

final report

Project code: B.NBP.0540
Prepared by: Désirée Jackson
Department of Agriculture,
Fisheries and Forestry
Date published: November 2012
ISBN: 9781741919592

PUBLISHED BY
Meat & Livestock Australia Limited
Locked Bag 991
NORTH SYDNEY NSW 2059

Producer phosphorus manual for the northern cattle industry

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

This publication is published by Meat & Livestock Australia Limited ABN 39 081 678 364 (MLA). Care is taken to ensure the accuracy of the information contained in this publication. However MLA cannot accept responsibility for the accuracy or completeness of the information or opinions contained in the publication. You should make your own enquiries before making decisions concerning your interests. Reproduction in whole or in part of this publication is prohibited without prior written consent of MLA.

Abstract

The *Feeding phosphorus to northern beef cattle* manual is a new guide for producers, building on the previous McCosker and Winks (1994) book on phosphorus feeding in northern Australia. Recent research on the phosphorus nutrition of cattle, captured in a review by Coates and Dixon (2011), has been used to update the information and recommendations for phosphorus management of grazing beef cattle in northern Australia. This phosphorus feeding manual is therefore a compilation of all of the scientific and practical knowledge on phosphorus management of cattle in northern Australia. The manual also comprises outcomes distilled from the phosphorus review, new methods for testing phosphorus status of grazing cattle, and case studies which clearly demonstrate the benefits of phosphorus supplementation using practical industry experience and associated economic analyses. This revised edition is written in a user-friendly format to allow easy access of information. This project also clearly identified those areas of phosphorus nutrition and its management that need further attention through research and adoption.

Executive Summary

Phosphorus is one of the most important nutritional deficiencies in grazing beef cattle in northern Australia. Despite the importance of phosphorus to productivity and considerable research and advisory efforts, the adoption of phosphorus supplementation (particularly during the wet season) appears to remain much lower than expected.

Confusion about the recommendations for feeding and the practical difficulties in getting lick out to cattle during the wet, the tests required to determine animal phosphorus status, and doubts about the economic returns from feeding, all contribute to poor uptake of phosphorus supplementation in northern Australia.

The McCosker and Winks (1994) book on phosphorus feeding in northern Australia provided valuable information on phosphorus nutrition of cattle. However, since its publication, new research on phosphorus feeding and testing have led to changes in management and feeding recommendations. In addition, producers needed a book that was easy to follow and where information was readily accessible.

A literature review on the phosphorus nutrition of grazing cattle in northern Australia was completed by Coates and Dixon (2011), which identified and discussed all phosphorus research that has been conducted since publication of the McCosker and Winks (1994) book. The key findings in the literature review were distilled and incorporated into the new *Feeding phosphorus to northern beef cattle* manual.

This manual provides producers with an easy-to-read, complete guide of information to assist with the phosphorus management of their cattle. It incorporates new research outcomes, including updated recommendations for feeding, as well as detailed property case studies where the benefits of phosphorus supplementation were clearly identified for both animal performance and profitability.

From the literature review and the compilation of the new phosphorus manual, a number of knowledge gaps were identified as well as avenues for improving the adoption of phosphorus management. Some of the key areas of research which can contribute to more effective phosphorus supplementation include:

- the prediction of phosphorus intake from faecal measurements and the effects of phosphorus supplementation on faecal phosphorus levels;
- improving the knowledge of the carry-over effects associated with deposition and mobilisation of phosphorus in both breeders and growing animals; and
- the efficacy of dry season supplementation on bone repletion in breeders.

Uptake of effective phosphorus management practices can be improved through:

- more clearly defining the cost-benefits of wet season P supplementation;
- on-property demonstration sites employing faecal P monitoring in conjunction with NIRS as a management tool for determining P status of animals and supplementary P requirements; and
- demonstrating the effectiveness of wet season phosphorus supplementation.

Further work to identify the key drivers that will motivate producers to implement phosphorus supplementation, particularly during the wet season, needs to be undertaken. This is because the considerable extension and advisory efforts by beef officers and consultants that clearly show the economic benefits from phosphorus supplementation hasn't resulted in the expected increase in uptake of phosphorus supplementation practices.

The immediate benefits of adopting improved phosphorus supplementation management include:

- reduced breeder mortality;
- improved weaning weights and reduced age-of-turn off; and
- improved cull cow weights.

The most important long-term benefits include an increase in herd fertility which will lead to surplus females for sale, at heavier weights, leading to increased gross income.

The phosphorus manual is an easy-to-read, practical book that will be a useful reference to all northern beef producers, agricultural students, beef advisors and consultants, and feed companies to gain a better understanding of the practical management of phosphorus nutrition of beef cattle.

Contents

1	Background.....	6
2	Project objectives	6
3	Methodology	6
4	Results and discussion.....	7
5	Success in achieving objectives	7
6	Impact on meat and livestock industry – Now and in five years time.....	8
6.1	Impact on meat and livestock industry – immediate.....	8
6.2	Impact on meat and livestock industry - 5 years' time.....	8
7	Conclusions and recommendations	8
7.1	Research	8
7.2	Extension and adoption.....	8
8	Bibliography.....	9
9	Appendices	10
9.1	Appendix 1	10

1 Background

It is well-documented that phosphorus is one of the most important nutrients in beef cattle grazing in northern Australia (Underwood 1966, cited in Winks 1990). However, despite all of the information available, adoption rates of phosphorus supplementation, particularly wet season supplementation, are low. There have been inconsistencies in the recommendations provided to producers for feeding as well as the practical difficulties producers are faced with on-property in getting lick out to cattle during the wet. The rising cost of phosphorus supplements has only further increased producers' scepticism about the economic returns from feeding phosphorus.

There has been significant research on animal phosphorus requirements as well as technologies to determine animal phosphorus status since the original phosphorus supplementation book was written by McCosker and Winks (1994). In addition, there are many producers across northern Australia who have since implemented phosphorus management practices that are profitable and effective. There was also a need to simplify and collate the latest research and technologies into practical management recommendations, and to provide proof of profit testimonials from producers who have successfully implemented phosphorus nutrition management plans on a geographically diverse range of properties.

2 Project objectives

Produce a producer-friendly publication on phosphorus supplementation of beef cattle for Northern Australian beef producers.

Complete an up-to-date literature review on phosphorus nutrition and supplementation.

Complete at least 6 cost-benefit analyses of wet season phosphorus supplementation for major regions in northern Australia.

Complete at least 6 case studies of producers who have used innovative methods to provide supplementation over the wet season or who have used data to demonstrate improved financial performance and animal productivity.

3 Methodology

Key beef extension and research officers from Queensland Department of Agriculture, Fisheries and Forestry, Northern Territory Department of Resources and the Western Australia Department of Agriculture and Food were identified to produce an updated and revised phosphorus feeding manual based on the latest research findings. The project team members represented the major geographical regions across northern Australia and have high levels of technical expertise and experience.

A literature review was conducted by Coates and Dixon (2011), from which key findings were distilled and incorporated into the manual.

The project team members developed case studies in conjunction with regionally diverse properties across northern Australia, to provide examples of best practice management of phosphorus supplementation, and associated benefits in increased production and profitability.

Collectively, the team identified the key areas where there were knowledge gaps in phosphorus supplementation in conjunction with the phosphorus literature review. Additionally, the team identified a number of issues associated with poor adoption of phosphorus supplementation and avenues for improving its uptake.

4 Results and discussion

There has been confusion in the northern beef industry about the recommendations for feeding phosphorus to cattle in conjunction with a number of other factors which have raised doubts about the benefits of phosphorus supplementation. This has contributed to the low level of adoption of effective phosphorus nutrition of cattle in northern Australia.

The literature review conducted by Coates and Dixon (2011) provides clearer guidelines for phosphorus supplementation. The literature review also showed that in addition to using faecal phosphorus as an indication of the dietary phosphorus status of cattle, the relationship between phosphorus and metabolisable energy provides a better indication of whether there is sufficient phosphorus in the diet. Current commercial testing uses a phosphorus and protein ratio. One immediate outcome from the review was that commercial testing has implemented its recommendation for using the relationship between phosphorus and metabolisable energy in future analyses of faecal NIRS

The phosphorus management manual that was produced is relevant to all phosphorus-deficient areas of northern Australia. It sets out general guidelines for phosphorus supplementation and management that may need to be adapted for each producer's property, taking into account regional differences such as freight, level of response expected to supplementation depending on the degree of phosphorus deficiency.

The producer case studies were conducted on different land types and geographically diverse areas to provide evidence of the production and economic benefits from effective phosphorus management. These properties implemented an effective phosphorus supplementation program despite the significant obstacles that some of these properties had to overcome to implement their management.

5 Success in achieving objectives

The project team has put together a comprehensive, practical manual on phosphorus supplementation in northern Australia. To ensure that the latest relevant phosphorus research findings were incorporated into the book, a comprehensive literature review on phosphorus nutrition was completed by Coates and Dixon (2011). In addition, detailed case studies were developed for 6 properties across northern Australia to clearly demonstrate the production and economic benefits of effective phosphorus supplementation practices. The information in the manual is easy to read, and will be a useful reference for a number of stakeholders including: producers, beef advisors and consultants, feed company nutritionists and agricultural students.

A number of knowledge gaps in phosphorus nutrition requiring further research were identified, as well as areas for improving the level of adoption of phosphorus supplementation in northern Australia.

6 Impact on meat and livestock industry – Now and in five years time

6.1 Impact on meat and livestock industry – immediate

Incorporation of phosphorus supplementation during the wet season will improve breeder body condition, leading to reduced breeder mortality. In addition, milk production will be increased, leading to improved weaning weights and reduced age-of-turnoff of weaners.

The reduction in mortality will enable producers to cull more heavily on pregnancy status. Those breeders that are culled will be heavier due to the supplementation. More surplus females coupled with heavier sale weights, will improve gross income. In initial years, this result will compensate for the extra cost of phosphorus supplementation. In subsequent years, this will be reflected in improved profits.

6.2 Impact on meat and livestock industry - 5 years' time

The longer term benefits will be improved fertility and improved weaning rates. This will allow producers to reduce stock numbers without affecting profitability as non-performers will be culled from the herd and more selection pressure placed on the breeding herd.

The sale weights of cull cows will increase, leading to improved gross margins from sale cattle.

7 Conclusions and recommendations

7.1 Research directions

1. Develop the prediction of phosphorus intake from the faecal measurements and combine with the P-screen approach as a means to validate results.
2. Improve the knowledge of the carry-over effects associated with deposition and mobilization of phosphorus in both breeders and growing animals (eg. effects of moving cattle between high-P and low-P land systems on P body reserves, and the effect of weaning to allow the breeder to recover body P reserves.
3. Investigate the bioavailability of various phosphorus sources for livestock feeding.
4. Determine the impact of phosphorus supplementation on faecal phosphorus levels.
5. Investigate the efficacy of bone P repletion through dry season supplementation in late pregnant breeders.
6. Improvement of phosphorus supplementation delivery processes during the wet season to increase the level and consistency of phosphorus intake.
7. More clearly define the cost-benefits of wet seasons P supplementation of various classes of cattle.

7.2 Extension and adoption

1. There is a need to explore various avenues to improve the adoption of phosphorus supplementation in the northern beef industry. There is sufficient information available on the technical aspects and production and economic benefits of phosphorus supplementation. Also, past Producer Demonstration Site (PDS) projects have demonstrated the benefits of good phosphorus management to raise awareness and

increase adoption, yet the uptake of phosphorus supplementation remains low, particularly the wet season. Additionally, there has been significant extension work and advice given by beef advisors to emphasize the economic benefits of phosphorus supplementation, and this hasn't resulted in widespread adoption. Other avenues for improving adoption need to be examined, as well as the drivers for change in the northern beef industry.

2. It has been a while since there were PDS's to highlight the benefits of wet season P feeding on animal growth, condition, fertility, and profitability through reduced age of turnoff and sale of surplus females. Because quite a number of properties have changed hands through property sales and succession, renewed focus on the use of PDS sites to raise new awareness of phosphorus supplementation would be timely.
3. Revision of educational and training notes such as the Nutrition EDGE workshop notes is required to reflect the new information in phosphorus manual. Specifically, in northern Australia where Nutrition EDGE workshops are run, further emphasis needs to be given to phosphorus nutritional management of cattle.
4. Further demonstration of faecal P monitoring in conjunction with NIRS as a management tool for determining P status of animals and resulting P supplementary requirements is needed.

8 Bibliography

Dixon, R, Coates D, Holmes B, English B, Rolfe J (2011) Phosphorus nutrition and management – overcoming constraints to wider adoption. In *Proceedings of the Northern Beef Research Update Conference*, 2011, 102-109.

Hasker PJS (2000) Beef cattle performance in northern Australia: a summary of recent research. Department of Primary Industries, Queensland, Brisbane.

McCosker T and Winks L (1994) Phosphorus Nutrition of beef cattle in northern Australia. Department of Primary Industries, Queensland, Brisbane.

Underwood, E (1966) *The Mineral Nutrition of Livestock*. CAB: Farnham Royal.

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

9 Appendices

9.1 Appendix 1

A review of phosphorus nutrition of cattle in northern Australian grazing systems

Rob Dixon^A and David Coates^B

© The State of Queensland through its Department of Employment, Economic Development and Innovation [2010]

- ^A, Agri-Science Queensland, Department of Employment, Economic Development and Innovation,
PO Box 6014, Rockhampton Qld 4702 Australia.
Phone: (07) 49360339 Fax: (07) 49360390 Email: rob.dixon@deedi.qld.gov.au
- ^B, Davies Laboratory, CSIRO Sustainable Ecosystems,
PO, Aitkenvale, Qld 4814 Australia.
Phone: (07) 47538545 Email: david.coates@csiro.au

Table of Contents

Summary

1. Introduction
2. Scope of the review
3. The requirements of cattle for dietary P
4. Estimation of the P status of grazing cattle
 - 4.1. A new approach for grazing cattle
 - 4.2. The concentration of P in the diet and the concentration of P in faeces
 - 4.3. ME intake from faecal NIRS measurements
 - 4.4. P status from the ratio of the concentration of P in faeces to the ME content of the diet
 - 4.5. Calculating requirements for supplementary P
 - 4.6. P status from the ratio of the concentration of P in faeces to the N concentration of the diet or the N concentration in faeces
5. Storage and availability of P in body reserves of the animal
 - 5.1. General
 - 5.2. Experimental approaches
 - 5.3. Rates of deposition and mobilization of body P and Ca reserves in growing and non-reproducing mature ruminants
 - 5.4. Rates of deposition and mobilization of body P reserves in reproducing ruminants
 - 5.5. The extent to which P body reserves can be mobilized to alleviate insufficient diet P
 - 5.6. The role of Ca and N on the rates of net deposition or mobilization of body P reserves
 - 5.7. Estimation and speculation of the likely magnitude of deposition and mobilization of body P reserves of cattle in northern Australian grazing systems
6. Concentration of inorganic P in blood (Pi) to estimate the P status
 - 6.1. Pi in growing cattle
 - 6.2. Pi in breeder cattle
7. Production responses to increases in diet P
8. P as a substrate in rumen microbial digestion
9. Delivery systems for P supplements
10. Concluding comments
11. References

Summary

1. The importance of P as a nutrient and the serious adverse effects of dietary P deficiency in cattle are well known and have been comprehensively described in previous reviews. The present review focuses on developments during the last 2 decades in P nutrition, and some aspects of P metabolism not addressed in earlier Australian reviews and which we consider pertinent to cattle grazing northern Australian pastures.
2. The nutritional requirements of cattle for P can be calculated using the current Australian feeding standards (CSIRO 2007) as a function of the expected mature weight of the animal (standard reference weight), current liveweight, productivity (as growth, milk, conceptus, etc), and DM intake.
3. A new approach was developed to estimate the P intake of grazing cattle. Recent experimental results indicate that dietary P concentration is closely related to faecal P concentration in unsupplemented cattle grazing tropical pastures. The faecal P concentration and the faecal P concentration per MJ ME concentration in the diet, required by various classes of cattle to obtain their dietary P requirements were calculated using CSIRO (2007) equations. The ME concentration of the diet can be measured using FNIRS, and the P concentration of faeces measured by wet chemistry. Thus the P adequacy of the diet selected by grazing cattle can be estimated.
4. The concentration of inorganic P in blood (Pi) is related to P intake. Pi provides a reliable indication of whether growing cattle will respond to P supplements. Interpretation of Pi in reproducing cattle is complex.
5. The skeleton provides P stores which the animal can potentially mobilize to alleviate dietary P deficiency. Studies in sheep, goats and dairy cows indicate that extensive mobilization of P often occurs as an adaptive mechanism to provide for the high demands during late pregnancy and lactation, and likely occurs to a lesser extent in non-reproducing cattle. Two studies suggest extensive mobilization of P occurs in beef cows grazing northern Australian pastures. Also deposition of P into skeletal reserves apparently occurs when P is in excess of immediate needs of the animal is available from the diet. The extent to which P stores are mobilized may be affected by interactions between P, Ca, N and ME intake.
6. In numerous experiments production responses to P supplementation have ranged from nil to large increases in growth and reproduction rates. It has been suggested that P supplements fed with low quality dry season pastures can affect animals adversely. We conclude that any such effects are more likely to be due to contamination of the sources of supplementary P used in those experiments.
7. P deficiency causes large reductions in voluntary intake of DM and thus ME intake. The efficiency of microbial crude protein synthesis (MCP) per MJ ME is also reduced by P deficiency. Thus absorbed amino acid supply to the animal is reduced markedly by the additive effects of lower ME intake and lower efficiency of MCP synthesis. In cattle grazing tropical pastures absorbed amino acid supply is often marginal for cattle productivity. P deficiency may have serious adverse effects further reducing supply of absorbed amino acids.
8. There are many aspects of P nutrition of cattle grazing northern Australia pastures which are poorly understood. Given the occurrence and importance of P nutrient deficiencies in further R, D&E appears necessary.

1. Introduction

The metabolism and importance of P and Ca in the nutrition of ruminants has been reviewed comprehensively from various perspectives (Hemmingway 1967; Cohen 1980; Horst 1986; Scott 1986; Ternouth 1991; Breves and Schroder 1991; AFRC 1991; Yano *et al.* 1991; Breves *et al.* 1995; Karn 2001; Block *et al.* 2004; Sehested 2004). The series of papers arising from a major workshop held in Townsville in 1988 (*Tropical Grasslands* 1990, volume 24, number 3), and the book *Phosphorus Nutrition of Beef Cattle in Northern Australia* by Terry McCosker and Lyle Winks published in 1994 provide overviews of the R&D, and practical perspectives, of the role of P in the nutrition of cattle in northern Australia at that time. A comprehensive meta-analysis of the nutrition and metabolism of P in ruminants by Bravo *et al.* (2003a,b,c) provides an excellent review of the factors influencing digestion, absorption excretion and quantitative flows of P in the animal, albeit with a bias towards European and north American livestock systems.

The metabolism and principal pathways of digestion, absorption and excretion of P in faeces and urine have been described. In brief, most (on average about 75%) P in forages is digested and absorbed from the gastrointestinal tract. When the P in feedstuffs is present as phytates the availability of the P is substantially reduced in monogastric animals and may also be reduced in ruminants (Bravo *et al.* 2003b), but this is not likely to be an issue with forages in northern Australian systems. The P in supplements may be of higher or lower availability than the P in forages depending on the source. Absorbed P passes to the blood inorganic phosphate pool. A large amount of inorganic P in the blood is transferred (recycled) to the rumen in saliva and in grazing ruminants is usually much greater than the P intake. At low to moderate P intakes almost all excretion of P is via faeces, and this is in part an obligatory loss. At high P intakes urine becomes an important pathway of P excretion.

Deficiency of dietary P can have large effects on animal health and animal productivity. Clinical symptoms of P deficiency such as abnormalities associated with skeletal structure and abnormal ingestive behaviour (pica, bone chewing) are thoroughly discussed by McCosker and Winks (1994). In highly P-deficient land systems the productivity of cattle is usually reduced severely and the problem may be obvious. Often the more difficult situation to evaluate is where cattle productivity as growth and reproduction is lower than expected and subclinical P deficiency is suspected, but the symptoms of P deficiency are not obvious. P deficiency in cattle is typically associated with reduced voluntary intake of forage (e.g. by up to 50%) and microbial protein synthesis in the rumen, and poor productivity. The effects of P deficiency on the animal seem to be mediated primarily through effects at the metabolic level rather than through direct effects on rumen digestion. The metabolism of P is closely linked to the metabolism of Ca as these two minerals form a large and essential component of bone and tend to be required by the animal for this purpose in a defined ratio. Thus there are interactions between the metabolism of P and Ca, and the P in bones can provide a reserve for animals through intervals of dietary P shortage akin to the fat reserves and energy requirements of the animal.

