values specific to classes of cattle below which phosphorus intake is likely to be lower than animal requirements. The amount of phosphorus supplement needed by the animal to meet current requirements can then be calculated by difference.

The role of bone phosphorus reserves

In cattle in replete phosphorus status there are about 7–8 g phosphorus/kg liveweight. Thus a 400 kg cow has about 3000 g phosphorus, and most is in bone. Experimentation from sheep, goats and dairy cows indicates that up to 40% of bone phosphorus in the replete animal may be mobilized to alleviate severe and prolonged phosphorus deficiency during late pregnancy and lactation, and the rate of mobilization can exceed 25 mg P/kg liveweight/day. Observations that growing cattle may not reduce voluntary intake until 2-4 months after a change to a phosphorus-deficient diet indicates that body reserves of phosphorus can also be used to alleviate dietary deficiencies in this class of animal. However, there is little information to estimate the rate and the interval over which mobilization of body reserves of phosphorus occurs in the northern Australian cattle, and most importantly in the breeder cow. Nevertheless, a conservative estimate that 20% of phosphorus reserves are mobilized would equate to 600 g phosphorus. This amount would be sufficient to provide 10 g P/day for a month at peak lactation plus 5 g P/day for a further 2 months, and thus make a major contribution to the phosphorus status of the breeder cow through the high requirements of late pregnancy and early lactation.

A South African study (Read *et al.* 1986a; 1986b; 1986c) where breeders grazed phosphorus deficient pasture for 5 years clearly demonstrated the role of body phosphorus reserves to alleviate the effects of dietary phosphorus deficiency. In initially phosphorus-replete heifers the provision of phosphorus supplements had only modest effects on metabolizable energy intake and liveweight during the first annual cycle. Effects of phosphorus supplementation on cow liveweight and calving rate were not observed until the second annual cycle, and effects on Pi and rib bone phosphorus composition not until the third annual cycle. The cows were apparently able to mobilize sufficient phosphorus reserves during the first annual cycle to avoid most of the effects of the diet deficiency.

Clearly if a cow mobilizes body phosphorus reserves to alleviate diet deficiency during late pregnancy and lactation, these body reserves must be replenished in late lactation and/or post-lactation before the next interval of high phosphorus demand. In the northern Australian context the cow which is calving in the early wet season each year will have limited opportunity to replenish reserves since late dry season pastures are generally low in phosphorus, although early weaning should allow increased replenishment. Cows which calve each second year should have ample opportunity for replenishment.

Metabolic control of phosphorus and mobilization of body phosphorus reserves depends primarily on the calcium status of the animal. A cow in dietary calcium deficiency can be expected to mobilize calcium from skeletal reserves to provide for this deficiency, and phosphorus will be mobilized even if dietary phosphorus intake exceeds the current requirements of the animal. Conversely, if intake of dietary calcium is in the excess of current animal requirements, the animal may not mobilize phosphorus, or will mobilize lesser amounts of phosphorus, even if the intake of phosphorous is less than the current requirements. Thus high calcium intakes, such as are likely to occur for stylo pastures with high Ca:P ratios (up to 20:1), may reduce mobilization of body phosphorus reserves. Also, because the concentration of phosphorus declines much more that that of calcium as tropical grass pastures mature, dry season pastures will often have elevated Ca:P ratios. A further implication is that inclusion of calcium as limestone in dry season supplements is not likely to be beneficial, and may even have adverse effects on the performance of grazing cattle if mobilization of phosphorus body reserves is reduced.

Diagnosis of phosphorus deficiency

Diagnosis of acute phosphorus deficiency is likely to be straight-forward when symptoms such as peg-leg, pica and bone chewing are observed or when soil is known to be uniformly phosphorus deficient. Diagnosis of sub-clinical deficiency associated with reduced cattle production is generally both more difficult and more important. Miller *et al.* (1990) outlined a useful decision tree approach to this problem.

In the growing animal not fed phosphorus supplements the concentration of inorganic phosphorus in blood (Pi) during the late wet or early dry seasons following the main interval of liveweight gain appears the most reliable diagnostic test. However defined sampling protocols (e.g. TCA precipitation of blood, adjustment for jugular or caudal vein sampling site) must be followed (Wadsworth *et al.* 1990; Coates 1995), and there are often serious obstacles to obtaining appropriate blood samples in commercial property situations. Pi primarily reflects intake of absorbed dietary phosphorus. Pi < 25 or 25-35 mg P/L indicates acute deficiency or deficiency respectively and a large response to phosphorus supplements. For Pi > 50 mg P/L only a low response, or no response, can be expected to phosphorus supplements. Associated F.NIRS evaluation of the diet quality indicates potential liveweight gain as constrained by diet metabolizable energy and nitrogen concentrations.