2. Scope of the review

The present review focuses on aspects of P in the nutrition of grazing cattle where considerable new information has become available during the last 2 decades. These aspects include consideration of the CSIRO (2007) revised estimates of P requirements of cattle, re-examination of estimation of dietary P concentration from faecal P concentration, the role of faecal NIRS technology, the role of body P reserves to buffer intervals of low dietary P in various circumstances and seasons of annual cycles of cattle in northern Australia and the likelihood of benefits to dry season supplementation. The review does not address aspects of P in the northern cattle industry which were comprehensively reviewed in

the publications cited above and for which there appears to be little new information since 1990. For example, the information on soils, mapping of soils and vegetation, variation in the concentrations of P in forages, associations between vegetation and likely soil P status, and symptoms of P deficiency in cattle appear complete. Also, although the availability of P in various supplements (or potential P supplements) may vary widely we understand the issue is being addressed in another review currently contracted by Meat and Livestock Australia, and therefore will not be addressed in the present review.

3. The requirements of cattle for dietary P

CSIRO (2007) provides a comprehensive discussion and, based on research on tropical pastures (Ternouth *et al.* 1996; Ternouth and Coates 1997), revised 'best estimates' of the requirements for P and Ca of cattle. Requirements for maintenance, growth, pregnancy and lactation are described as functions of current LW, standard reference weight, LW gain, DM intake, stage of pregnancy and amount of milk produced. A spreadsheet program available at www.pi.csiro.au./grazplan can be used to calculate requirements as a function of these variables. These estimates supersede those given in ARC (1980), AFRC (1990) and CSIRO (1990), and are somewhat lower.

The dietary P requirements for growing steers for ranges in LW and growth (Tables 1) were calculated using the spreadsheet above. Diet DM intake of steers was estimated from the LW and LW gain of the animal using spreadsheet QuikIntake (McLennan, unpublished). This spreadsheet calculates DM intake from a description of the animal and the LW change, but requires as an input an estimate of the diet DMD. The relationship between LW change and DMD in a large data set (ADG7) where FNIRS measurements were made in cattle in northern Australia (Coates 2004) was used to estimate the DMD for each value of LW change between -0.3 and +1.2 kg/day and for steers ranging in LW from 150 to 600 kg. Absorption of P was assumed to be 0.75 (Ternouth and Coates 1997) rather than the 0.70 used in CSIRO (2007). The P concentration in faeces equivalent to each P concentration in the diet when the dietary requirement was met was calculated from the relationship described in section 4.2 (Fig 1) below. As discussed therein this relationship may not be reliable when diet P concentrations are greater than about 2.2 g P/kg DM. Thus the estimated concentration of P in faeces equivalent to the dietary requirement may not be reliable when requirements are high, such as for smaller animals in high LW gain (e.g. a 200 kg animal growing at greater than 0.9 kg/day, or a 300 kg animal growing at 1.2 kg/day). For such animals the concentration of P in faeces is likely to underestimate the concentration of P in the diet. The ratio of faecal P concentration to ME concentration in the diet (the M/D of the diet) was calculated from the DMD used in the QuikIntake spreadsheet calculations. Also the ratio of the diet DMD to the faecal P concentration was calculated.

Table 1. The estimated P requirements of growing steers 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.

THE VALUES IN THIS TABLE ARE NOT FINAL & ARE LIKELY TO BE REVISED

Liveweight (kg)	Liveweight gain (kg/day)	Estimated DM intake (kg/day)	Diet P required (g/day)	Diet P required (g/kg DM)	Requirement FaecP (g/kg DM)	FaecP/DietME (mg /MJ ME)	DietDMD /FaecP (g/g)
150	-0.3	3.1	0	0.0	0.5	70	1050
150	0	3.4	3	0.9	2.0	270	260
150	0.3	4.6	7	1.5	3.0	390	180
150	0.6	5.6	11	1.9	3.6	450	160
150	0.9	6.6	14	2.2	4.0	480	150
150	1.2	7.4	18	2.4	4.4	510	140
200	-0.3	3.9	1	0.2	0.9	130	570
200	0	4.3	4	0.9	2.0	280	260
200	0.3	5.6	8	1.4	2.7	360	200
200	0.6	6.8	11	1.7	3.2	410	170
200	0.9	7.8	15	1.9	3.6	440	160
200	1.2	8.8	19	2.1	3.9	450	150
300	-0.3	5.4	2	0.5	1.3	190	390
300	0	6.0	6	0.9	2.0	280	260
300	0.3	7.7	9	1.2	2.5	330	220
300	0.6	9.2	13	1.4	2.8	360	200
300	0.9	10.5	17	1.6	3.1	370	190
300	1.2	11.6	20	1.7	3.3	380	180
400	-0.3	6.8	4	0.6	1.5	220	330
400	0	7.5	7	0.9	2.1	280	250
400	0.3	9.6	11	1.2	2.4	310	230
400	0.6	11.4	15	1.3	2.6	330	210
400	0.9	12.9	18	1.4	2.8	340	210
400	1.2	14.2	22	1.5	3.0	350	200
500	-0.3	8.2	6	0.7	1.7	240	300
500	0	8.9	9	1.0	2.1	290	250
500	0.3	11.3	13	1.1	2.3	310	230
500	0.6	13.2	16	1.2	2.5	320	220
500	0.9	14.8	20	1.3	2.7	330	220
500	1.2	16.2	23	1.4	2.8	330	210
600	-0.3	9.5	7	0.7	1.8	250	290
600	0	10.2	10	1.0	2.1	290	250
600	0.3	12.6	14	1.1	2.3	300	230
600	0.6	14.6	18	1.2	2.5	310	230
600	0.9	16.3	21	1.3	2.6	320	220
600	1.2	17.6	24	1.4	2.8	320	220

Requirement FecP (g/kg DM), the concentration of P in faeces at which dietary requirements should be met;
 Ratio FaecP/Diet ME (mg/MJ ME), the ratio of the concentration of P in faeces (mg/kg) to ME content of the diet at which dietary requirements should be met;

Table 2. The estimated P requirements of lactating breeders producing 5 kg milk/day 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.

THE VALUES IN THIS TABLE ARE NOT FINAL & ARE LIKELY TO BE REVISED

Liveweight (kg)	Liveweight gain (kg/day)	Estimated DM intake (kg/day)	Diet P required (g/day)	Diet P required (g/kgDM)	Requirement FecP (g/kgDM)	FecP/DietME (mg/MJME)	DietDMD /FaecP (g/g)
350	-0.3	8.3	13	1.6	3.0	420	170
350	0	10.1	17	1.6	3.2	400	180
350	0.3	11.8	20	1.7	3.3	390	180
350	0.6	13.6	24	1.8	3.4	370	190
350	0.9	15.3	28	1.8	3.4	350	200
400	-0.3	9.1	14	1.5	3.0	410	180
400	0	10.5	17	1.6	3.2	400	180
400	0.3	11.9	21	1.7	3.3	390	180
400	0.6	13.3	24	1.8	3.4	370	190
400	0.9	14.8	27	1.9	3.5	360	190
450	-0.3	12.6	16	1.3	2.6	360	200
450	0	14.4	20	1.4	2.8	350	200
450	0.3	16.2	24	1.5	2.9	340	210
450	0.6	18.1	27	1.5	3.0	320	210
450	0.9	19.9	31	1.6	3.0	310	220

Requirement FecP (g/kg DM), the concentration of P in faeces at which dietary requirements should be met; FecP/Diet ME (mg/MJ ME), the ratio of the concentration of P in faeces (mg/kg) to ME content of the diet at which dietary requirements should be met.

Note (a). Ratio FaecP/DietME (Faecal P in g/kg DM and ME in MJ/kg diet DM measured with FNIRS). If the value measured is less than the threshold given above then the dietary P intake is likely to be less than the amount needed by the animal.

Note (b). Ratio DietDMD/FaecP (Diet DMD measured with FNIRS in g/kg and the faecal P concentration in g P/kg DM). If the value measured is greater than the threshold given above then the dietary P intake is likely to be less than the amount needed by the animal.

The P requirements for lactating cows could not be calculated using the procedures adopted for growing animals because the voluntary intake of lactating animals is greater than that of growing animals at the same diet DMD. Based on reports that the voluntary intake of *Bos indicus* breeders ingesting low to medium quality forages is increased by 20-30% during lactation (Penzhorn and Meintjes 1972; Hunter and Siebert 1996; Dixon *et al.* 2010), the voluntary DM intake of lactating cows was assumed to be 25% greater than the estimate for growing animals at the same LW and LW gain. Furthermore, because substantial ME is required for milk production, the LW change of the lactating breeder is much less than that of the growing animal at the same ME or DM intake. A second spreadsheet QuikMEI based on CSIRO (2007) equations was used to calculate the expected LW change of the lactating cow which was producing 5 kg milk per day and was 8 week pregnant for each increment of DMD and MEI. The estimates of the P requirements of lactating cows are shown in Table 2.

These results demonstrate the large amounts of P required per day, and of P concentration in the diet and in faeces, for liveweight gain and milk production. This is exacerbated by the high intakes of DM which are needed for high productivity from forage diets. For example, in

a 300 kg steer increasing growth from maintenance to 1.2 kg/day would increase the amount of P required from 6 to 20 g P/day, and the required concentration in the diet from 0.9 to 1.7 g P/kg DM. If the relationship in Fig 1 below can be extrapolated to this high LW gain situation (which requires validation) then the concentration of P in faecal DM required for this high LW gain would be 3.3 g P/kg DM. High LW gains of steers are possible during the peak pasture quality during the wet season, and in high output grazing systems such as *Leucaena*-grass pastures. It seems possible that in some situations dietary P would constrain animal growth. Another example of a high production system where attention needs to be given to dietary P is where high levels of molasses are fed such as with molasses-urea-protein meal supplements fed *ad libitum* to grazing cattle (Lindsay *et al.* 1998). Since molasses contains low concentrations of P addition of a source of P to the supplement will be essential. The importance of lactation can be observed by comparing between tables e.g. for a 400 kg growing steer or lactating breeder at the same LW gain. The production of 5 kg milk per day will increase P requirements by about 8 g P/day, and in a 400 kg breeder growing at 0.3 kg/day the production of 5 kg milk/day would increase the P concentration required in the diet from 1.2 to 1.7 g P/kg DM. Conversely, a non-lactating animal in LW loss has a very low requirement for dietary P.

4. Estimation of the dietary P intakes of grazing cattle

Evaluation of the P requirements of grazing cattle, and more specifically whether a response can be expected to supplementary P, is difficult because this outcome is a consequence of a many interacting factors. The most important of these include:

- (i) The requirements of the animal for immediate productive purposes (maintenance of body functions, muscle growth, conceptus growth, lactation),
- (ii) The supply of absorbed P from the diet,
- (iii) The net supply of P from mobilization of and deposition to body stores of P in the soft tissues and skeletal tissues.

These issues have been well recognized, and R&D has provided considerable information about points (i) and (ii) above. However, point (iii), the potential supply of P from body stores, particularly bone P, has been difficult to address quantitatively due largely to the difficulty and resources required to measure experimentally the magnitude of such P reserves and the rate and extent to which they are mobilized when supply of P from the diet is less than the requirements of the animal. There are a complexity of factors involved in the deposition and mobilization of P in body reserves, and it will usually not be possible to predict quantitatively the net mobilization or deposition of P from or to body reserves in a specific set of circumstances.

4.1. A new approach for grazing cattle

In this review we propose a new approach to estimate the current dietary P requirements of grazing cattle. This is based on the known principle that P requirement is directly related to productivity, which in turn is directly related to metabolisable energy (ME) intake. As such the new approach depends on two estimates. First the ME concentration of the diet is estimated from F.NIRS. Second, from established relationships the concentration of P in forage diets can be estimated from the concentration of P in faeces, and the latter measured by conventional wet chemistry. It is recognized that net mobilization of P from body stores may, for limited intervals, substitute for and reduce the need for dietary P. However, we consider that insufficient information is available to make quantitative estimates of this contribution to substitute for dietary P requirements.

4.2. The concentration of P in the diet and the concentration of P in faeces

The usefulness of the concentration of P in faeces to estimate the concentration of P in the diet or dietary P intake has been examined in a number of studies. A comprehensive analysis of such data from large field experiments at Springmount and at Lansdown in north Queensland indicated that in this dataset there was a close relationship between the concentrations of total P the diet and in faeces (Fig 1; D. B. Coates, unpublished). Cattle grazed pastures based on native or introduced grasses, sometimes augmented with stylo legumes and/or with P fertilization. Diets where inorganic P supplements were fed were excluded from the data set. Clearly an excellent relationship was observed between faecal P concentration and dietary P concentration.

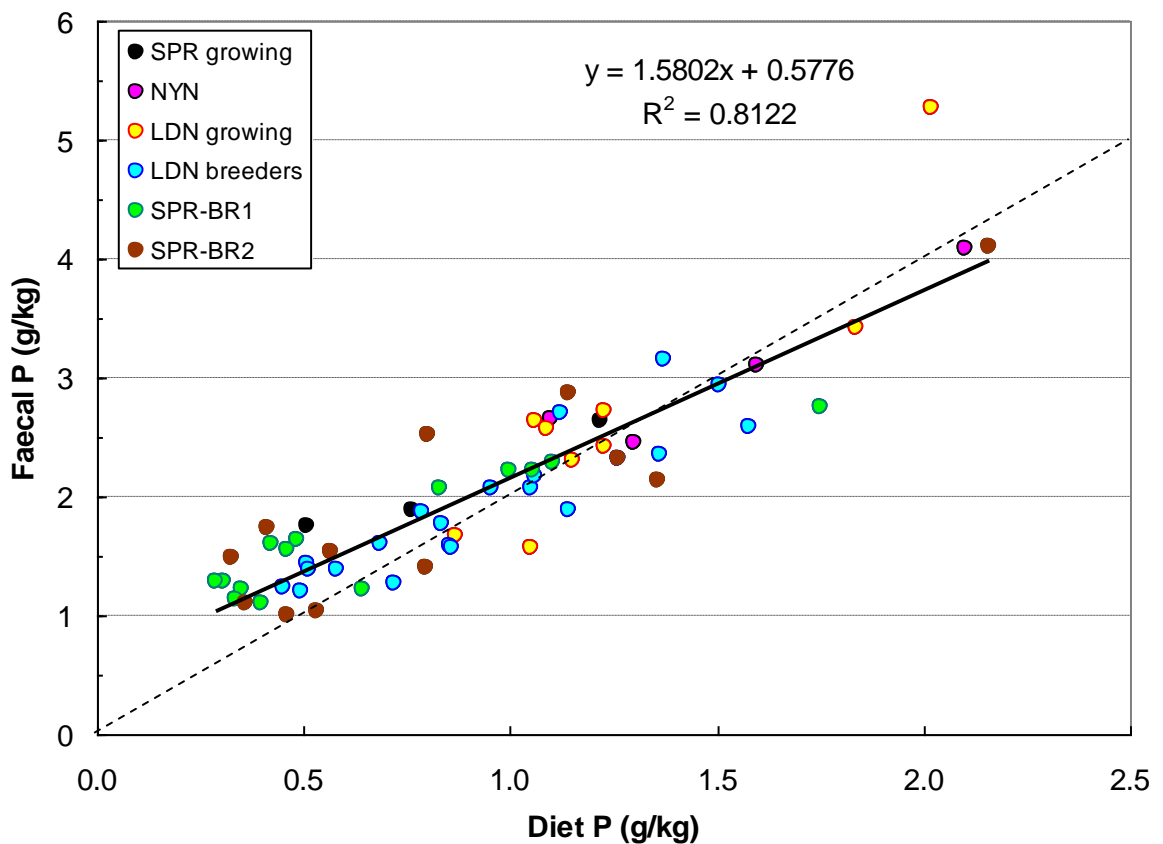


Fig 1. The relationship between the concentration of P in the diet measured using oesophageal-fistulated animals and ³²P tracer and the concentration of P in faeces of *Bos indicus* cross cattle (growing animals or breeders) grazing tropical pastures at Springmount (SPR) or Lansdown (LDN) in north Queensland and not fed P supplements (D B Coates, unpublished results). The inverse relationship was:

$$\text{Diet P (g/kg)} = 0.514 (\text{Faecal P g/kg}) - 0.12 \quad (n=63, R^2=0.81, \text{rsd}=0.205)$$

See text for further details of animals and pastures.

It seems likely that the relationship described in Fig 1 depends on the pasture system. The results of earlier studies in cattle examining the relationships between faecal P concentration and dietary P concentration of cattle fed forage-based diets are shown in Fig 2. Faecal P versus dietary P concentrations were well described by linear relationships within each experiment. Except for the 2 experiments of Cohen (1974) where the basal forage was a low quality tropical grass hay, the slopes of the relationship were remarkably similar. The elevations of the regressions varied such that predicted dietary P concentration would have

been predicted to differ by on average up to 0.5 g/kg DM. Because of the origin of the data the relationship described in Fig 1 may be most appropriate for similar grass-stylo pasture systems in northern Australia. We are not aware of any information to evaluate its applicability across other pasture systems in northern Australia or elsewhere. Although the results of Moir (1960) shown in Fig 2 support the hypothesis that the linear relationship holds for dietary P concentrations up to 5 g P/kg dietary DM, it should be pointed out that in this experiment the concentration of P was measured in plucked pasture samples and therefore could be quite erroneous.

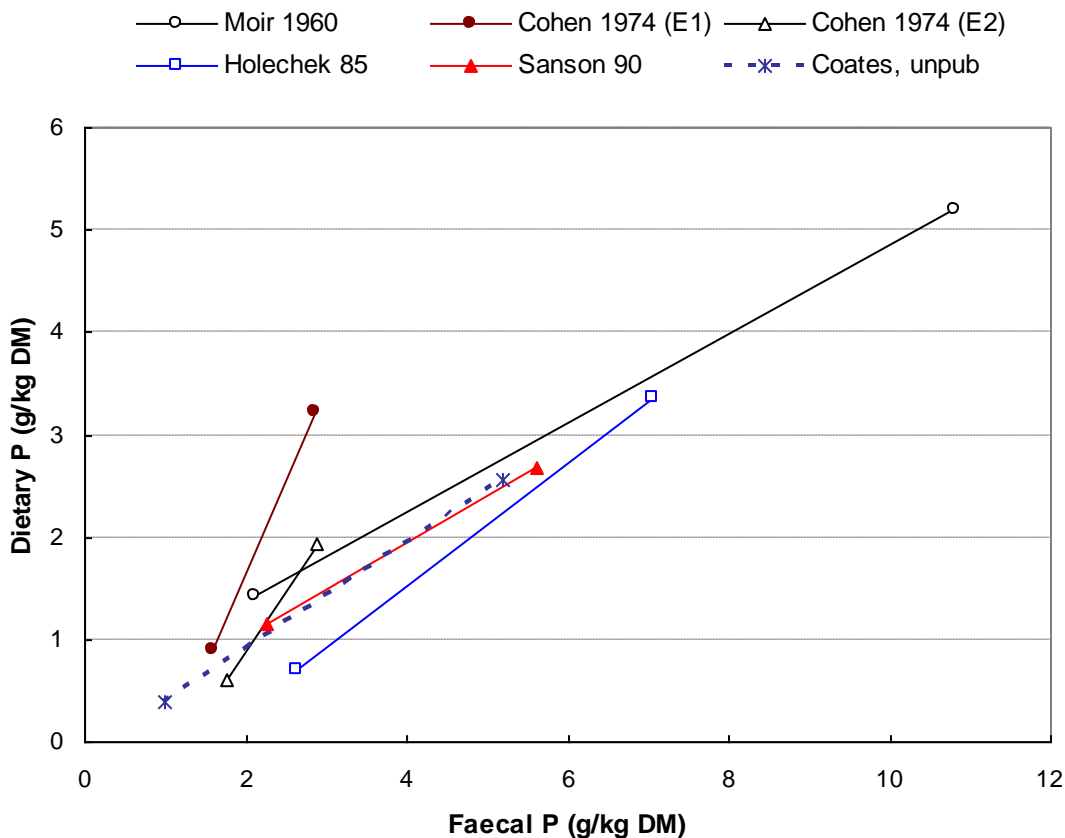


Fig 2. The relationship between the concentration of P in the diet and concentration of P in the faeces in cattle fed forage based diets in Expt (a) tropical grass pastures (○) ($R^2 = 0.76$) (Moir 1960), Expt (b) mixtures of a tropical grass and lucerne (△) ($R^2 = 0.79$) (Cohen 1974), Expt (c) a range of north American forages (□) ($R^2 = 0.92$) (Holechek *et al.* 1985), Expt (d) a tropical grass supplemented with various amounts of inorganic P (●) ($R^2 = 0.80$) and Expt (e) a range of north American forages supplemented with various amounts of inorganic P (▲) ($R^2 = 0.95$) (Sanson *et al.* 1990), or Expt (f) the data of Coates (unpublished) shown in detail in Fig. 1. In each of experiments (a) to (e) 5 to 10 diets were measured in 3-10 animals. In Expt (a) diet P concentration was estimated from plucked pasture samples. In Expts (b) through to (e) cattle were fed in pens.