In lactating cows satisfactory reproductive performance can be maintained when Pi is as low as 30 mg P/L, and possibly at even lower Pi concentrations. The lactating cow can apparently often mobilize sufficient phosphorus from body reserves to maintain performance even when Pi is very low. In cows in late pregnancy and lactation the most appropriate diagnosis is likely to be by measurement of the concentration of phosphorus in faeces of animals not fed phosphorus supplements to estimate the concentration of phosphorus in the diet pasture selected. Estimation of the phosphorus status will require consideration of the expected phosphorus requirement of the animal (from estimates of the metabolizable energy intake derived from F.NIRS) and the potential for mobilization of phosphorus from body reserves to provide for dietary deficiency of phosphorus at least over restricted intervals. In addition the Pi of growing steers or non-pregnant heifers in the same herd should provide a diagnosis. Where herds are being fed phosphorus supplements, the removal of supplements for 1-2 weeks before blood or faecal sampling should allow the Pi or faecal P concentrations to decrease and to be similar to cattle not fed phosphorus supplements, and thus allow satisfactory diagnosis.

Likely responses to phosphorus supplements

Whether cattle in a specific situation respond to phosphorus supplements, and the magnitude of this response, depends on numerous factors, but the principal issue is whether phosphorus is the first-limiting nutrient. The majority, or all, of the annual response in growing cattle occurs during the wet and wet-dry transition seasons. Dry season pastures are usually primarily deficient in nitrogen or available energy, not phosphorus. In addition, because animal responses generally depend on an increase in voluntary intake of pasture, responses will only occur when there is sufficient pasture available for cattle to be able to increase their pasture intake when phosphorus supplements are given.

Indicative estimates of the cattle responses to phosphorus supplements (Table 3) are based on reported trials (Winks 1990; Miller *et al.* 1998), observation and experience. Clearly responses have varied widely between trials and between years within a trial, and sometimes were less than or occasionally much greater than indicated (e.g. up to 130 kg liveweight per annum).

Established recommendations (McCosker and Winks 1994) are that phosphorus supplements should be fed to growing cattle only during the wet and the wet-dry transition seasons when pasture quality is sufficient for liveweight gain. In addition they should be fed during the dry season to lactating breeders with their high demand for phosphorus for milk production. However, recent knowledge suggests that benefits can also be expected from dry season phosphorus supplementation of breeders post-lactation. First, the evidence from other ruminants indicates that there is normally extensive deposition of phosphorus into bone reserves in late lactation and post-lactation, and extensive mobilization of phosphorus from bone reserves in late pregnancy and early to mid lactation. Although there is little experimental evidence for the northern breeder cow, it is likely that in late pregnancy such breeders grazing dry season pastures can deposit additional supplementary phosphorus into bone reserves which can be subsequently mobilized during the wet season. Regardless of the extent of deposition of phosphorus, provision of supplementary phosphorus to the late pregnant cow grazing dry season pasture should allow the high phosphorus demands of the foetus to be met without the need to mobilize bone reserves, and thus improve the overall phosphorus status of the reproducing cow for lactation. Second, de Brouwer *et al.* (2000) have demonstrated substantial production benefit to dry season supplementation of breeder cows grazing phosphorus deficient pastures. Clearly more experimental information is needed.

Table 3. Indicative estimates of increases in production due to feeding phosphorus (P) supplements to cattle grazing wet season pastures of good quality and adequate availability.

Indicative measurement or variable	Acutely deficient or very deficient	Deficient	Marginal
Soil, plant and animal estimators			
Soil P ($P_{B\ ppm}$) [A]	< 4	4 - 6	7 - 8
Plant P (mg P/g DM)	< 0.5	0.5 - 1.0	1.0 - 1.5
Diet g P/MJ ME in the diet	180 - 240	240 - 300	300 - 360
Faecal mg P/g diet DM digestibility	2.5 - 3.0	3 - 4	4 - 5
Blood Pi of growing cattle (mg/L) [B]	< 25	25 - 35	35 - 45
Likely liveweight change response of growing cattle (kg/annum)			
Native pasture	40 - 60	20 - 40	0 - 20
Stylo pasture	------	40 - 80	0 - 40
Stylo pasture + moderate P fertilizer	------	0 - 20	nil
Likely response of breeder cattle grazing native pastures			
Weaning rate (%)	10 - 30	10 - 30	nil - 10
Calf weaning weight (kg)	10 - 30	5 - 15	0 - 10

[A], $P_{B\ ppm}$, bicarbonate extractable phosphorus. [B], Pi, concentration of inorganic phosphorus in blood.