Although there is little direct experimental evidence, on the basis of the digestive physiology of ruminants a number of factors might be expected to influence the relationship described above. The relationship in Fig 1 clearly depends on a reasonably constant apparent digestibility of dietary P by cattle. Much of the P in faeces consists of undigested microbial debris and endogenous materials. Since the majority (60-90%, Coates and Ternouth 1992; Hendricksen *et al.* 1994) of P in faeces is of endogenous origin and derived from salivary P, changes in blood inorganic P and salivary secretion are likely to affect faecal P concentration. Furthermore the digestion and absorption of dietary P in ruminants may be

influenced by the form of the P in the diet, such as in an inorganic P supplement, by some forms of phytate, starch, and tannins (Konishi *et al.* 1999; Kincaid and Rodehutschord 2005; Riestra *et al.* 2010). Two of the studies shown in Fig 2 changed diet P concentration by inclusion of inorganic supplementary P. Of these, the results of Sanson *et al.* (1990) appeared to conform to the pattern for forages, while the results of Cohen (1974a) did not. Faecal P has been shown to be related to the DM digestibility of the diet, and to be related to the digestible fraction rather than the indigestible fraction (Rodehutschord *et al.* 2000). Dietary starch which escapes rumen fermentation but is fermented in the large intestine, such as from some concentrates, is likely to increase microbial protein synthesis at this site and therefore increase P excretion in faeces. Thus dietary starch may reduce the apparent digestibility of dietary P. These observations may be useful to improve the prediction of dietary P concentration; Cohen (1974) observed that a multiple regression model which included both diet DMD and faecal P concentration as independent variables improved the prediction of dietary P concentration. Clearly diet DMD may be estimated from faecal NIRS.

4.3. Estimation of ME intake from faecal NIRS measurements

Near infrared reflectance (NIRS) is seldom a preferred method for mineral analysis. Although NIR calibrations have been developed to measure P concentrations of both feedstuffs and faeces (Dixon and Coates 2009) the accuracy and robustness of predictions may not be satisfactory. P concentrations in forages and faeces are best measured with established wet chemistry procedures.

F.NIRS has a valuable role in estimation of P status of grazing cattle by providing estimates of the quality of the diet as DM digestibility, crude protein concentration, legume content, and expected voluntary intakes of pasture DM and metabolizable energy. In the approach adopted by CSIRO (2007) the P requirements of cattle are calculated as a function of the liveweight, DM intake and the growth rate of the animal. ME intake is the basis of all modern feeding systems, and estimation of ME intake is generally the most satisfactory approach to relate diet quality to animal LW change. CSIRO (2007) is the only current feeding system which attempts to address the nutrient requirements of *Bos indicus* cattle grazing tropical pastures. With knowledge of the class of the animal, expected (or target) productivity, FNIRS estimates of DM digestibility (DMD), and the concentration of P in the diet (derived from the concentration of P in the faeces), it is possible to make improved estimates of the likelihood of the diet meeting the current P requirements of the animal.

4.4. Estimation of P status of grazing cattle from the ratio of the concentration of P in faeces to the ME content of the diet

Using the information derived from the QuikIntake spreadsheet, and for breeders additional calculations also based on CSIRO (2007), the ratio of the concentration of P in faecal DM to concentration of ME in the diet ingested (mg faecal P/MJME) was calculated for each level of production of a range of growing steers and lactating breeders (Table 1). It is proposed that these values can be used as an indicator of the thresholds at which dietary P concentration is sufficient to meet the current P requirements of the animal. An alternative is to use the effective inversion of this ratio, the ratio diet DMD/faecal P. The latter may be a simpler expression for use at the industry level by people without specialized knowledge in ruminant nutrition.

We propose that the ratio faecal P/ MJ ME in the diet is likely to provide the most reliable indicator from faeces of the P status of the animal. It is fundamental to ruminant nutrition that productivity as growth, milk production etc are better described as a function of dietary ME intake than by any other dietary variable. For example, the results in Table 1 indicate that a steer at maintenance would require 270-290 mg faecal P per MJ ME. At LW gains of

0.9 kg/day (if this could be achieved in practice) the threshold of this indicator would range from 44 in 200 kg steers to 330 in 500 kg steers. Threshold indicator values for lactating breeders were in the range 310-420 mg faecal P per MJ ME across a range of LW and LW gains, the range being smaller because the requirements for P and ME tend to increase in similar proportions.

The faecal P/ MJ ME ratio has a number of limitations each of which has considerable potential to introduce error. These include:

- (i) The ratio depends on the correlation between the concentrations of P in the diet and in the faeces, and if the relationship differs from that shown in Figure 1 the indicator value will vary proportionally.
- (ii) Calculation of the ratio depends on assumptions of the relationships between diet DM digestibility, DM intake and LW gain.
- (iii) No consideration is given to supply of P by mobilization of body reserves. Mobilization of P from the body reserves of the animal, and which is expected to occur especially during lactation, will reduce the amount of dietary P required during some intervals.
- (iv) The ratio will only be applicable to circumstances where the availability of pasture is not limiting voluntary intake.
- (v) The indicator ratios may not apply when P supplements are being fed.

Furthermore the validity of these proposed threshold values as indicators have not been tested.

4.5. Estimation of the requirements for supplementary P in a specific situation

Calculation of the P supplement required follow from the estimates of the P requirements of the animal as described above, and estimates of the P intake. Diet P concentration can be estimated from measurements of faecal P concentration and the relationship in Figure 1. Diet P intake can then be calculated from the expected DM intake given in Table 1.

4.6. Estimation of dietary P status from the ratio of the concentration of P in faeces to the N concentration of the diet, or to the N concentration of faeces

The ratio faecal P/diet N has been previously proposed by David Coates (unpublished) as an indicator of dietary P status. It was based on the concept that dietary N, as estimated by F.NIRS, was a reliable indicator of the productive potential of the diet with regard to dietary protein and energy. Also that this faecal P/diet N ratio should provide a more reliable guide to dietary P status than the faecal P/faecal N ratio recommended by McCosker and Winks (1994). While dietary N concentration is likely to be a better indicator than faecal N concentration of the diet DMD and voluntary intake of ME, it is not likely to be as reliable as the prediction from the ME concentration of the diet, as estimated from diet DMD. Therefore we recommend that the faecal P/ diet N ratio should be replaced by the faecal P/diet ME ratio or the DMD/faecal P ratio discussed above.

Faecal NIRS technology was not available when the McCosker and Winks (1994) manual was being written. In this manual (pages 54-56) considerable emphasis was placed on the use of the concentration of P in faeces in conjunction with the concentration of N in faeces, and/or the concentration of inorganic P in blood, as indicators of dietary P status. Faecal N does not have any direct association with dietary P concentration or the P status of the animal, but was adopted as a proxy for diet quality which as described above does have a major effect on P requirements. If the ratio faecal N/ faecal P were to provide an indicator of P status then FNIRS estimation of the diet quality would not be required, and the indicator ratio could be readily determined from wet chemistry of faeces.

There is a major difficulty with this approach. Although excellent linear relationships have often been observed between faecal N concentration and diet digestibility and diet N concentration within data sets from specific experiments, a number of studies have shown that these relationships are not consistent and can differ substantially with pasture system, season of the year and between years (Langlands 1975; Holechek *et al.* 1985; Hobbs *et al.* 1987). In the context of northern Australian pastures, the FNIRS data sets generated during the last decade and where diet digestibility, diet N and faecal N are all routinely predicted provide an opportunity to examine these relationships in various pasture systems and situations. These data support the hypothesis that faecal N concentration is a poor and unreliable indicator of the digestibility or the N content of the diet ingested. An additional consideration is that where browse containing condensed tannins forms a substantial proportion of the diet the concentration of N in faeces will be elevated, presumably independently of the P in the diet. In conclusion the ratio faecal P/faecal N is not likely to be a reliable indicator of P adequacy of the diet.

5. The role of P skeletal reserves as a store to provide for animal demands when dietary P does not meet requirements

5.1. General

It is well established that the amounts of P and Ca in the skeleton, and to some extent in the soft tissues, of ruminants and which comprise the body reserves are large in proportion to the daily requirements of the animal for these nutrients. Furthermore these often provide a store for the animal to meet demands when these nutrients are deficient in the diet. In cattle there are about 7-8 g P per kg LW in an adult animal in replete P status (i.e. about 3 kg P in a 400 kg breeder cow). About 80% of this P is in the bones and the remainder is in soft tissues. The latter contain about 1.2 g P/kg. Almost all of the Ca is in the bones. During prolonged deficiency of Ca and P the amount of these minerals in the bones can be markedly reduced. The ratio of Ca to P in bone tissue is usually about 2:1, but can deviate from this range.

Metabolism of Ca and P are closely linked. There are complex endocrine and physiological mechanisms which control the metabolism of Ca and P as absorption from the gastrointestinal tract, transfer of P from blood to saliva and thence to the rumen, excretion in faeces and urine, and accretion (i.e. deposition) into bones and resorption (i.e. mobilization) from bones. The deposition and mobilization of Ca and P in bone are usually highly correlated and tend to occur in the same ratio as they are present in bone. The homeostatic mechanisms which control Ca concentration in plasma generally dominate over the mechanisms controlling blood inorganic P concentration. Ca in the plasma is regulated within a very narrow range, and it is generally the control mechanisms for Ca which regulate the deposition and mobilization of both Ca and P into and from bone. Thus in general the extent to which an animal mobilizes P is more highly dependent on the Ca status than the P status, and an animal may not be able to mobilize bone P reserves to meet a requirement for P. Nevertheless, in at least some circumstances cattle do mobilize bone P to alleviate shortages of dietary P even when Ca is not deficient, but Ca:P ratios in the diet will affect P mobilization rates. Alternatively if an animal is deficient in Ca the animal may mobilize bone to provide Ca, and thus mobilize bone P even when the animal does not require additional P. Because Ca should rarely be nutritionally limiting in cattle in northern Australia, this is not likely to occur in practice. When an animal loses liveweight the P in mobilized soft tissues will become available to the animal. Also, although the P concentration in muscle and brain tissue appears not to be affected by P deficiency, the P concentration in other soft tissues can decrease (e.g. by up to 33% in lambs fed P deficient diets for extended intervals; Ternouth and Sevilla 1990a, b; Pfeffer *et al.* 1994). It also seems likely that some

demineralization of bones and thus mobilization of P from bones occurs with liveweight loss by the animal.

Many studies have examined the effects of the dietary intakes of Ca and P in animals in a wide range of physiological states on metabolism of these minerals. Most studies have examined sheep or goats, and a few high-producing dairy cows in pregnancy and lactation. Some have examined growing cattle, but studies of beef cattle in pregnancy and lactation are limited to field experiments at Lansdown and Springmount (Ternouth and Coates 1997; Miller *et al.* 1998). The conclusions from various studies have sometimes not been in accord, and it is often difficult to draw firm conclusions about P metabolism in grazing *Bos indicus* cattle in northern Australia.

5.2. Experimental approaches

A number of experimental approaches have been used to measure the body stores (defined as the total amount in the body), the changes in body reserves, and metabolism of Ca and P. Arguably the most definitive approach to measure P and Ca body stores has been to feed animals on specified diets for extended intervals (usually for months and sometimes for years) and then to slaughter the animals to make complete and direct measurements of the Ca and P in various skeletal and soft tissue components (e.g. Benzie *et al.* 1959). The major disadvantages are that such experimentation is very costly, especially for cattle, and repeated measures are not possible. A variation of this approach to reduce experimental costs has been to restrict the measurements at slaughter to selected bones (Williams *et al.* 1990, 1991; Pfeffer *et al.* 1996; Erickson *et al.* 2002).

To circumvent the need to slaughter animals to measure their Ca and P status, procedures have been developed to use samples of rib-bone obtained by biopsy as an alternative to assess skeletal mineral reserves (Little 1972, 1983). The procedure involves the surgical removal of a disc of bone comprising the outer layer of cortical (i.e. compact) bone of the 11th or 12th rib, in cattle usually about 20 cm below the level of the vertebral spines. Early studies generally reported the P per unit of dry, fat-free bone (Little 1972, Cohen 1973a, b, Little and Minson 1977, Hoey *et al.* 1982) or the P per unit weight or per unit volume of fresh bone (Little 1972, Little and Minson 1977, Little and Shaw 1979, Engels 1981, Hoey *et al.* 1982). Subsequently, Little (1984) concluded that rib compact bone thickness (CBT) provided a more sensitive and simpler measure of animal P status. A variation of the rib bone biopsy technique involves removing a complete core comprising external and internal cortical bone complete with medullary trabecular bone (Read 1984), and the P concentration of the full core is used as the measure of the P status (Read *et al.* 1986c, De Waal and Koekemoer 1997). The composition of bone samples obtained using this technique is likely to provide a more reliable measure of the body P stores than the method proposed by Little (1972, 1984), but the surgical procedure required has animal welfare implications.

Measurements obtained from rib bone biopsies have been reported in numerous experiments and do provide an indication of whether the animal is in adequate or deficient P status following extended P deficiency or P adequacy over periods of months. The threshold values indicating P status have been reviewed by Minson (1990). Unfortunately, there is no clear or consistent delineation between P adequacy and P sufficiency in bone biopsy measurements, and they are of no value in estimating current dietary status. Little (1984) concluded that a CBT thickness of < 2 mm indicated a deficiency of P stores, and a CBT > 3 mm indicated adequate body P stores. However values for CBT intermediate between 2 and 3 mm are often observed, and it is difficult to categorise the status of these animals. In addition, the Little (1984) values related to young cattle and do not apply to adult males or to breeders. A further limitation is that considerable intervals (e.g. 6 months) must be allowed before a second biopsy sample is obtained from a specific rib bone. Measurements

obtained from rib bone biopsies have been reported in numerous experiments and presumably do provide an indication of whether the animal is in adequate or deficient P status. However, it is of concern that a poor relationship was observed in the experiment of Hoey *et al.* (1982) when sequential measurements of rib bone over an extended interval were compared with changes measured by slaughter. We suggest that the results need to be considered with caution, and are of limited value to measure sequential changes in body P reserves. Moreover, while the bone biopsy has been a useful research tool a number of considerations prevent its routine use as a diagnostic in commercial situations.

A major difficulty with any measurement based on a selected bone (or bones) is that various parts of the skeleton accrete or mobilize P at different rates and to different extents (Benzie *et al.* 1955, 1959; Hill 1962). In general the cancellous bones (i.e. the vertebrae and ribs) change in Ca and P composition and mobilize these minerals much more readily than the compact bones (e.g. long bones of the limbs), but there is also large variation within these classes of bones (Benzie *et al.* 1959). The limitation remains that the change in P concentration of a specific bone such as the 12th rib bone usually sampled will not necessarily be in proportion to the change in total skeletal P stores. It is therefore difficult, or arguably not possible, to use the rib bone as a direct measure of body reserves of P or Ca or of P mobilization. An example of this difficulty is that in one study where heifers were fed P adequate or P deficient diets for 15 months, there was poor agreement between changes in rib bone P content measured at intervals and the P contents of individual bones and of the total skeleton measured at slaughter at the end of the experiment (Hoey *et al.* 1982). Data on the changes in the P content of the total skeleton, and the P content of the rib and metatarsal bones, in young sheep have also been reported by Ternouth and Sevilla (1990a, b). More comprehensive information to compare changes in P contents of both rib bone and of total skeleton in the same experiment would be valuable to allow direct evaluation of the rib bone as a measure of the changes in the total body.

An alternative approach to estimate changes in the reserves of P and Ca has been to measure apparent balance of P and Ca during total collection experiments, usually in a sequence during growth, pregnancy or lactation. The balance provides a measure of net storage or mobilization of P during the interval of measurement, but this usually involves several total collections each of about a week which are then extrapolated to represent changes over many weeks or months. A second major shortcoming is that because the balance is calculated as the difference between 2 relatively large amounts (i.e. P intake in feed and P excretion in faeces and urine), it is inevitably subject to substantial experimental error. Measurements of P balance have often been combined with ³²P and ⁴⁵Ca radiotracers to measure P and Ca kinetics and deposition into and mobilization from body reserves in the animal. Numerous studies of this type have led to extensive information on the magnitude of the transfers of plasma P to the rumen via saliva, utilization of P by rumen microorganisms, absorption of P from various sections of the gastrointestinal tract, and the transfers of P among body pools representing the P and Ca in the various soft tissue and skeletal structures. Such data have been used to develop complex multi-pool models representing the kinetics of P and Ca of ruminants in various physiological states such as growing sheep (Grace 1981; Schneider *et al.* 1982; Dias *et al.* 2006), growing goats (Vitti *et al.* 2000) and lactating dairy cows (Hill *et al.* 2007). We are not aware of any published studies describing such a model for beef cattle in either growth or in pregnancy and lactation.

A difficulty with the above experimentation is that the measurements of P deposition and mobilization obtained using the balance and slaughter experimental approaches are not always in agreement. In one study where P adequate or P deficient diets were fed to lactating goats for 7 weeks, the decrease in P body stores estimated from sequential P balance measurements was 27% higher than that estimated by slaughter (Pfeffer *et al.* 1994). Similar difficulties in reconciling balance and slaughter approaches have been

observed in measuring energy and N metabolism, and it is not unexpected that such discrepancies should also occur in measurement of P metabolism. It follows that the experimental information tends to be indicative of the process and trends, and quantitative estimation of the mobilization of P is subject to large potential error.

5.3. Rates of deposition and mobilization of body P and Ca reserves in growing and non-reproducing mature ruminants

A number of studies developing kinetic models of P and Ca flows in growing sheep or goats (Grace 1981; Schneider *et al.* 1982; Vitti *et al.* 2000; Dias *et al.* 2006) or lactating dairy cows (Hill *et al.* 2007) have shown that there are extensive transfers of Ca and P between the rapid-turnover labile pools (such as inorganic phosphorus in blood) and the large slow-turnover pools (the soft tissues and bones) in the 'normal' animal. Thus there is extensive bone turnover as accretion (i.e. deposition) and resorption (i.e. mobilization) of P and Ca. The net daily deposition or mobilization is the difference between these large flows. The models have indicated that such flows of P to and from the bone pools were up to about 7 times the P intake. Thus only a small proportional change in flows between body pools will have a large effect on the net mobilization or deposition of P for the animal to replace a shortage of P in the diet or to replenish body P reserves when P intake is in excess of requirements. Importantly there is usually a close association between the flows of P and Ca, and net deposition or mobilization of P and Ca are usually closely correlated.

Bone turnover as deposition and mobilization is much lower in mature than in young animals. In sheep ingesting a wide range of Ca intakes the deposition rates of Ca in young (6 months) sheep were 4-7 times higher than in mature sheep (Braithwaite 1975). Bone mobilization varied through a wide range, from nil up to about 60 mg/kg LW.day in young sheep and from nil to 30 mg /kg LW in mature sheep, and it was concluded that changes in mobilization rather than deposition were mainly responsible for Ca homeostasis. Ramberg *et al.* (1975) also reported that as the animal matures it becomes more dependent on modifying the rate of bone mobilization to control net Ca transfer. Given the close association often observed between Ca and P retention it appears that deposition and mobilization of P are also much lower in the mature animals than young animals. These studies are in accord with observations of very high deposition and mobilization of P and Ca, often greatly exceeding dietary intake, in young growing cattle (Challa and Braithwaite 1989). The higher rates of deposition and mobilization of P and Ca in young animals are consistent with skeletal growth being relatively rapid in such animals.