R D & E areas with greatest potential to deliver productivity and efficiency gains

There is extensive evidence that more effective management of phosphorus nutrition can provide large herd productivity gains through improved reproductive performance and growth in many regions of the rangelands of northern Australia.

Major obstacles to more widespread and effective use of phosphorus supplementation appear to be lack of recognition of the importance of phosphorus and the economic returns to supplementation, knowledge of the phosphorus status of cattle in specific situations, and the cost of supplementation. These are associated with the difficulty to definitively diagnose sub-clinical phosphorus deficiency. Advances in understanding the role of phosphorus concentration in faeces and in blood to estimate diet phosphorus intake, and F.NIRS to estimate metabolizable energy and nitrogen in the diet, provide opportunity to improve diagnosis. However more robust information is needed for reliable predictions of phosphorus intake across northern Australian rangeland systems.

Research is needed to improve understanding of the extent to which short-term dietary deficiencies of phosphorus are alleviated by mobilization of body phosphorus reserves, particularly in the breeder cow. Improved understanding is needed of the efficacy of phosphorus supplementation during the dry season to preserve body phosphorus reserves in the late pregnant cow, when body reserves of phosphorus are repleted from phosphorus ingested in supplements and/or in forage, and whether repletion occurs during the dry season and particularly in the breeder cow. The benefits of phosphorus supplementation in relation to timing and to amounts (including dose-response curves) need to be more clearly defined for the variety of circumstances which occur in the industry.

From an on-property perspective, innovative approaches are needed to improve supplement delivery systems during the wet season when the nutritional demands of cattle for phosphorus are greatest. It is suggested that D & E should focus on encouraging adoption with emphasis on better targeting of the classes of animals with most favourable cost/benefit, the need for herd records, the assembly of case studies where managers have successively addressed nutritional phosphorus deficiency, and on on-property demonstrations to demonstrate the implementation and benefits of phosphorus supplementation.

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References

Coates DB (1995) Effect of phosphorus as fertiliser or supplement on the forage intake of heifers grazing stylo based pastures. *Australian Journal of Experimental Agriculture* **35**, 181-188.

Coates DB, Ternouth JH (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.

CSIRO (2007) Nutrient Requirements of Domesticated Ruminants. CSIRO Publishing, Melbourne, Australia.

de Brouwer CHM, Cilliers JW, Vermaak LM, van der Merwe HJ, Groenewald PCN (2000) Phosphorus supplementation to natural pasture grazing for beef cows in the Western Highveld region of South Africa. *South African Journal of Animal Science* **30,** 43-52.

Donaghy P, Gowen R, Star M, Murphy K, Sullivan M, Best M (2010) Strategies to improve the profitably of extensive grazing systems in central Queensland. DEEDI, Queensland Government.

McCosker T, Winks L (1994) Phosphorus Nutrition of Beef Cattle in Northern Australia. Department of Primary Industries, Brisbane, Australia.

Miller CP, Coates DB, Ternouth JH, White SJ (1998) Phosphorus management for breeding cattle in northern Australia. Final Report Project DAQ093. Meat and Livestock Australia, North Sydney, NSW 2059.

Miller CP, Winter WH, Coates DB, Kerridge PC (1990) Phosphorus and beef production in northern Australia. 10. Strategies for phosphorus use. *Tropical Grasslands* **24**, 239-249.

Read MVP, Engels EAN, Smith WA (1986a) Phosphorus and the grazing ruminant. 2. The effects of supplementary P on cattle at Glen and Armoedsvlakte. *South African Journal of Animal Science* **16,** 7-12.

Read MVP, Engels EAN, Smith WA (1986b) Phosphorus and the grazing ruminant. 3. Rib bone samples as an indicator of the P status of cattle. *South African Journal of Animal Science* **16,** 13-17.

Read MVP, Engels EAN, Smith WA (1986c) Phosphorus and the grazing ruminant. 4. Blood and faecal grab samples as indicators of the P status of cattle. *South African Journal of Animal Science* **16,** 18-22.

Ternouth JH, Bortolussi G, Coates DB, Hendricksen RE, McLean RW (1996) The phosphorus requirements of growing cattle consuming forage diets. *Journal of Agricultural Science, Cambridge* **126,** 503-510.

Ternouth JH, Coates DB (1997) Phosphorus homoeostasis in grazing breeder cattle. *Journal of Agricultural Science, Cambridge* **128,** 331-337.

Wadsworth JC, McLean RW, Coates DB, Winter WH (1990) Phosphorus and beef production in northern Australia. 5. Animal phosphorus status and diagnosis. *Tropical Grasslands* **24**, 185-196.

Winks L (1990) Phosphorus and beef production in northern Australia. 2. Responses to phosphorus by ruminants: a review. *Tropical Grasslands* **24**, 140-158.