When animals are growing and ingest adequate P and Ca, balances of these minerals will be positive with the magnitude depending on ME intake. Nevertheless, a number of studies have examined the capacity of the growing and/or mature animal ingesting diets adequate in P and Ca to be able, when given P deficient diets, to mobilize body reserves of P and Ca and maintain a higher growth rate (or more usually a lesser LW loss) than would otherwise occur based on the current intake of dietary P. Studies in sheep have reported small negative P balances when P deficient diets were fed, equivalent to P balances of up to -3 g P/day in a 400 kg steer (Braithwaite 1980; Ternouth and Sevilla 1990a, b). Studies with cattle have reported small negative P balances up to the equivalent of -4 g P/day in a 400 kg animal (Tuen *et al.* 1984; Bortolussi *et al.* 1996). These studies support the hypothesis that when P concentration in the diet is insufficient to meet current requirements as determined by ME intake, P can be mobilized from body stores to contribute to requirements (e.g. for soft tissue growth and obligatory losses in faeces) thus allowing the animal to continue gaining or to alleviate a LW loss. Obviously the capacity to mobilize skeletal P and Ca decreases as the reserves are depleted, but mobilization of bone mineral provides animals with adequate skeletal reserves some capacity to cope with short term dietary deficiencies with lesser adverse effects.

5.4. Rates of deposition and mobilization of body P reserves in reproducing ruminants

Numerous studies have reported that during late pregnancy and early lactation there is a large increase in the turnover of bone, and extensive mobilization of body reserves of Ca and P to meet the high demands of the animal in these physiological states. It is widely accepted that such mobilization is a normal mechanism to meet the demands of early lactation, and particularly in the high-producing dairy cow (Horst 1986). The changes in P and Ca deposition, mobilization and retention through the stages of pregnancy, lactation and post-lactation have been clearly demonstrated in the reproducing ewe given diets to provide the requirements for P as estimated by ARC (1980) (Figure 3) (Braithwaite 1986). Even though the intake of P was increased, the mobilization of P (and also of Ca, not shown in Figure 3) increased markedly in late pregnancy and early lactation. Deposition of P did not change markedly. Retention (i.e. balance) of P and Ca was highly negative in late pregnancy and early lactation. The similarity of the trends in balance of Ca and P demonstrate the linkage between these minerals. The negative P balance of -35 mg/kg LW.day in these ewes in early lactation would be equivalent to a net mobilization of 14 g P/day from body reserves in a 400 kg breeder cow. In studies with goats in early lactation, there was net mobilization of P from body reserves of up to 25 mg P/kg LW.day (equivalent to 10 g P/day in a 400 kg breeder) when low P diets were fed, and about half this mobilization with diets intended to be adequate in P (Deitert and Pfeffer 1993; Rodehutsord *et al.* 2000). Even higher rates of mobilization in goats in early lactation (up to 42 mg P/kg LW.day) have been observed, with the total amount of P mobilized during early lactation ranging from 0.8 to 1.6 g P/kg LW (equivalent to 340-560 g P in a 400 kg breeder) (Rodehutsord *et al.* 1994b).

Measurements of P balance in high-producing dairy cows, of about 600 kg liveweight, in early and mid lactation has provided information on net mobilization and deposition of body P reserves in this class of animal (Knowlton and Herbein 2002). Where diet P was expected to provide less than the P required, net mobilization from body reserves ranged from 5 to 25 g P/day during the first weeks of lactation, while there was net retention (deposition) of up to 5 g P/day in late lactation. Cows fed high P diets in the same study had lower net P mobilization in early lactation and high P retention (net deposition) of up to about 20 g P/day in mid-lactation. In another study (Valk *et al.* 2002) measurements of P balance indicated that when low P diets were fed cows mobilized up to 7 g P/day early in the first lactation, but as the low P diet was continued into a second lactation the cows did not mobilize body P but instead milk production and milk P output decreased by a similar amount (8 g P/day). Presumably by the second lactation the cows fed the low P diet had depleted the body P reserves which could be mobilized, and accommodated the shortage of P from the low P diet by reducing the P secretion in milk.

Bone turnover increases substantially during lactation. First, this is indicated by the magnitude of the rates of deposition and mobilization in lactating animals such as in the experiments of Braithwaite (1983) or Braithwaite (1986) in Figure 3 above. Second, it has been observed in high-producing dairy cows that a marker of bone formation, osteocalcin, increased substantially through early and mid lactation and then declined in late lactation and the next dry period (Holtenius and Ekelund 2005; Ekelund *et al.* 2006). Concurrently the plasma concentration of a bone resorption marker, CTx (C-telopeptide fragments of collagen type I), increased 2-6 fold immediately after parturition and then declined through lactation.

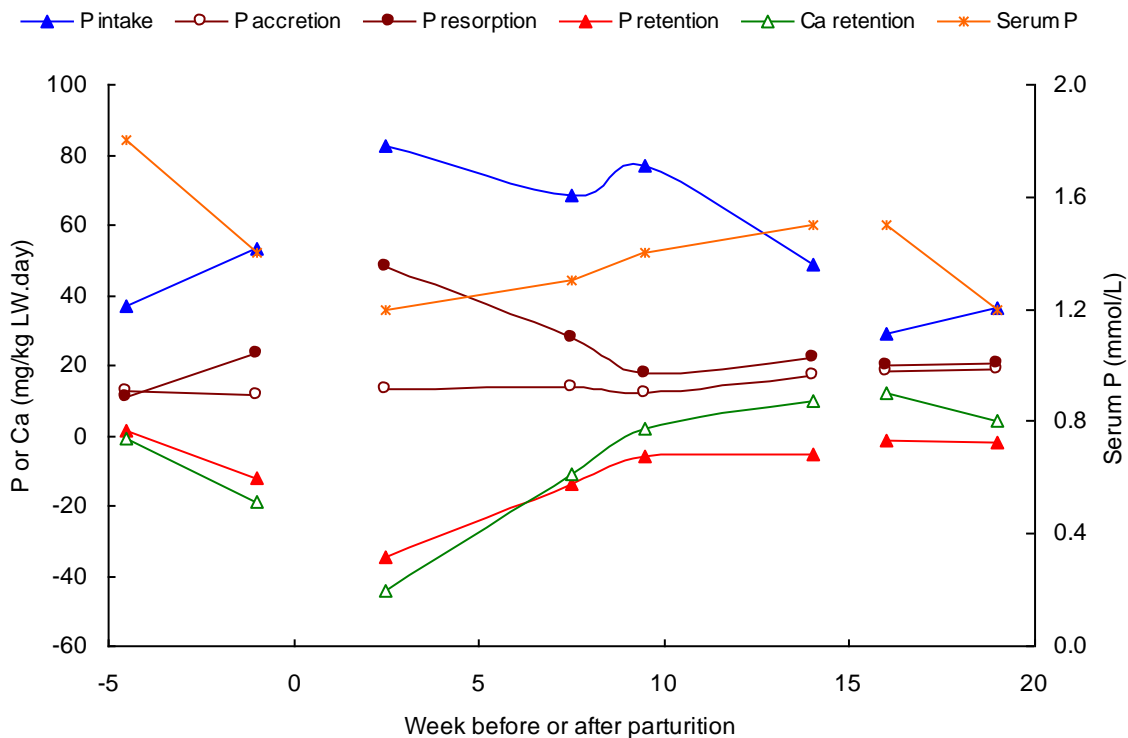


Fig. 3. The Intake, deposition, mobilization, retention of P, and the retention of Ca, of ewes during late pregnancy, lactation, or post-lactation fed diets calculated to provide the ARC (1980) recommendations for dietary P (Braithwaite 1986).

5.5. The extent to which P body reserves can be mobilized to alleviate insufficient dietary P

The amount of P which can be mobilized from skeletal body reserves has been estimated to range, in extreme circumstance, up to 30% (Little 1983) or 40% (Benzie *et al.* 1959) of that present in the P-replete animal. Since a 400 kg animal would be expected to have about 2.5 - 3.0 kg P in bone reserves, a 40% mobilization would correspond to about 1.0 - 1.2 kg P. However the conditions in the experiment of Benzie *et al.* (1959) were extreme, and the amount of bone P which could be mobilized might be considerably less in most situations. Net mobilization of 800 g P over perhaps 3 months would be equivalent to 9 g P per day. This amount is consistent with the rates of net mobilization of P described above for lactating sheep and goats. Sehested (2004) suggested that "it is realistic to expect a mobilization of between 100 and 500 g P during early lactation" (in a 600 kg dairy cow), although the experimental results on which this statement was based are not entirely clear. Presumably this statement is in the context of well-managed dairy herds with generally good nutrition, in contrast to the low nutritional inputs in extensive grazing systems. The equivalent mobilization of P in a 400 kg beef breeder cow, scaled on a LW basis, would be 80 - 400 g P.

The interval over which available bone P reserves can be mobilized is clearly important. The P balance studies in lactating sheep and goats discussed above suggest that net mobilization of up to about 15 g P /day could occur in a 400 kg lactating beef cow. This value is in accord with the measurements of P mobilization in dairy cows in early lactation exceeding 20 g P/day. However, mobilization of body P at such high rates would presumably rapidly deplete the available reserves. When P adequate animals are changed to P deficient diets there may be almost no lag (Long *et al.* 1957; Preston and Pfander 1964;

Little 1968), an appreciable time lag (e.g. 5-10 weeks; Call *et al.* 1987; Ternouth and Sevilla 1990b; Bortolussi *et al.* 1996), or many months (Gartner *et al.* 1982; Call *et al.* 1986), before voluntary feed intake declines as is expected in P deficient animals. In this context, in the study of Read *et al.* (1986c) the decline in rib bone P concentration (Table 3) appeared to occur over about an 18 month interval, suggesting that under the conditions of that study the body P reserves provided the shortfall of P requirements during a complete pregnancy and lactation, and there was a long delay before the animals were severely deficient. It would seem likely that, as with depletion of body fat reserves by the animal, the interval over which net mobilization of body P reserves occurs will be a function of the initial reserves and the extent of the dietary deficiency relative to the requirements of the animal.

Table 3. Composition of rib bone samples and plasma inorganic phosphorus (PIP) in a herd of cows mated as heifers in 1978 and grazed with or without P supplementation through 5 reproductive cycles (Read *et al.* 1986c,d). All the cattle were given a P supplement (a salt and DCP lick) during growth preceding the experiment, and the +P treatment were fed this supplement during the 5 years of the experiment. Cows calved from mid September to the end of November and calves were weaned at about 7 months.

Year	Rib bone composition (mg P/cm ³)						Plasma inorganic phosphate (PIP) (mg P/L)					
	Lactation			Late pregnancy			Lactation			Late pregnancy		
	-P	+P	Signif.	-P	+P	Signif.	-P	+P	Signif.	-P	+P	Signif.
1978	-	-	-	183	172	ns	-	-	-	59	55	ns
1979	160	157	ns	134	136	ns	34	38	ns	48	50	ns
1980	110	136	*	108	147	*	20	49	*	16	63	*
1981	98	143	*	121	142	*	20	69	*	36	52	ns
1982	-	-	-	101	133	*	15	38	*	20	54	*
1983	99	135	*	-	-	-	13	44	*	-	-	-

Given the paucity of experimental data on the bone reserves of P replete and P deficient breeder cows through pregnancy and lactation, the difference in skeletal P reserves of animals grown for extended intervals on P adequate or P deficient diets at the same feed intake give an indication of the extent to which the non-reproducing animal can adjust skeletal reserves. The decrease in skeletal P reserves has occurred as both a decrease in the weight of skeletal tissues and a reduced mineralization of the skeletal tissue, and to some extent a reduction in the proportion of P to Ca in bone. In the study of Hoey *et al.* (1982) heifers of about 400 kg LW contained 535 g less P (i.e. about 19% less) than heifers fed the same amount of a P-adequate diet, indicating that this was the difference in the amount of bone P stored under high P and low P dietary conditions. Mobilization of the additional P in the P replete animal over 3 months would be equivalent to about 6 g P/day. In the studies of Ternouth and Sevilla (1990a, b) with growing lambs the body P reserves of P deficient lambs were only about 60% of the reserves of lambs fed P adequate diets, suggesting a difference similar to that reported by Benzie *et al.* (1959). In this context it is of interest that if an animal is fed for extended periods on a diet which provides P in excess of that required for maximum liveweight gain (as evidenced by the absence of a LW gain response to additional P), then the animal has some capacity to store additional P in the bones. This has been observed in several studies as increased P concentration and P:Ca ratio in bone (Williams *et al.* 1991; Hutcheson *et al.* 1992; Block *et al.* 2004; Esser *et al.*

2009). However, the differences are small, and in the latter study for example, bone P concentration in coccygeal vertebrae bone tended to increase by only 6% indicating that this will not have a major effect on the total body P reserves of the animal.

5.6. *The role of Ca and N on the rates of net deposition or mobilization of body P reserves*

It is clear that the metabolism of Ca and P are closely linked and that in some circumstances the control of Ca deposition and mobilization affects P deposition and mobilization. For example in the study of Braithwaite (1978a) in the reproducing ewe Ca deficiency during pregnancy resulted in extensive demineralization of bone (i.e. mobilization). This then resulted in positive balances of both Ca and P during early lactation as the ewe recovered from the Ca deficient status. However, Ca adequacy during pregnancy resulted in large negative Ca and P balances in early lactation associated with increased bone turnover as the ewe mobilized Ca and P for milk production. There is also evidence in the growing animal of interactions between Ca and P, where depressed feed intakes and growth in animals fed a low P diet are alleviated if dietary Ca is also low (Field *et al.* 1975; Table 4). Thus when dietary P was low, intake and growth was higher when dietary Ca was also low. This was consistent with higher blood inorganic P concentrations for much of the feeding interval in the LowCa-LowP diet than in the AdequateCa-LowP diet in this study. Other experiments with lambs or goats also indicate that a high dietary Ca appeared to amplify the adverse effects of P deficiency (Boxebeld *et al.* 1983; Pfeffer *et al.* 1995), and similar results have been reported from a number of early South African studies (Theiler *et al.* 1937; Otto 1938). It appears that when Ca intakes are high the animal was less able to mobilize bone reserves to alleviate the P deficiency; thus the animal was better able to gain LW or lose less LW when both Ca and P were low in the diet. In the experiment of Field *et al.* (1975) the depletion of bone reserves of P were similar for the AdequateCa-LowP, LowCa-AdequateP and LowCa-LowP diets after an extended interval. In the South African studies the cattle fed the diets low in P and high in Ca also displayed symptoms of P deficiency much sooner and to a greater extent than the animals fed the low Ca diets, but after extended intervals the P status was deficient irrespective of the dietary Ca supply.

Table 4. The feed intake and liveweight gain during, and the total P in the skeleton of lambs (initially 8 weeks of age, 13 kg) at the end of a 4 month feeding interval. Diets contained adequate Ca and adequate P (AdCa-AdP), adequate Ca and low P (AdCa-LowP), low Ca and adequate P (LowCa-AdP), or low Ca and low P (LowCa-LowP) (Field *et al.* 1975)

Measurement	Diets				s.e.
	AdCa-AdP	AdCa-LowP	LowCa-AdP	LowCa-LowP	
Voluntary intake (g DM/day)	1411	821	1054	1268	-
LW gain (g/day)	221	89	153	168	14
Total P in skeleton (g)	187	99	99	103	9.4

In the context of northern Australia there is evidence that high diet Ca:P ratios had important consequences in cattle grazing unfertilized stylo dominant pastures in the studies reported by Winter (1988) and Coates (1994). Stylos typically have high Ca concentrations and, being able to grow well on soils low in available P, Ca:P ratios in stylos and in the diet of cattle grazing unfertilized stylo pastures can be unusually wide (e.g. up to 20:1) (Coates 1990). Coates (1994) reported that responses to P supplement were much greater in cattle grazing unfertilized pasture (stylo dominant, high-Ca and low-P diet) than for once fertilized pasture

(grass dominant, moderate-Ca and low-P diet) although dietary P concentrations were similar.

In contrast to this evidence, many other studies with growing animals, including with animals and diets intended to represent the Australian context, have reported little effect of dietary Ca on the voluntary feed intake or mobilization of body P reserves in sheep or cattle. These studies have indicated that dietary Ca had little effect on voluntary intake or the mobilization of P from body reserves irrespective of body Ca status (Young *et al.* 1966; Ternouth and Sevilla 1990a, b; Bortolussi *et al.* 1992; Pfeffer *et al.* 1996). Studies have also observed little effect of dietary Ca on P utilization in lactating animals (Dietert and Pfeffer 1993; Pfeffer *et al.* 1993).

In conclusion, apart from diets high in stylo, there is little evidence that dietary Ca is likely to have a major effect on mobilization of body P reserves or dietary P utilization by cattle grazing pastures in northern Australia. However, given the high ratio of Ca to P in tropical pastures, particularly after pastures have matured in the dry season, it does appear desirable to avoid use of supplements with high Ca:P ratios. Thus we suggest that inclusion of limestone in supplements is seldom appropriate.

A further consideration is that the dietary N is also important since absorption of dietary Ca is severely reduced when dietary N is deficient. Ca absorption by sheep fed a protein deficient diet (4.9% CP) was only 40% of that by sheep fed a protein adequate (8.0% CP) diet, and this led to much greater negative Ca balances in the protein deficient sheep (Braithwaite 1978b). In steers fed low quality speargrass hay (2.4% CP) true digestibility of Ca was only 4%, but this was increased to 35%, when the hay was supplemented with N (Tuen *et al.* 1984). Concurrently there was a change from a large negative Ca balance (-64 mg/kg $W^{0.75}$.day) to a positive Ca balance (6 mg/kg $W^{0.75}$.day). Thus in cattle grazing N deficient dry season pastures, the ratio of absorbed Ca : absorbed P may be much lower than the Ca:P ratio in the pasture ingested.

The complexities of the amounts of absorbed Ca and P, and the changes in diet quality and animal requirements (e.g. with changes of seasons and parturition) makes it difficult to predict whether Ca and P will be mobilized or deposited into body reserves in cattle grazing dry season pastures, or in the early wet season when carryover effects would be expected. N supplementation in the dry season may increase Ca absorption and reduce bone mobilization due to Ca deficiency, and so prevent loss of bone P. This will be a consideration for the N, P and Ca composition of dry season supplements.

5.7. The likely magnitude of deposition and mobilization of body P reserves of cattle in northern Australian grazing systems

The studies of Miller *et al.* (1998) and Ternouth and Coates (1997) (Tables 5 and 6) have reported P intakes and P balances of *Bos indicus* cross breeder cows grazing pastures in low P land systems in northern Australia. In the Springmount experiment the P balance of unsupplemented cows grazing a fertilized pasture of moderate soil P was generally close to zero, with the greatest net mobilization (negative P balance) in lactating cows in the mid wet season in one year (-3 g P/day), and the greatest retention (positive P balance) in weaned cows in the early dry season (+4 g P/day). Lactating breeders grazing very low P pasture during the mid wet season were in negative P balance (-5 and -9 g P/day for years 1 and 2, respectively) indicating net mobilization, and P balance was estimated to be negative throughout the annual cycle. In the experiment at Lansdown extensive mobilization (negative P balances of -11 and -15 g P/day) were observed in breeders in early lactation grazing the unfertilized pastures, and generally some deposition (small positive P balances) were observed in cows during pregnancy in the dry season, and for the fertilized pasture

during early lactation. In this study negative P balances were measured in both fertilized and unfertilized pasture systems during lactation (May). This was unexpected for fertilized pasture and was due to low plant P concentrations likely caused by soil nutrient imbalances following wet and waterlogged conditions during the mid to late wet season (D. B. Coates, personal communication). Overall these experiments do indicate that high net mobilization of P can occur and contribute up to perhaps 10-15 g P/day, at least for short intervals.

The studies discussed above support the hypothesis that there may be extensive net mobilization of body P reserves by breeder cows in northern Australia during late pregnancy and lactation, and that this is a normal adaptive mechanism. The contribution of net P mobilization could range up to as much as 15 g P/day during short intervals, and up to 800 g P during early and mid lactation. From the studies with dairy cows and lactating goats discussed above there is clear evidence that net P deposition normally occurs during late lactation and post-lactation, and the magnitude of this P deposition is sufficient to explain the recovery of P reserves. The consequences of mobilization on dietary P requirements are substantial. A lactating cow growing at 0.3 kg/day and ingesting 12 kg DM/day would require about 21 g P/day, and in the absence of any net mobilization of body P reserves would require a concentration of 1.7 g P/kg dietary DM (Table 1). Mobilization of 9 g P/day would reduce the required concentration of P in the diet to about 1.0 g P/kg dietary DM.

If a breeder cow does mobilize large amounts of P during late pregnancy and/or lactation during each reproductive cycle, then obviously these reserves must be replenished. It is clear that goats depleted in P due to inadequate P intake during early lactation can deposit large amounts of P into body reserves (up to 24 mg P/kg LW.day and 1.0 g P/kg LW over 10 weeks, the latter equivalent to 400 g P in a 400 kg breeder) when high P diets were fed during a repletion phase (Rodehutsord *et al.* 1994b). This suggests that the breeder cow has the capacity to rapidly recover body P reserves in late lactation and post-lactation if P intake exceeds the current P requirements. In the case of a cow calving each 12 months and in the absence of P supplementation, presumably any replenishment is most likely to occur in late lactation and after weaning as current P requirements decrease. Since tropical pastures decrease markedly in P concentration with maturity, the dry season pastures available to breeders in late lactation and post-lactation will usually be lower in P concentration than during the wet season. However because the P requirements of the non-lactating cow will be low during the dry season it may be possible for the cow to recover, in part or in full, the body P stores depending on dietary P intake. Measurements of large positive P balances (retention) in P supplemented non-lactating cows grazing dry season pasture in the Springmount study in 1994 indicate that the *Bos indicus* breeder cow has the capacity to deposit any P surplus to immediate requirements into body P reserves at this time of the annual cycle (Table 5). The P supplemented cows had net P retention of up to 15 g P/day. This is consistent with a study where P deficient steers given high P diets deposited 7-17 g P/day into body reserves even though the ME content of the diet was sufficient for only slow growth (Bortolussi *et al.* 1999).

Table 5. Intake and balance of P in *Bos indicus* cross breeders grazing pastures in a P-deficient land system at Springmount, Mareeba (Miller *et al.* 1998)

Measurement	Forage and phosphorus intakes					
	V. low P	Low P	Low P+N	Low P+P	Low P+N+P	Moderate P
Dietary P intake (g P/day)						
Late dry season (Sept 93)	1	2	2	1 ^x	2 ^x	4
Mid wet season (Feb 94)	6	9	8	30	28	14
Early dry season (May 94)	3	3	3	23	21	8
Late dry season (Sept 94)	2	3	3	22 ^y	22 ^y	5
Mid wet season (Feb 95)	8	10	9	19	18	21
Early dry season (May 95)	2	4	2	14	15	12
P balance (g P/day)						
Late dry season (Sept 93)	-2	-2	1	-2	-2	0
Mid wet season (Feb 94)	-5	-3	-3	16	13	-3
Early dry season (May 94)	-2	-2	-3	10	13	1
Late dry season (Sept 94)	-1	0	0	13 ^y	15 ^y	1
Mid wet season (Feb 95)	-9	-2	-6	-1	-1	0
Early dry season (May 95)	-3	-1	-2	3	7	4

Diets were: V. low P indicates pasture growing on very low P soils of 2 ppm P; Low P indicates pasture growing on soils of 3-4 ppm P with no supplement, with N supplement (Low P+N), with P supplement (Low P+P), or with N and P supplement (Low P+N+P); Moderate P, indicates pasture growing on soils of 6-10 ppm P following application of P fertilizer. Supplements were fed year-round at 10 g P or 28 g urea N/cow.day.

Cows calved in November-December and were weaned in March 1994 or April 1995; thus measurements represented pregnant non-lactating cows in the late dry season, lactating cows in the mid wet season, and weaned non-lactating cows in the early dry season.

Note x, no supplement was fed during the 1993 dry season.

Note y, During the week when P kinetic measurements were made in the late dry season of September 1994 20 g rather than 10 g P supplement was inadvertently fed.

When a cow does not become pregnant during an annual cycle there is presumably ample opportunity to recover the P reserves. Indeed, for both drafts of breeders in the Springmount experiment, those breeders grazing in the lowest P pastures were in negative P balance at each of the measurement times. Presumably the only manner in which cows in these circumstances could recover body reserves is by not calving in some years.

These observations emphasize the role and importance of weaning the cow in the late wet season, or as early as possible in the dry season, to reduce the P requirements of the breeder. Earlier weaning also allows the breeder maximum opportunity to recover P reserves in the late wet and transition seasons.

Table 6. Intake and balance of P (mg P/kg LW.day) in *Bos indicus* cross breeders (initially 370 - 450 kg) grazing tropical pastures in a P-deficient land system at Lansdown, Townsville (Ternouth and Coates 1997)

Measurement	Pasture and phosphorus status		
	Urochloa/Stylo (fertilized)	Urochloa/Stylo (Not fertilized)	Native pasture (Not fertilized)
Dry matter intake (g DM/kg LW.day)			
Mid pregnancy	16.0	11.6	10.6
Late pregnancy	15.4	12.6	15.1
Early lactation	25.5	20.0	22.3
Late lactation	22.4	17.4	22.4
P intake (mg P/kg LW.day)			
Mid pregnancy	21.9	12.2	8.4
Late pregnancy	17.3	6.4	6.8
Early lactation	40.2	17.2	11.5
Late lactation	13.0	12.5	11.1
Milk volume (L/day)			
Early lactation	5.3	4.4	4.0
Late lactation	4.0	2.1	2.6
Phosphorus balance (mg P/kg LW.day)			
Mid pregnancy	-1.9	1.0	-2.0
Late pregnancy	-1.3	-2.4	-3.6
Early lactation	2.0	-10.8	-15.0
Late lactation	-13.6	-3.7	-8.1

Cows calved in late November to early January. P kinetics measurements were made in June, October, December and May.

6. The concentration of inorganic P (Pi) in blood or plasma

6.1. Some principles about Pi

The central role of the pool of inorganic P (Pi) in the blood in P metabolism, and the simplicity and ease of sampling has led to considerable attention to this metabolite as an indicator of P intake and status of the animal. The concentration of Pi in blood was proposed as an indicator of animal P status by the early South African work (Theiler *et al.* 1937).

The site of sampling of blood, whether the analysis is of plasma, whole blood or serum, and animal factors such as low ME intake, excitement and dehydration all affect Pi and need to be considered and accommodated in application of Pi as a diagnostic tool. There are differences in Pi concentrations between plasma, serum, whole blood, and also between blood sampled from the jugular and from the tail vein (McCosker and Winks 1994). Thus comparisons between studies, and estimation of threshold values for Pi to indicate P intake or animal responses have to be cognizant of sampling site and sample preparation.

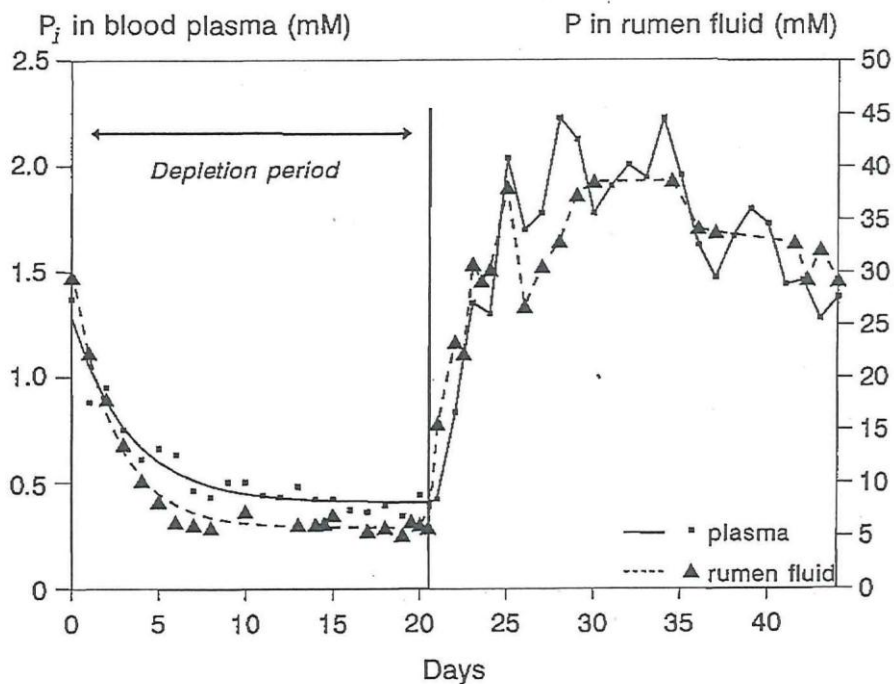


Fig. 4. The concentration of P_i and of soluble P in the rumen fluid of lactating goats initially adequate in P status and during a 21 day interval of dietary P depletion followed by a 25 day interval of P repletion (Rodeshutsord *et al.* 1994a).

In general P_i concentrations primarily reflect the dietary P intake, or more specifically of absorbed P. This has been demonstrated clearly in several experiments when lactating goats or cows in adequate P status were given low P diets during a depletion interval, or conversely were subsequently given high P diets during a repletion phase (Figure 4; Rodeshutsord *et al.* 1994a). During a depletion phase it required 10-20 days for plasma P_i concentration to decrease from concentrations in the 'normal' range (1.5 - 2.0 mM) to a stable low concentration in the range 0.3 - 0.4 mM. During a repletion phase P_i briefly increased to very high concentrations before declining to reach a high stable plateau concentration in the 'normal' range within about 30 days (Pfeffer *et al.* 1993; Rodeshutsord *et al.* 1994a).

Despite the rapid changes in P_i observed in the experiments above, it appears that P mobilized from body reserves may in some situations contribute to, and elevate, P_i for many months or even years. In other experiments the decrease in P_i following a change to a low P diet has occurred over months (Benzie *et al.* 1959; Gartner *et al.* 1982; Valk *et al.* 2002) or years (Read *et al.* 1986c). In the latter study (Table 3 above), where initially replete reproducing breeders grazed P-deficient pastures, a decrease in P_i concentrations in the absence of P supplements was not evident until the second lactation some 2 years after the treatments were imposed. Presumably the -P cows were able to mobilize sufficient body P reserves to maintain P_i concentration. There were, however, large differences in intake of digestible organic matter. P supplemented cows had intakes that were 29%, 63% and 80% higher than in unsupplemented cows for sequential measurements made during the first 2 years, leading to moderate treatment differences in cow liveweight through the first year (30-40 kg) and 150 kg difference at the end of the second year. This difference was attributable to liveweight gain in the supplemented cows, since liveweight of the unsupplemented cows changed little during the second year. The absence of treatment differences in P_i under these circumstances is difficult to understand but it does indicate that P_i is not always a reliable indicator of P intake. Unexpectedly, there were no differences in P content of rib

biopsy samples (mg/cm³ of full core samples) between + and – P supplement treatments for the first 2 years. In this study the P content of the rib biopsy samples was a poor indicator of bone P reserves, and Pi was a poor indicator of the P intake of these animals, while the growth and reproductive performance of the animals suggested that their P status was adequate.

Numerous experiments have reported that Pi concentration was directly related to the rate of P absorption and salivary P secretion. For example, Challa *et al.* (1989) reported that P retention increased in direct relation to serum Pi concentration between 0.8 - 2.2 mM/L up to a maximum retention of 20 mg P/kg LW.day. In a comprehensive meta-analysis Bravo *et al.* (2003c) reported that there is a general curvilinear relationship between P concentration in the diet (X) and Pi (Y, mmol/L), and for X < 2.5 g P/kg DM the relationship was approximately $Y = 0.5 + 0.90 X$ (n = 28). At X=2.5 the Pi = 2.5 mmol (75 mg Pi/L), and the curvilinearity of the relationship was such that there was little further increase in Pi with further increases in dietary P concentration. Inversion of this relationship suggests that increases in Pi in the range 0.8 mmol (25 mg P/L) to 2.0 mmol/L (60 mg P/L) were associated with increases in diet P concentration from 0.3 to 1.7 g P/kg DM. When Pi exceeded about 2 mmol/L there was a rapid increase in urinary excretion of P, explaining the absence of increases in Pi as P intake increases to > 2.5 g P/kg DM. However this meta-analysis was based largely on experimentation in Europe and North America, included many concentrate diets, and thus may not be representative of cattle grazing tropical pastures.

Numerous experiments have reported decreases or increases in Pi as a consequence of decreasing, or increasing, respectively, P intake regardless of whether the dietary P was provided as a constituent of feedstuffs or as an inorganic P supplement (Noller *et al.* 1977; Call *et al.* 1978; Lebdosoekojo *et al.* 1980; Winter 1988; Deitert and Pfeffer 1993). However such relationships have often not been adequate to predict P intake from Pi. For example when pregnant beef cows were fed hay and increasing amounts of ammonium phosphate supplement, although the Pi in control cows (29 mg P/L) indicated a P deficiency, the relationship between Pi and P intake had an $R^2 = 0.05$ (Sanson *et al.* 1990). In the northern Australia context, Pi has been closely correlated with P intake in some experiments (e.g. Hendricksen *et al.* 1994; $R^2 = 0.94$), but not in others (e.g. Coates and Ternouth 1992).

In general, there seems to be a consensus that Pi concentrations can be used as an indicator of the P intake of the animal (e.g. Karn 2001) although consideration needs to be given to a number of factors as discussed above. The most important considerations are whether P is likely to be the first limiting nutrient, and whether mobilization of P reserves is likely to contribute substantially to the demands of the animal for P.

6.2. Pi in growing cattle

Some authors have proposed that in the growing animal a response to P supplementation when the Pi is less than 30 mg P/L, while other authors have proposed a value of less than 40 mg P/L. Clearly this will depend partly on the methods used to measure Pi. Excellent LW gain responses to P supplementation have been observed when Pi was in the range 30-40 mg P/L (Van Schalkwyk and Lombard 1969; Winks *et al.* 1974; Winks *et al.* 1977; Gartner *et al.* 1982; Winter 1988). When Pi has been less than 30 mg P/L voluntary feed intake has been substantially reduced in sheep (Milton and Ternouth 1985; Ternouth and Sevilla 1990a, b) and in cattle (Belonje 1978; Gartner *et al.* 1982). However Pi values of greater than 40 mg P/L are of little value in estimating P intake. The latter hypothesis is supported by the data of Bravo *et al.* (2003c) which show that the Pi concentration tends to plateau as diet P concentration increases above about 2 g P/kg DM, indicating that at Pi is an indicator only in the lower range of P intakes.

In a comprehensive study with *Bos indicus* cross heifers grazing *Urochloa* - *Stylosanthes* pastures in north Queensland, Coates (1994) observed a close relationship between the LW gain response to P supplementation and the Pi concentration (Figure 5). The increase in LW gain due to P supplementation, which was 0.30-0.35 kg/day when Pi concentrations were 30-40 mg P/L, decreased curvilinearly as Pi increased and were extinguished when Pi was 60-70 mg P/L.

A major study across 4 sites in northern Australia (Wadsworth *et al.* 1990) reported relationships between Pi and LW gain measured over 4 periods in each year (early wet, late wet, early dry and late dry seasons) of several years. Measured Pi varied with P fertilizer rate and P supplement. Regression relationships for each seasonal period were developed and those for periods of maximum and minimum gain are shown in Figure 6 for example years at each site. These data suggested that during the period of maximum gain Pi below 60 mg P/L was indicative of a restriction on rate of gain and a likely response to higher P intake. There were significant differences between sites, years and seasons of the year which prevented derivation of a general relationship between LW change and Pi. The success rate of diagnosis of P deficiency based on Pi < 40 mg P/L as a reference value and positive LW gain averaged only 55%.

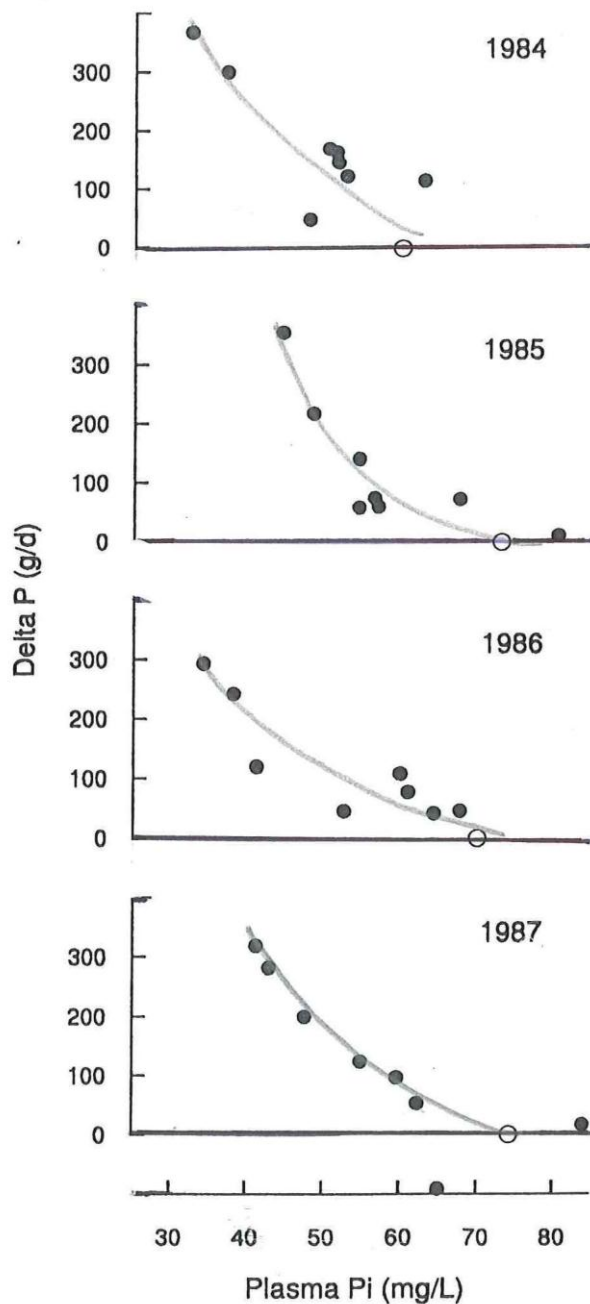


Fig. 5. The relationship between the Delta P (the difference between the average daily gain of unsupplemented and supplemented heifers over the main growing period (210-224 days)) and plasma Pi concentrations of unsupplemented heifers (Coates 1994). Pi are the mean of 2 samplings (May and August) for the 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. The Pi of supplemented heifers is shown as (○).

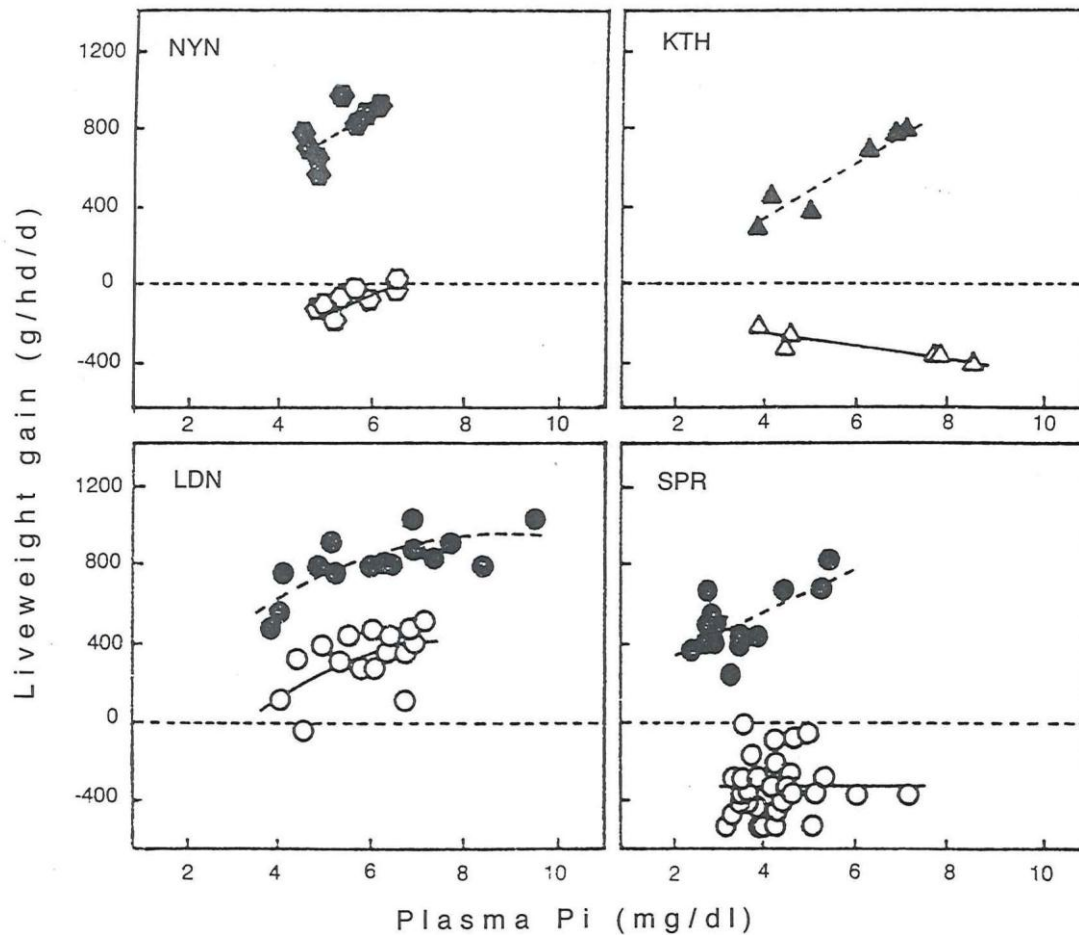


Fig. 6. Relationships between mean liveweight gain and Pi of cattle during seasons of maximum (●) and minimum (○) liveweight gain for example years at 4 sites (NYN, Narayen; KTH, Katherine; LDN, Lansdown; SPR, Springmount) in northern Australia (Wadsworth *et al.* 1990).

6.3. Pi in reproducing cattle

It seems likely that during pregnancy and lactation the Pi concentrations will be related to flows of P as absorption, excretion and transfer to the rumen in a similar manner to growing animals, although there are the additional sinks of conceptus and milk. Differences associated with pregnancy and lactation are likely to be associated with these large demands for P and, as discussed above, a greater capacity of the reproducing ruminant to mobilize P reserves to meet a deficiency of dietary P. Pi concentrations are lower in lactating cows than non-lactating cows (e.g. Dixon *et al.* 2010), but this is not unexpected given the demand for P for milk synthesis. In the Springmount experiment (Miller *et al.* 1998) Pi was related to P intake with R^2 ranging from 0.70 to 0.96, but the relationships differed between sampling dates.

Other studies with beef cattle in pregnancy and lactation (Fishwick *et al.* 1977; Bass *et al.* 1981) indicate differences between reproducing and growing animals. In these studies voluntary intakes of unsupplemented cows in late pregnancy were similar to those of P supplemented cows despite low Pi concentrations (0.6 and 1.1 mmol/L in the 2 studies). This appears to be in contrast to the growing animal. However, during the subsequent early lactation when Pi in the 2 studies was on average 0.41 and 0.90 mmol/L in the unsupplemented cows, there was a major 30% depression in voluntary intake of roughage and of total ME (Figure 7). Also LW loss of the cows in early lactation, and growth of the

suckling calves was increased substantially by increased dietary P supply, indicating that the low P status of the control unsupplemented cows reduced milk production. The depression of voluntary intake in lactation may have been due to the greater demands for P for milk or because of depletion of the P reserves.

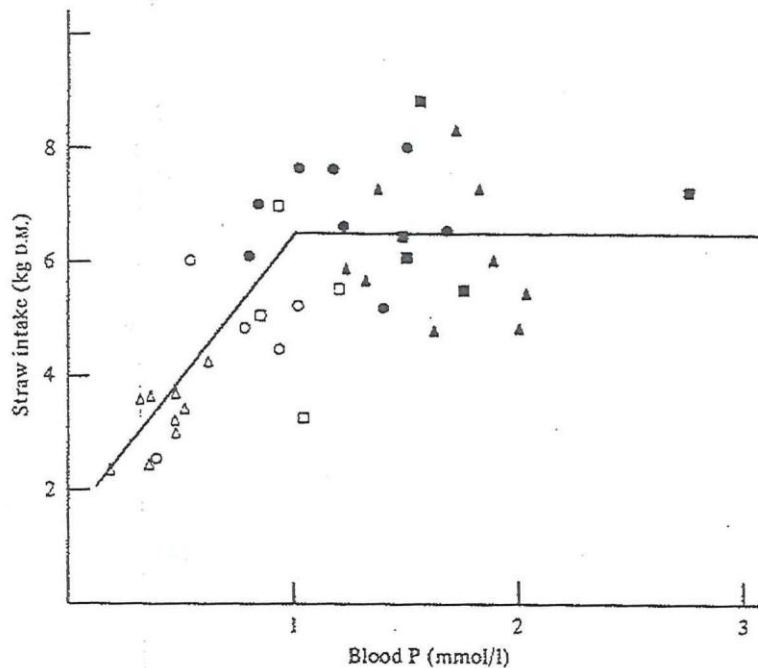


Fig. 7. The relationship between P_i and the voluntary intake of oat straw by *Bos taurus* beef cows in early lactation (open symbols indicate unsupplemented diets and filled symbols P supplemented diets in the experiments of Fishwick *et al.* (1977) and Bass *et al.* (1981).

The study of Valk *et al.* (2002) with high producing dairy cows is generally consistent with these studies with beef cows. During the first year of the study (a first lactation and subsequent dry period) the cows were largely able to maintain DM intake, milk secretion and P_i concentrations. However when dietary treatments were continued during a second lactation the effects of dietary P deficiency on these parameters became most apparent. In this study P_i was inversely related to milk secretion, with a relationship with a greater slope in cows fed the lowest P diet (Figure 8).

A number of studies with sheep and goats have reported reduced voluntary intake and milk secretion in animals fed a P deficient diet (Muschen *et al.* 1988; Rodehutschord *et al.* 1994). In the former study this was associated with much lower P_i (0.35-0.52 mmol/L) in P deficient than in P adequate goats (2.40 - 2.60 mmol/L). Negative correlations have been observed between P_i and milk secretion, and between P balance and milk secretion, in lactating ewes, indicating that ewes fed low P diets could maintain P milk production by mobilizing body P reserves and one of the consequences of this was lower P_i concentrations (Rajaratne *et al.* 1990).

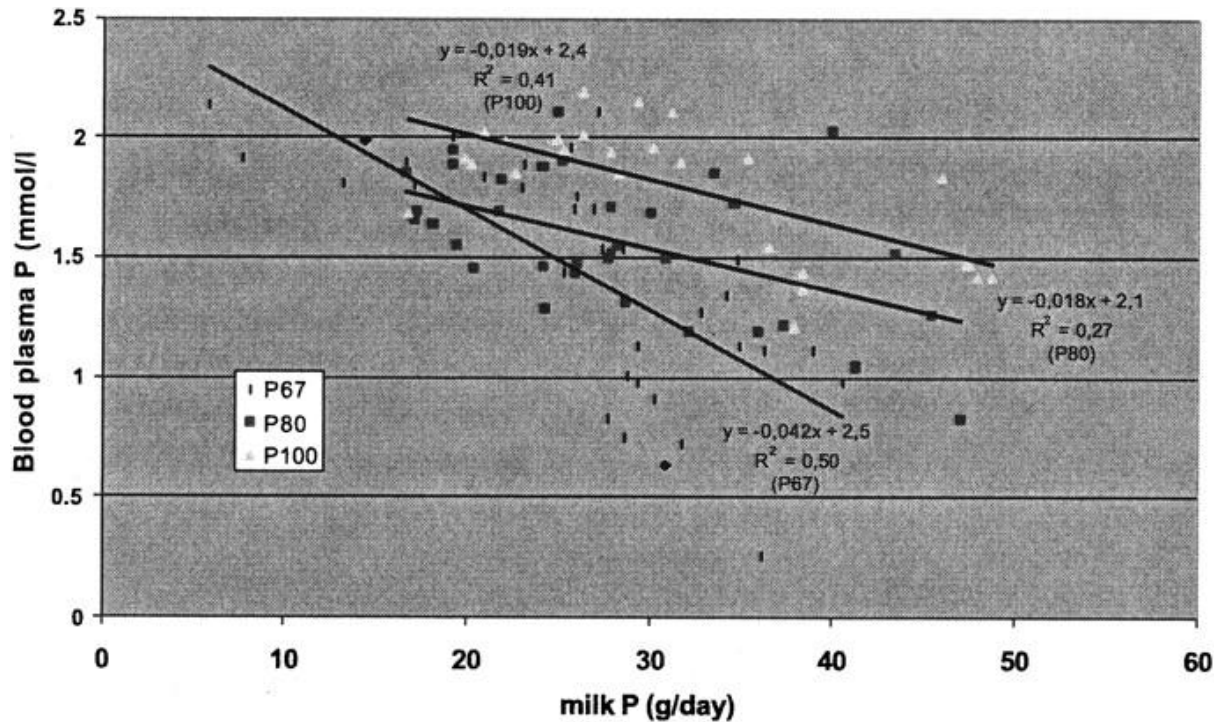


Fig. 8. The relationship between the P secreted in milk and blood plasma P concentration in dairy cows fed 67%, 80% and 100% (P67, P80 and P100 respectively) of expected P requirements over two consecutive lactations (Valk *et al.* 2002). In the first lactation cows fed the P67 diet were able to mobilize body P reserves and were generally able to maintain DM intake, milk P secretion and blood PIP concentration. However in the second lactation the cows fed diet P67 did not mobilize any body P reserves and had reduced DM intake, milk P secretion and blood PIP concentration.

In the study of Ternouth and Coates (1997) Pi changed little from mid-pregnancy to late pregnancy in the dry season, but then declined appreciably in both high and low P treatments in early lactation even though diet P was much higher than during the dry season. There was a further decline in Pi in late lactation demonstrating the effect of high P demand during lactation on Pi. Although Pi was positively related to P intake at each sampling occasion, except at late lactation when P intakes were similar in all treatments, there was no correlation when data were combined across sampling times. Thus it is not possible to establish Pi concentrations that reliably distinguish between dietary P sufficiency and P deficiency in lactating cows because the values change with stage of lactation. In the Ternouth and Coates (1997) study, and in a similar study at Springmount (Miller *et al.* 1998), Pi in lactating cows was correlated with P intake within sampling occasion because calving was restricted to a relatively short period so that cows were at a similar stage of lactation at individual sampling occasions. In the north Australian cattle industry calving is often spread over many months. Therefore at any point in time various cows in the herd are likely to vary widely in their stage of lactation and hence in their Pi concentrations. Thus it will be difficult to use Pi as a reliable diagnostic indicator.

Results from the Springmount study (Miller *et al.* 1998) also showed that lactation effects on Pi persisted for some time after calves were weaned. Pi concentrations measured in May (9 and 5 weeks after weaning for drafts 1 and 2 respectively) remained much lower than those in late pregnancy, even in supplemented cows that had large positive P balances measured in February (lactation) and May (post weaning) of draft 1 and moderate positive P balances measured in May of draft 2 (Table 5). Presumably Pi concentrations remained low due to the need to replace bone P reserves depleted during lactation. These results also indicate the difficulties in interpreting dietary P status from Pi measured in breeders.

Information is also available for lactating cows grazing native pastures at Swans Lagoon Research Station. A number of studies with both growing animals and breeders (Holroyd *et al.* 1977; Winks *et al.* 1977) on this land system have concluded that the pastures are 'marginal' to 'adequate' and that no response or small responses are likely to occur to P supplementation. In a later study (Dixon 1998) small responses to P supplements were observed in cow LW (20-30 kg) in 2 consecutive years, and a small increase in weaning weight (6 kg) in one of these years, when the late wet season Pi was <40 and < 50 mg P/L for the 2 years in unsupplemented cows. Observations from the breeder herd in one year provide further information (Fordyce *et al.* 1995). Pi in tail-vein blood averaged from 21-28 mg P/L, and faecal N was 1.3% N, in young lactating cows in the early dry season. According to a threshold criteria of <30 mg Pi/L, and also as summarized by McCosker and Winks (1994, page 56) these herds would be classed as in 'deficient' P status. This was in accord with extensive soil testing in the same paddocks which concluded that 70% of the area was 'acutely deficient' (0-3.5 ppm) or 'deficient' (3.6-6.5 ppm), 10% was 'marginal' (6.6-8.5 ppm), and 20% was 'adequate' (>8.5 ppm). However a classification that these breeders were P deficient was not in accord with observations that the fertility of these herds was high (long-term average calving rate 82%) and mortality rate was low (long-term annual average 1.5%); this productivity is high by industry standards and there would clearly be limited scope for improvement in reproductive productivity of the herd. We speculate that regimes of a conservative stocking rate for this breeder herd allowed cattle to select diets higher in P than would otherwise be the case, and that a rigorous early weaning program reduced the annual demands for dietary P. The early weaning program allowed long phases during which replenishment of body P reserves could occur. However, it is quite possible that P supplementation of this herd would increase breeder liveweight and milk for calf growth. Nevertheless these observations suggest that breeder productivity can be high even where the Pi was indicating that responses would likely occur to P supplementation.

In conclusion, from the studies discussed above it seems difficult to nominate minimum threshold values of Pi for breeder cows in late pregnancy or during lactation. It seem likely that LW and milk production responses to P supplementation will occur when Pi is < 30 mg P/L, but such responses may not be economically viable.

6.4. The P-Screen test

Given a consensus in the early 1990's that Pi was the 'best bet' as a diagnostic indicator of the responses of cattle to P supplementation, the 'P-Screen' test was developed and made available to the cattle industry through the (then) Queensland DPI laboratory services. The test specified blood sampling of 20 animals in the herd to measure blood Pi, and an associated faecal sample to measure faecal nitrogen concentration. It was recommended that sampling be done in the late wet season when animals had been in high LW gain, and / or lactating, for some months, and thus when body P reserves were expected to be depleted. It was suggested that the groups of animals tested should be chosen to be those likely to be more sensitive to P in the diet, such as young lactating cows. The measurement of faecal N was intended to be a proxy for diet quality and thus of the potential LW gain of the animals. This was based on the observation that on wet season pastures the faecal N concentration is correlated with diet DMD and metabolizable energy intake, and in a season when diet N is not expected to be limiting.

The P-screen test has not been widely adopted across northern Australia during the last 15 years. From anecdotal information it appears that the principal problems have been a lack of awareness of the test in the cattle industry, understanding and confidence in the results if the test is done, and the practical difficulties associated with conducting the test in the commercial cattle industry environment. Availability of the test kits on property at the appropriate times, skills on-property to collect and process blood samples or the high cost

for outsiders to conduct this task, plus storage and transport of samples to laboratories for analysis all create substantial obstacles.

We recommend that blood sampling for Pi still provides the most reliable indicator of the P intake of growing animals, and that this is more reliable than the method based on the concentration of P in faeces. With breeders interpretation of Pi is much more difficult. Low Pi still indicates that dietary P intake is less than the requirements of the animal, but does not necessarily indicate economical production responses to P supplementation. We recommend that when Pi sampling is conducted that it be combined with FNIRS estimates of diet quality and wet chemistry measurement of P in faeces to obtain the best possible information. As discussed by McCosker and Winks (1994) timing of the test (usually in the late wet season after extended growth and/or milk production) and careful selection of the most appropriate animals to test are important.

7. Production responses of cattle to increases in diet P

Winks (1990) provided a comprehensive review of LW gain and reproduction responses in cattle to P supplement from the literature at that time. Since there have been few papers during the last 2 decades reporting responses by grazing cattle to P supplementation, the review of Winks (1990) still provides a comprehensive summary and we have little to add. Winks (1990) summarized both pen feeding and grazing experiments, mainly in Australia, South Africa, Zimbabwe and USA. Some of the issues identified were:

- (i) P supplements do not generally increase the digestibility of forage diets, and LW gain responses can almost always be attributed to increased DM intake. There appears to be only one study (Gartner *et al.* 1982) where high and low P diets were fed at the same DM intake and there appeared to be improved feed conversion efficiency due to higher P intake.
- (ii) LW gain responses occur only when P is the primary limiting nutrient. For cattle grazing native grass pastures in northern Australia LW gain responses to P supplement are likely only during the wet and transition (or green) seasons when dietary protein and energy levels are sufficient to allow weight gain. Winks (1990) suggested that "Most work suggests that N concentration needs to be above 1.5% (9.4% CP) for responses to occur". We disagree with this as a criterion. Extensive faecal NIRS measurements from cattle grazing native pastures in northern Australia indicate that diets seldom exceed 1.5% N, and are usually considerably less than 1.5% N even in the wet season. Moreover, diet quality estimates obtained using faecal NIRS indicate that *Bos indicus* and *Bos indicus* cross cattle can gain LW when diet N concentration exceeds about 0.8% (5% CP). Second, with legume-based pastures CP and ME concentrations are often sufficient for LW gain well into the dry season. Thus responses to P supplement can be expected and have been well demonstrated in cattle grazing such legume based pastures (see below).
- (iii) In the studies reviewed by Winks (1990) there was enormous variation in responses to P supplements. Examples of large positive responses include (a) 256 kg over 28 months at Vryburg, South Africa (Bisschop 1964), (b) 100 kg over 15 months in Papua New Guinea (Holmes 1981), (c) 89 kg over 8 months at Charters Towers, Queensland (Turner *et al.* 1935), and (d) 50 kg over 11 months in Texas, USA (Black *et al.* 1943). Examples of small or nil (not statistically significant) responses include the studies of Murray and Romyn (1937), Little (1968, 1980), Cohen (1972) and Holm *et al.* (1981). It is to be expected that the magnitude of responses in LW gain depends on the severity of the dietary P deficiency and the productive potential of the other dietary nutrients, especially energy and protein. The range of responses

observed presumably reflects variation in P concentrations in forages among land systems and variation among the P requirements of various classes of animals.

7.1. Reports of negative effects of P supplements

A number of studies have suggested P supplements may have adverse effects on LW change of cattle grazing dry season pastures, and that this has particularly occurred when phosphoric acid was used a P supplement. We suggest that there are several explanations for such observations, and conclude that there is little evidence that adverse effects of P supplementation are likely in practice in the northern Australian situation providing that supplementation technology is applied appropriately.

Small negative LW change responses to a supplement of phosphoric acid mixed with molasses and fed during the dry season were reported by Winks and Laing (1972) and Winks *et al.* (1976, 1979). However, only in 2 of 7 years was the depression statistically significant. With breeder cows Holroyd *et al.* (1977) observed no effect of the same type of supplement during 3 consecutive dry seasons. When phosphoric acid was provided in drinking water to steers grazing stylo or native pastures (Winks *et al.* 1977) there was no significant effect of the P supplement on LW change during the dry season. The only experiment of which we are aware where major adverse effects were observed from supplementation of breeders with phosphoric acid in the drinking water was that of Playne *et al.* (1974), and may have been associated with poor water quality. It seems likely that a contaminant(s) in the fertilizer grade 'black phosphoric acid' used as the P supplement in these early experiments caused some of the adverse effects. McMeniman (1983) reported a marked toxic effect of 'black phosphoric acid' which contained 12% sulphuric acid as an impurity. Sulphuric acid is known to cause metabolic acidosis in ruminants at much lower intakes than hydrochloric acid or phosphoric acid (L'Estrange *et al.* 1969; L'Estrange and Murphy 1972). This may explain the adverse effects occasionally observed when phosphoric acid - molasses mixtures have been used as supplements. Technical grade phosphoric acid would not be expected to cause these problems.

A second possible reason for adverse effects of phosphoric acid when provided as a supplement through the drinking water is that voluntary intake of the water may be reduced. It is well established (Goatcher and Church 1970) that acidity causes sour flavours and reduced palatability, and sometimes reduced voluntary intake. Phosphoric acid, as for any strong acid, will reduce the pH of water, although the extent will clearly depend on the quality of the water and the amount of acid. Reduced intake of drinking water will be expected to reduce voluntary forage intake and, in the more extreme situation, dehydration of the animal.

From an experiment where cattle were fed a low quality forage diet and were supplemented with energy, nitrogen or phosphorus (as mono-calcium phosphate) van Niekerk and Jacobs (1985) concluded that phosphorus supplements given alone or with nitrogen supplements with such forage tended to have a negative effect on feed intake and LW change. However scrutiny of their results indicates the provision of P supplement reduced total DM intake by 55 or 104 g/day (<4%), and LW change by 30 or 48 g/day in the absence or presence of N supplements, respectively. These differences were apparently not statistically significant. Therefore we conclude that there was no evidence from this experiment of adverse effects of P supplements in low quality forage diets and where animals are losing LW, as typically occurs in the late dry season.

A recent pen feeding experiment reporting the effects of N and P supplements in young steers fed a low quality diet (0.6% N for 15 weeks (Bortolussi *et al.* 1996) is difficult to interpret within the classical conceptual framework that responses will occur in sequence depending on which nutrient is first-limiting. There were 3 levels of dietary N (low, L;

moderate, M; high, H) and also 3 levels of dietary P (also L, M and H). LW losses occurred in steers fed both low-P and moderate-P treatments (-23 and -12 kg/hd, respectively). Steers in the LN/MP treatment responded positively to additional P when compared with the LN/LP treatment, indicating that P was the primary limiting nutrient in the LN/LP treatment and that cattle could respond to P supplement even when they were losing liveweight. However, steers in the MN/LP treatment responded positively to additional N when compared with the LN/LP treatment, indicating that N was the primary limiting nutrient in the LN/LP treatment. Thus LW change of the steers increased in response to an increase in either P or N nutrient alone. Also, the response to additional P increased with increasing N concentration in the diet, while the response to additional N increased with increasing P in the diet. Thus there were interactions between these nutrients, possibly due to varying mobilization of body reserves, which obscure interpretation of the responses to N and P supplements of cattle fed low quality diets.

7.2. Response to P supplements by growing cattle in recent grazing trials

Grazing trials conducted on legume based pastures at 4 locations in northern Australia (Narayan near Mundubbera, Lansdown near Townsville, Springmount near Mareeba, Manbulloo Station near Katherine) provided additional important information on LW gain responses to P supplementation (Winter *et al.* 1990). These were chosen for their low P soils and where cattle grazing unfertilized pasture would be P deficient. At Narayan the pasture legume was Siratro (*Macroptilium atropurpureum*), while *Stylosanthes* species were used at the northern sites. The LW gain responses to P fertilizer and P supplement have been described in detail by Winter *et al.* (1990) with gains apportioned to 4 periods in each year, these periods corresponding to the early wet, late wet, early dry and late dry seasons at the northern, tropical sites, and to spring, summer, autumn and winter at Narayan. Annual LW gain responses to P supplement on various treatments at Katherine, Springmount and Lansdown exceeded 60 kg/hd while responses to P supplement on the low fertility treatments at Narayan were substantially less (see Winter *et al.* 1990). Of particular interest were the seasonal responses to P supplement as shown in Table 7 below.

These results indicate that for pastures with a strong legume component responses to P supplement can occur well into the dry season due to the legume providing higher dietary N levels than in grass pastures without legume. The negative responses recorded in the early dry at Lansdown and the late dry at Katherine were probably not due to the effect of P supplement being consumed at that time but rather to heavier and better conditioned cattle suffering greater weight loss than lighter, lesser conditioned cattle on poor quality diets. More detailed data from the Lansdown site (Coates 1994) showed that the annual LW gain response to P supplement for Droughtmaster heifers grazing unfertilized stylo/grass pasture averaged 55 kg/head (range 20 to 101) over 6 years. Most of the response occurred during the early wet and late wet seasons but there was a positive response to supplement in 5 of 6 years in the early dry season.

Table 7. Liveweight change responses to P supplement according to seasons (Winter *et al.* 1990). The seasonal responses relate to those treatments where the annual response to P supplement was large (> 60 kg/animal). Large responses were greater than 300 g/day, while moderate responses in the range 100-300 g/day.

Season	Katherine	Springmount	Lansdown
Early wet	Positive & large	Positive & moderate	Positive & large
Late wet	Positive & large	Positive & moderate	Positive & large
Early dry	Positive & small	Positive & moderate	Nil to negative
Late dry	Negative & moderate	Positive & small	Variable

In another trial at Lansdown, on soil lower in available P than the Lansdown trial presented in Table 7, unsupplemented steers grazing unfertilized stylo/grass pastures gained only 53 kg/head while those receiving P supplement in the water gained 171 kg/head, a response of 118 kg/head in one year, August 1989 to August 1990 (Coates unpublished). Adverse seasonal conditions in 1990/91 reduced LWG in supplemented and unsupplemented steers to 67 and 35 kg/head respectively but large responses to P supplement were again recorded in 1992/93 with supplemented steers gaining 150 kg compared with 59 kg/hd for unsupplemented steers (Coates and Murray 1994).

7.3. Response to P supplements by breeder cattle in recent grazing trials

Winks (1990) comments that 'Invariably, breeding cattle grazing in a P deficient situation have poor reproduction rates' and provides examples of increased conception rates in response to P supplementation. These included studies in South Africa (Theiler *et al.* 1928, Bisschop 1964, Read *et al.* 1986), Zimbabwe (Ward 1968), Texas, USA (Black 1943), and Australia (Hart and Mitchell 1965) where large increases were recorded. Nevertheless, Winks concluded that 'Under Australian conditions.....few studies have shown a significant benefit'. We suggest that this is likely to be the result of studies not targeting land systems with low soil P status and the lack of comprehensive and well designed studies involving breeders.

A grazing trial at Springmount with breeders in 1993-95 demonstrated large biological responses to P supplementation in a land system known to be acutely P deficient (Miller *et al.* 1996, Coates *et al.* 1996, Miller *et al.* 1998). Treatments most relevant to P supplementation responses were based on stylo/grass pastures at low soil P (3-4 ppm bicarbonate extractable P), and comprised low soil P with nil supplement (LP), low soil P with P supplement (10 g P/cow.day; LP + P), low soil P with N supplement (28 g N/cow.day as urea; LP + N), and low soil P with both P and N supplement (LP +NP). Supplements were fed year round except during the 1993 dry season. Each annual cycle involved a separate draft, and the cows in each draft were initially pregnant and in good body condition. Treatment paddocks were not replicated so that differences between treatments were confounded with possible paddock effects. Cows responded positively to P supplement in terms of wet season weight change, milk production and condition score at weaning (Table 7). Despite differences in milk production measured once for each draft, calf growth rates did not differ in draft 1 and differences were small in draft 2 (Table 7). Cow condition scores at weaning suggested that supplement would have had a substantial effect on post-calving fertility. P kinetics studies were conducted during late pregnancy, early lactation and in the early dry season after calves were weaned. The late pregnancy P kinetics studies were conducted in September, late in the dry season when feed quality was poor. In September 1994 (draft 2) cows in LP, LP+N and LP+NP treatments were at about

maintenance or starting to lose weight while cows in LP+P had been losing LW since late July. Inadvertently the cows in treatments LP+P and LP+NP had high intakes of P supplement during the P kinetics study such that their total daily P intakes averaged about 22 g compared with only 3 g in treatments LP and LP+N. Measured P balances were 13 and 15 g/day for LP+P and LP+NP cows respectively. This demonstrated that cows in late pregnancy can retain P fed as supplement even when forage quality is poor and when cows are losing LW. This supplementary P would have provided the requirements of the developing conceptus and potentially contributed to increased bone P reserves. In contrast, measured P balances of cows in the LP and LP+N treatments were 1.1 and -2.5 g/day respectively. There would necessarily have been an internal transfer of P to the conceptus in these cows and thus a decrease in their bone P reserves. While P supplementation during the late dry season did not result in a LW benefit to cows at this time, the higher reserves of P would be expected to have been beneficial during the period of high P demand during lactation.

Table 8. Treatment means for cow LW changes post-calving to end of each draft, cow condition scores at weaning, milk production and calf gains at Springmount, Mareeba (Miller *et al.* 1998).

Measurement	LP	LP+P	LP+N	LP+NP
Cow LW change post calving to weaning (kg)				
Draft 1: 21/12/93 – 13/6/94	-49	-16	-90	30
Draft 2: 16/1/95 – 10/7/95	-51	-22	-74	-3
Cow condition score at weaning (1 – 5)				
Draft 1	2.2	3.1	2.2	3.1
Draft 2	2.8	3.2	2.9	3.2
Milk production (kg/cow.day)				
Draft 1	3.6	5.1	3.5	4.8
Draft 2	4.5	6.2	5.9	7.0
Growth of calves (kg)				
Draft 1: 21/12/93 – 21/3/94	91	92	82	90
Draft 2: 16/1/95 – 19/4/95	89	102	94	101

Although dietary P levels are lowest in the dry season the best responses to P supplement in cattle grazing P deficient pastures occur during the wet or green season. The imbalance between dietary P and dietary protein/energy levels is most severe during the green season when protein and energy levels are high. During the dry season, although dietary P levels are lower than in the green season, protein is likely to be the primary limiting nutrient and responses to P supplement are unlikely to occur unless the protein deficiency is alleviated. Even then the response to P supplement will be limited by low forage digestibility. Based on this premise the general recommendation has been that dry season P supplementation is ineffective and uneconomical.

In contrast to the above concept, relatively recent information from a major study in South Africa has provided strong evidence for substantial benefits from winter P supplementation of breeding cows grazing P deficient pasture (de Brouwer *et al.* 2000). For the 4 years of the study (1985-89), there were 3 levels of P supplement during the summer-autumn (December-May inclusive). These were 8.3 (summer high: S-HP), 5.0 (summer moderate: S-MP) and nil (summer nil: S-nilP) g P/day. In addition all treatments were fed 10 g/day of P supplement during winter-spring (June-November) plus 60 g urea/day. However, in the final year of the study (December 1989-November 1990) P supplement was fed at 3 rates during

the winter-spring: 9 (W-HP), 5 (W-MP) and 0 (W-nilP) g P/day. Supplementation during winter-spring was arranged so that 3 sub-groups of cows in each of the summer treatments received the different winter P regimes. Mating was from mid-December to mid-February so that calving was during spring (September-November). Calves were weaned in May. The late autumn-winter-early spring period corresponds to the dry season of northern Australia.

The culling policy adopted throughout the trial meant that treatment effects on calving and weaning rates could not be determined. Summer supplement regime had a significant effect on cow liveweight at the end of autumn with 4-year means of 548, 528 and 509 for S-HP, S-MP and S-nilP treatments respectively. Autumn condition score of S-nilP cows was significantly less than that of S-HP and S-MP cows but there was no difference following winter-spring supplementation with P and urea. There were treatment differences in the P concentration (weight/volume) of rib-bone biopsy samples where samples consisted of a complete core through the rib. Interestingly, P concentrations that were low in biopsy samples from S-nilP cows in autumn (113 mg P/cm³) increased substantially in response to P plus urea supplement during winter-spring (139 mg P/cm³). P concentrations also increased in the other treatments but to a lesser extent than in S-nilP cows. Nevertheless, it was clear that cows in all treatments were able to lay down bone P reserves during the winter-spring period. There was no difference between treatments in calf birth weights or growth rates. It appeared that lack of P supplement during summer-autumn had little adverse effect on overall cow/calf performance provided that cows received the P plus urea supplement during winter-spring. It can be concluded that cows in the S-nilP treatment mobilised bone P reserves to maintain milk production during the summer.

The results in the final year were most informative. Mean cow liveweights and condition scores at the start of the winter-spring period were similar across the W-HP, W-MP and W-nilP treatments as a result of reallocation of cows to winter-spring supplement regimes. Winter weight gains, attributed to the developing foetuses, were lower in treatment W-nilP than in treatments receiving P supplement despite W-nilP cows consuming more urea than the other treatments. End-of-spring (post calving) mean liveweight and condition score of W-nilP cows were significantly lower than for P supplemented cows. Importantly, although there was no significant differences in P concentration of rib biopsy cores between winter-spring supplement treatments at the start of winter, concentrations measured at the end of spring were very low in W-nilP cows and just over half the concentration measured in P-supplemented cows which were virtually unchanged from the end of autumn concentrations. This demonstrated that cows receiving sufficient P supplement in winter-spring were able to maintain bone P reserves despite the demands for P associated with pregnancy, calving and early lactation at a time when, for most of the period, forage P concentrations and overall forage quality would be low. Nevertheless, cows in treatment W-MP which had received no supplement during the previous summer-autumn also had very low rib P concentrations at the end of spring. All cows in treatment W-nilP displayed classic symptoms of aphosphorosis at the end of spring and 3 of the 24 cows in the group died.

These results of de Brouwer *et al.* (2000) and those from the Springmount breeder experiment (Miller *et al.* 1998) demonstrate an important difference between breeding cows and growing cattle in relation to potential benefits from dry season P supplementation. In growing cattle demand for P is directly related to growth rate such that if potential growth rate is at or below maintenance requirements due to dietary protein or energy limitations then demand for P will be low and a LW gain response to P supplement would not be expected. However, we are not aware of any definitive evidence showing that severely depleted bone P reserves could not be restored to some extent by dry season supplementation with a combination of P and N. In breeding cows, however, demand for P can be high when feed quality is low if the cows are in late pregnancy or lactating. Net P requirements for the whole conceptus in late pregnancy increases from about 2 g/day in the

7th month to 5 g/day in the 9th month (CSIRO 2007) while the net P requirement for milk in a cow producing 5 kg milk/day is 8 g/day (Ternouth and Coates 1997, CSIRO 2007) in addition to the normal maintenance requirements. If these net requirements cannot be met from the diet then the required P necessarily must come from bone P reserves or from bone P plus soft tissue P if the cow is losing weight as determined by a change in conceptus free liveweight. We suggest that providing P supplement during these times when forage quality is low will halt or lessen the net mobilisation of bone P reserves thus preserving them for later use should the need arise. The results reported by Miller *et al.* (1998) and de Brouwer *et al.* (2000) indicate that not only can these requirements be met by supplementary P but that sufficient P supplement can result in net deposition of P into P-depleted bone.

If the above supposition is correct this can have important implications with regard to supplementation strategies in many areas of northern Australia where it is difficult or not possible to provide P supplement to cattle in the early to mid wet season because of access problems. The provision of P and N supplements during the dry season, especially to pregnant or lactating cows, should maintain bone P reserves. These could subsequently be mobilised in sufficient quantities to meet P demands during intervals when P supplementation is not possible.

7.3. Comparison of the provision of P indirectly by fertilizers or by direct supplementation

Increased P intake may be achieved indirectly by applying fertilizer to the pasture or directly by means of supplementation. Application of fertilizer usually has a three-fold effect: (i) an increase in the yield of the pasture, (ii) an increase in the P concentration of the plant material, and therefore an increase in the P intake of the grazing animal, and (iii) an improvement in the nutritive value of the diet due to improvements in digestibility and protein content, especially in regard to legume-based pastures. Since all three effects are likely to contribute to improved animal productivity it is often difficult to determine that portion of the response resulting from the change in P intake. On the other hand responses by grazing cattle to P supplementation will be due to increased P intake without any change to the pasture on offer, at least in the short term. Changes to the pasture on offer may occur over time due to changes in grazing pressure resulting from increased DM intake by P-supplemented cattle in deficiency situations and to changes in pasture botanical composition that can occur as a result of increased P concentration in the dung of supplemented cattle (e.g. Winter 1988). Moreover, P supplementation can also affect diet selection and the quality of the diet ingested (Coates 1995; Coates 1996; Coates and Le Feuvre 1998). Nevertheless, responses to P supplementation are usually directly attributable to changes in P intake and we have therefore focused on production responses to P supplement rather than to the application of P fertilizer to pasture. Moreover, the cost of applying P fertilizer to overcome a P deficiency is prohibitive over most of northern Australia.

8. P as a substrate in rumen microbial digestion

Numerous studies, as summarized by Winks (1990), have reported that voluntary intake of forage diets is often severely reduced (e.g. by up to 30-60%) by a P deficiency. It appears clear that the adverse effects of P deficiency on voluntary intake are mediated primarily at the metabolic level rather than being due to the effects on rumen digestion (Boxebeld *et al.* 1983; Milton and Ternouth 1985).

Rumen microorganisms have a requirement for P as a substrate as they do for N, S and a number of other minerals. The minimum requirement for P has been reported to be between 50 and 100 mg P/L (Milton and Ternouth 1984; Komisarczuk *et al.* 1987; Breves and Holler 1989). Suboptimal availability of P substrate has often led to substantial decreases in the

digestion of DM in both the rumen and in the entire gastrointestinal tract (Field *et al.* 1975; Fishwick *et al.* 1977; Bass *et al.* 1981; Ternouth and Sevilla 1990a, b). Digestibility of the fibrous components of the diet such as neutral detergent fibre appear to be more adversely affected than that of the more readily digestible components (Milton and Ternouth 1984). This is comparable with the greater effects of N deficiency on digestion of the more fibrous components of the diet (Dixon and Stockdale 1999). In ruminants the concentrations of Pi and soluble inorganic P in rumen fluid are closely correlated (Figure 4 above; Breves and Holler 1989; Rodehutsord *et al.* 2000). This is most obviously due to the extensive transfer of blood Pi to the rumen via saliva which usually exceeds the dietary intake of P.

The N:P ratio of rumen microorganisms is generally in the range 6-8 (Komisarczuk-Bony and Durand 1991). A number of studies have reported that both total microbial crude protein (MCP) synthesis and the efficiency of MCP synthesis per MJ ME have been severely and adversely affected by low availability of P as a substrate for rumen microorganisms (Komisarczuk *et al.* 1987; Petri *et al.* 1988; Breves and Holler 1989; Gunn and Ternouth 1994a, b). There is extensive evidence that dietary nitrogen is the primary limiting nutrient in cattle grazing tropical pasture in northern Australia for much of the annual cycle, and this is exacerbated by low efficiency of MCP synthesis and thus low absorbed amino acid supply (Poppi and McLennan 1995, 2010; Dixon *et al.* 2010). A reduced efficiency of MCP synthesis due to P deficiency will be expected to further exacerbate difficulties of protein supply to the animal and thus further reduce the efficiency of utilization of tropical forages for cattle productivity.

9. Delivery systems for P supplements

Supplementation of cattle in extensive rangeland situations with minerals such as P were summarized by McCosker and Winks (1994), and more recently by McDowell (1996, 1997). The delivery systems can be classed into the following categories:

- (i) Blocks,
- (ii) Mixtures of minerals and conventional feedstuffs. These can range from a simple mixture of salt and calcium phosphate (loose mixes or dry licks) through to mixtures containing feedstuffs providing protein as a protein meal or ME as for example grain.
- (iii) Water medication,
- (iv) Liquid supplements based on molasses fed through roller drums or similar devices to restrict intake,
- (v) Molasses-based supplements fed in open troughs and containing ingredients to constrain voluntary intake. The traditional mixes are M8U (80 kg urea mixed with 1 tonne molasses), MUC (30 kg urea and 100 kg protein meal mixed with 1 tonne molasses), etc. In recent years commercial mixtures such as Anipro, and Dunder (the byproduct following fermentation of molasses to produce industrial alcohol) have become readily available.

The problems of achieving target intakes of low palatability supplements fed ad libitum (or free choice) are well known, and the solutions developed in the industry seem to depend as much on observations and experience as on current science. The problems include acceptability without excessive intakes, achieving target intakes of the key ingredients (e.g. P or urea N), large variability among animals and over time within mobs, variability between paddocks, feeding through rainy weather and the wet season, and the risk of urea toxicity when this ingredient is used. Voluntary intake can change radically with events such as rain. It is generally difficult to predict voluntary intake of supplement mob in a paddock in a new situation.

In general it appears that the following factors are most important:

- (i) Whether an animal ingests supplement obviously depends on the attractiveness (palatability) of the supplement relative to the attractiveness (palatability) of the pasture available.
- (ii) Voluntary intake of a supplement is increased by inclusion of ingredients which are highly palatable and / or attractive (e.g. salt in land systems where cattle are 'salt-hungry', grain, most protein meals, molasses, lucerne). Voluntary intake of a supplement is decreased by inclusion of ingredients which are unpalatable and/or unattractive (e.g. salt at higher levels and especially where soils are high in salt, hardness of blocks, urea at high concentrations, ammonium sulphate as 'Gran-am' fertilizer, acids which cause 'sour' flavours e.g. phosphoric acid, hydrochloric acid as used in Anipro). Post-ingestive feedback mechanisms appear important in influencing voluntary intake of supplement.
- (iii) Experience of animals with similar types of supplements has some benefits for acceptability.
- (iv) The proportion of non-consumer animals, and the variability in supplement intake among animals, appears to be closely and inversely related to the voluntary intake of supplements. The proportion of non-consumers and the coefficient of variation are much higher when voluntary intakes are low (e.g. less than 100 g/day) than when they are high (e.g. 0.5 to 1.0 kg/day) (Dixon *et al.* 2001, 2003).

10. Concluding comments

As a consequence of extensive experimentation, much in Europe and North America, many aspects of the metabolism of P and the nutritional requirements of cattle for P appear to be reasonably well understood. CSIRO (2007) feeding standards can be used to calculate the expected P requirements of cattle in northern Australian grazing systems. However, a serious difficulty is that there is a poor understanding of the extent and the circumstances in which skeletal P reserves can alleviate short-term dietary deficiencies of P, and the limits to mobilization of P stores in *Bos indicus* cattle. There is also a poor understanding of the replenishment of P stores when dietary P intake is in excess of immediate requirements. The interactions between P supply and mobilization with ME intake and dietary concentrations of N and Ca are complex. Most experimental information on the role of P stores and these interactions is derived from sheep, goats or high producing dairy cows. Obviously the diets, levels of production and production systems involved in this experimentation were vastly different to northern Australian circumstances, and application of such information from other species and dairy cows to *Bos indicus* cattle in northern Australia is subject to considerable uncertainty.

We suggest that the procedure proposed and developed in this review to predict P adequacy of grazing cattle needs to be extended and validated. The most serious uncertainty appears to be in relation to the key regression relationship used to estimate diet P concentration from faecal P concentration.

Field tests available to examine the P status of grazing cattle are based on measurement of the concentration of P in faeces using wet chemistry, the measurement of diet quality and ME intake from FNIRS combined with application of CSIRO (2007) nutritional models, and Pi in blood. Each has been developed in fairly specific circumstances, each has its limitations, and each needs to be further developed, improved and validated for the range of grazing systems in northern Australia. For example, quite small changes in the assumed input values for the CSIRO (2007) calculation of the requirements of a grazing animal in a specific set of conditions can have substantial effects on the estimated requirement. Use of the various approaches together is likely to improve the reliability of prediction.

11. References

- AFRC (1991) Technical Committee on Responses to Nutrients. Report 6. A Reappraisal of the Calcium and Phosphorus Requirements of Sheep and Cattle, *Nutritional Abstracts and Reviews (Series B)* 61, pp. 573-612.
- ARC (1980) *The Nutrient Requirements of Ruminant Livestock*. Commonwealth Agricultural Bureaux, Farnham Royal.
- Bass JM, Fishwick R, Hemingway RG, Parkins JJ, Ritchie NS (1981) The effects of supplementary phosphorus on the voluntary consumption and digestibility of a low phosphorus straw-based diet given to beef cows during pregnancy and early lactation. *Journal of Agricultural Science, Cambridge* 97, 365-372.
- Belonje PC (1978) An investigation into possible methods of assessing the intake of calcium and phosphorus by grazing sheep. *Onderstepoort Journal of Veterinary Research* 45, 7-22.
- Benzie D, Boyne AW, Dalgarno AC, Duckworth J, Hill R (1959) Studies of the skeleton of the sheep. III. The relationship between phosphorus intake and resorption and repair of the skeleton in pregnancy and lactation. *Journal of Agricultural Science, Cambridge* 52, 1-12.
- Benzie D, Boyne AW, Dalgarno AC, Duckworth J, Hill R, Walker DM (1955) Studies of the skeleton of the sheep. I. The effect of different levels of dietary calcium during pregnancy and lactation on individual bones. *Journal of Agricultural Science, Cambridge* 46, 425-444.
- Bisschop JHR (1964) Feeding phosphates to cattle. Science Bulletin No 365, Department of Agricultural Technical Services, Pretoria, South Africa.
- Black WH, Tash LH, Jones JM, Kleberg RJ (1943) Effects of Phosphorus Supplements on Cattle Grazing on Range Deficient in this Mineral. USDA Technical Bulletin No. 856.
- Black WH, Tash LH, Jones JM, Kleberg RJ (1943) Effects of phosphorus supplements on cattle grazing on range deficient in this mineral. Technical Bulletin No 856, United States Department of agriculture, Washington DC.
- Block HC, Erickson GE, Klopfenstein TJ (2004) Re-evaluation of phosphorus requirements and phosphorus retention of feedlot cattle. *Professional Animal Scientist* 20, 319-329.
- Bortolussi G, Ternouth JH, McMeniman NP (1988) Dietary nitrogen and phosphorus interactions in *Bos indicus* cattle. *Proceedings of the Nutrition Society of Australia* 13, 124.
- Bortolussi G, Ternouth JH, McMeniman NP (1992) The effects of dietary nitrogen and calcium supplementation in *Bos indicus* cross cattle offered low P diets. *Proceedings of the Australian Society of Animal Production* 19, 381-384.
- Bortolussi G, Ternouth JH, McMeniman NP (1996) Dietary nitrogen and phosphorus depletion in cattle and their effects on liveweight gain, blood metabolite concentrations and phosphorus kinetics. *Journal of Agricultural Science, Cambridge* 126, 493-501.
- Bortolussi G, Ternouth JH, McMeniman NP (1999) Phosphorus repletion of cattle previously exposed to dietary nitrogen and phosphorus deficiencies. *Australian Journal of Agricultural Research* 50, 93-99.
- Boxebeld A, Guéguen L, Hannequart G, Durand M (1983) Utilization of phosphorus and calcium and minimal maintenance requirement for phosphorus in growing sheep fed a low-phosphorus diet. *Reproduction, Nutrition and Development* 23, 1043-1053.
- Braithwaite GD (1975) Studies on the absorption and retention of calcium and phosphorus by young and mature Ca-deficient sheep. *British Journal of Nutrition* 34, 311-324.
- Braithwaite GD (1978a) The effect of dietary calcium intake of ewes in pregnancy on their Ca and phosphorus metabolism in lactation. *British Journal of Nutrition* 39, 213-218.
- Braithwaite GD (1978b) The effect of dietary protein on calcium metabolism of the pregnant ewe. *British Journal of Nutrition* 40, 505-507.
- Braithwaite GD (1980) - hydroxycholecalciferol on calcium and phosphorus metabolism in sheep. The effect of a dose rate of 1-phosphorus metabolism in sheep. *British Journal of Nutrition* 44, 183-191.

- Braithwaite GD (1983) Calcium and phosphorus requirements of the ewe during pregnancy and lactation. 2. Phosphorus. *British Journal of Nutrition* 50, 723-736.
- Braithwaite GD (1986) Phosphorus requirements of ewes in pregnancy and lactation. *Journal of Agricultural Science, Cambridge* 106, 271-278.
- Bravo D, Sauvant D, Bogaert C, Meschy F (2003a) I. A bibliographic database for quantitative analysis of phosphorus flow in ruminants. *Reproduction, Nutrition and Development* 43, 251-269.
- Bravo D, Sauvant D, Bogaert C, Meschy F (2003b) II. Quantitative aspects of phosphorus absorption in ruminants. *Reproduction, Nutrition and Development* 43, 271-284.
- Bravo D, Sauvant D, Bogaert C, Meschy F (2003c) III. Quantitative aspects of phosphorus excretion in ruminants. *Reproduction, Nutrition and Development* 43, 285-300.
- Breves G, Goff JP, Schroder B, Horst RL (1995) Gastrointestinal calcium and phosphate metabolism in ruminants. In: *Ruminant Physiology: Digestion, Metabolism, Growth and Reproduction*. Eds Engelhardt Wv, Leonhard-Marek S, Breves G, Giesecke D. pp. 135-151. Ferdinand Enke Verlag Stuttgart.
- Breves G, Schroder B (1991) Comparative aspects of gastrointestinal phosphorus metabolism. *Nutrition Research Reviews* 4, 125-140.
- Call JW, Butcher JE, Blake JT, Smart RA, Shupe JL (1978) Phosphorus influence on growth and reproduction of beef cattle. *Journal of Animal Science* 47, 216-225.
- Call JW, Butcher JE, Shupe JL, Blake JT, Olson AE (1986) Dietary phosphorus for beef cows. *American Journal of Veterinary Research* 47, 475-481.
- Call JW, Butcher JE, Shupe JL, Lamb RC, Boman RL, Olson AE (1987) Clinical effects of low dietary phosphorus concentrations in feed given to lactating dairy cows. *American Journal of Veterinary Research* 48, 133-136.
- Challa J, Braithwaite GD, Dhanoa MS (1989) Phosphorus homeostasis in growing calves. *Journal of Agricultural Science, Cambridge* 112, 217-226.
- Coates DB (1994) Effect of phosphorus as fertiliser or supplement on pasture and cattle productivity in the semi-arid tropics of north Queensland. *Tropical Grasslands* 28, 90-108.
- 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 (1996) Diet selection by cattle grazing *Stylosanthes*-grass pastures in the seasonally dry tropics: effect of year, season, stylo species and botanical composition. *Australian Journal of Experimental Agriculture* 36, 781-789.
- Coates DB (2004) Faecal NIRS – Technology for improving nutritional management of grazing cattle. Final Report of Project NAP3.121. Meat and Livestock Australia, Sydney.
- Coates DB, Murray RM (1994) Tail-bone density compared with other indicators of phosphorus deficiency in cattle. *Proceedings of the Australian Society of Animal Production* 20, 329-332.
- Coates DB, Le Feuvre RP (1998) Diet composition of cattle grazing *Stylosanthes* - grass pastures in the seasonally dry tropics: the effect of phosphorus as fertiliser or supplement. *Australian Journal of Experimental Agriculture* 38, 7-15.
- 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.
- Coates DB, Ternouth JH, Miller CP, White SJ (1996) Phosphorus kinetics in grazing Brahman-cross cows. *Proceedings of the Australian Society of Animal Production* 21, 380.
- Cohen RDH (1972) Phosphorus nutrition of beef cattle. 1. Effect of supplementation on liveweight of steers and digestibility of diet. *Australian Journal of Experimental Agriculture and Animal Husbandry* 12, 455-459.

- Cohen RDH (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 RDH (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. *Australian Journal of Experimental Agriculture and Animal Husbandry* **13**, 625-629.
- Cohen RDH (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**, 709-715.
- Cohen RDH (1980) Phosphorus in rangeland nutrition: A review. *Livestock Production Science* **7**, 25-37.
- CSIRO (1990) Feeding Standards for Australian Livestock. Ruminants. Standing Committee on Agriculture. CSIRO Publishing, Melbourne, Australia.
- 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.
- de Waal HO, Koekemoer GJ (1997) Blood, rib bone and rumen fluid as indicators of phosphorus status of grazing beef cows supplemented with different levels of phosphorus at Armoedsvlakte. *South African Journal of Animal Science* **27**, 76-84.
- de Waal HO, Randall JH, Koekemoer GJ (1996) The effects of phosphorus supplementation on body mass and reproduction of grazing beef cows supplemented with different levels of phosphorus at Armoedsvlakte. *South African Journal of Animal Science* **26**, 29-36.
- Deitert C, Pfeffer E (1993) Effects of reduced P supply in combination with adequate or high Ca intake on performance and mineral balances in dairy goats during pregnancy and lactation. *Journal of Animal Physiology and Animal Nutrition*. **69**, 12-21.
- Dias RS, Kebreab E, Vitti DMSS, Roque AP, Bueno ICS, France J (2006) A revised model for studying phosphorus and calcium kinetics in growing sheep. *Journal of Animal Science* **84**, 2787-2794.
- Dias RS, Lopez S, Silva T, Pardo RMP, Filho JCS, Vitti DMSS, Kebreab E, France J (2009) Rumen phosphorus metabolism in sheep. *Journal of Agricultural Science, Cambridge* **147**, 391-398.
- Dixon RM (1998) Improving cost-effectiveness of supplementation systems for breeder herds in northern Australia. Final Report, Project DAQ.098 to the Meat Research Corporation.
- Dixon RM (2008) Utilizing faecal NIRS measurements to improve prediction of grower and breeder cattle performance and supplement management. Final Report of Project NBP.302. Meat and Livestock Australia, Sydney.
- Dixon RM, Coates DB (2009) NIR spectroscopy of faeces to evaluate the nutrition and physiology of herbivores. A review. *Journal of Near Infrared Spectroscopy* **17**, 1-31.
- Dixon RM, Playford C, Coates DB (2010) Nutrition of the breeder cow in the dry tropics. 1. Effects of nitrogen supplementation and weaning on breeder performance. Under review.
- Dixon RM, Smith DR, Porch I, Petherick JC (2001) Effects of experience on voluntary intake of supplements by cattle. *Australian Journal of Experimental Agriculture* **41**, 581-592.
- Dixon RM, Stockdale CR (1999) Associative effects between forages and grains: consequences for feed utilization. *Australian Journal of Agricultural Research* **50**, 757-773.
- Dixon RM, White A, Fry P, Petherick JC (2003) Effects of supplement type and previous experience on variability in intake of supplements by heifers. *Australian Journal of Agricultural Research* **54**, 529-540.

- Eeckhout W, Paepe M De (1994) Total phosphorus, phytate phosphorus and phytase activity in plant feedstuffs. *Animal Feed Science and Technology* 47, 19-29.
- Ekelund A, Sporndly, Holtenius K (2006) Influence of low phosphorus intake during early lactation on apparent digestibility of phosphorus and bone metabolism in dairy cows. *Livestock Science* 99, 227-236.
- Engels EAN (1981) Mineral status and profiles (blood, bone and milk) of the grazing ruminant with special reference to calcium, phosphorus and magnesium. *South African Journal of Animal Science* 11, 171-182.
- Erickson GE, Klopfenstein TJ, Milton CT, Brink D, Orth MW, Whittet KM (2002) Phosphorus requirement of finishing feedlot calves. *Journal of Animal Science* 80, 1690-1695.
- Esser NM, Hoffman PC, Coblenz WK, Orth MW, Weigel KA (2009) The effect of dietary phosphorus on bone development in dairy heifers. *Journal of Dairy Science* 92, 1741-1749.
- Field AC, Suttle NF, Nisbet DI (1975) Effect of diets low in calcium and phosphorus on the development of growing lambs. *Journal of Agricultural Science, Cambridge* 85, 435-442.
- Fishwick G, Fraser J, Hemingway RG, Parkins JJ, Ritchie NS (1977) The effects of dietary phosphorus inadequacy during pregnancy and lactation on the voluntary intake and digestibility of oat straw by beef cows and the performance of their calves. *Journal of Agricultural Science, Cambridge* 88, 143-150.
- Fordyce G, Cooper N, Batterham I, White A (1995) Breeder herd management and production. Swans Lagoon Research Report, Queensland Department of Primary Industries.
- Gartner RJW, Murphy GM, Hoey WA (1982) Effects on induced, subclinical phosphorus deficiency on feed intake and growth of beef heifers. *Journal of Agricultural Science, Cambridge* 98, 23-29.
- Goatcher WD, Church DC (1970) Review of some nutritional aspects of the sense of taste. *Journal of Animal Science* 31, 973-981.
- Grace ND. (1981) Phosphorus kinetics in the sheep. *British Journal of Nutrition* 45, 367-374.
- Gunn KJ, Ternouth JH (1994a) The urinary excretion of purine derivatives in sheep offered nitrogen and phosphorus deficient diets. *Proceedings of the Australian Society of Animal Production* 20, 444.
- Gunn KJ, Ternouth JH (1994b) The effect of phosphorus deficiency upon ruminal microbial activity and nitrogen balance in lambs. *Proceedings of the Australian Society of Animal Production* 20, 445.
- Hart B, Mitchell GL (1965) Effect of phosphorus supplementation on the fertility of an open range beef cattle herd on the Barkley Tableland. *Australian Veterinary Journal* 41, 305-309.
- Hemingway RG (1967) Phosphorus in the ruminant. *Outlook on Agriculture* 5, 172-180.
- Hendricksen RE, Ternouth JH, Punter LD (1994) Seasonal nutrient intake and phosphorus kinetics of grazing steers in northern Australia. *Australian Journal of Agricultural Research* 45, 1817-1829.
- Hill R (1962) The provision and metabolism of calcium and phosphorus in ruminants. *World Review of Nutrition and Dietetics* 3, 131-148.
- Hill SR, Knowlton KF, Kebreab E, France J, Hanigan MD (2007) A model of phosphorus digestion and metabolism in the lactating dairy cow. *Journal of Dairy Science* 91, 2021-2032.
- Hobbs NT (1987) Fecal indices to dietary quality: a critique. *Journal of Wildlife Management* 51, 317-320.
- Hoey WA, Murphy GM, Gartner RJW (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.
- Holeczek JL, Galyean ML, Wallace JD, Wofford H (1985) Evaluation of faecal indices for predicting phosphorus status of cattle. *Grass and Forage Science* 40, 489-492.

- Holm AMcR, Payne AL, Morgan PD, Speijers EJ (1981) The response of weaner cattle grazing natural pastures in the north western Australia to phosphoric acid, non-protein nitrogen and sulphur in the drinking water. *Australian Rangelands Journal* 3, 133-141.
- Holmes JHG (1981) Phosphate deficiency in cattle on the Sepik Plains, Papua New Guinea. *Tropical Animal Production and Health* 13, 169-176.
- Holroyd RG, Allan PJ, O'Rourke PK (1977) Effect of pasture type and supplementary feeding on the reproductive performance of cattle in the dry tropics of north Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17, 197-206.
- Holtenius K, Ekelund A (2005) Biochemical markers of bone turnover in the dairy cow during lactation and the dry period. *Research in Veterinary Science* 78, 17-19.
- Horst RL (1986) Regulation of calcium and phosphorus homeostasis in the dairy cow. *Journal of Dairy Science* 69, 604-616.
- Hunter RA and Siebert BD (1986) The effect of genotype, age, pregnancy, lactation and rumen characteristics on voluntary intake of roughage diets by cattle. *Australian Journal of Agricultural Research* 37, 549-560.
- Hutcheson JP, Greene LW, Carstens GE, Byers FM (1992) Effects of zeranol and two dietary levels of calcium and phosphorus on performance, carcass and bone characteristics, and calcium status in growing lambs. *Journal of Animal Science* 70, 1346-1351.
- Karn JF (2001) Phosphorus nutrition of grazing cattle: a review. *Animal Feed Science and Technology* 89, 133-153.
- Kincaid RL, Rodehutsord M (2005) Phosphorus metabolism in the rumen. In: Nitrogen and Phosphorus nutrition of cattle. Eds E Pfeffer, A N Hristov. pp. 187-193. CAB International.
- Knowlton KF, Herbein JH (2002) Phosphorus partitioning during early lactation in dairy cows fed diets varying in phosphorus content. *Journal of Dairy Science* 85, 1227-1236.
- Komisarczuk S, Merry RJ, McAllan AB (1987) Effect of different levels of phosphorus on rumen microbial fermentation and synthesis determined using a continuous culture technique. *British Journal of Nutrition* 57, 279-290.
- Komisarczuk-Bony S, Durand M (1991) Effects of minerals on microbial metabolism. In: Jouany, J. P. (ed.), Rumen microbial metabolism and ruminant digestion. INRA Editions, Paris, pp. 179-198.
- Konishi C, Matsui T, Park W, Yano H, Yano F (1999) Heat treatment of soybean meal and rapeseed meal suppress rumen degradation of phytate phosphorus in sheep. *Animal Feed Science and Technology* 80, 115-122.
- Langlands JP (1975) Techniques for estimating nutrient intake and its utilization by the grazing ruminant. In: Digestion and Metabolism in the Ruminant. Eds I W McDonald and ACI Warner pp 320-332. The University of New England Publishing Unit, Armidale.
- L'Estrange JL, Clarke JJ, McAleese DM (1969) Studies on high intakes of various sulphate salts and sulphuric acid in sheep. 1. Effects on voluntary feed intake, digestibility and acid-base balance. *Irish Journal of Agricultural Research* 8, 133-150.
- L'Estrange JL, Murphy F (1972) Effects of dietary mineral acids on voluntary food intake, digestion, mineral metabolism and acid-base balance of sheep. *British Journal of Nutrition* 28, 1-17.
- Little DA (1968) Effect of dietary phosphorus on the voluntary consumption of Townsville lucerne (*Stylosanthes humilis*) by cattle. *Proceedings of the Australian Society of Animal Production* 7, 376-380.
- Little DA (1972) Bone biopsy in cattle and sheep for studies of phosphorus status. *Australian Veterinary Journal* 48, 668-670.
- Little DA (1980) Observations on the phosphorus requirement of cattle for growth. *Research in Veterinary Science* 28, 258-260.

- Little DA (1983) Bovine body composition and phosphorus storage: the in vivo assessment of body composition and phosphorus status, and the dietary phosphorus requirements of cattle for growth. PhD thesis, University of Queensland, Australia.
- Little DA (1984) Definition of an objective criterion of body phosphorus reserves in cattle and its evaluation in vivo. *Canadian Journal of Animal Science* 64, 229-231.
- Little DA, Minson DJ (1977) Variation in the phosphorus content of bone samples obtained from the last three ribs of cattle. *Research in Veterinary Science* 23, 393.
- Little DA, Shaw NH (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.
- Lindsay JA, Cooper NJ, Batterham I (1998) A molasses based production feeding system for Brahman cattle. *Animal Production in Australia* 22, 119-121.
- Lobdosoekojo S, Ammerman CB, Raun NS, Gomez J, Littell RC (1980) Mineral nutrition of beef cattle grazing native pastures on the Eastern Plains of Colombia. *Journal of Animal Science* 51, 1249-1260.
- Long TA, Tillman AD, Nelson AB, Gallup WD, Willis D, Davis B (1957) Availability of phosphorus in mineral supplements for beef cattle. *Journal of Animal Science* 16, 444-450.
- Loxton ID, Murphy GM, Toleman MA (1983) Effect of superphosphate application on the phosphorus status of breeding cattle grazing Townsville stylo based pastures in northern Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* 23, 340-347.
- McCosker T, Winks L (1994) Phosphorus Nutrition of Beef Cattle in Northern Australia. Department of Primary Industries, Brisbane, Australia.
- McDowell L (1997) Minerals for Grazing Ruminants in Tropical Regions. 3rd Edition, Department of Animal Science Bulletin, Center for Tropical Agriculture, University of Fla, Gainesville.
- McDowell LR (1996) Feeding minerals to cattle on pasture. *Animal Feed Science and Technology* 60, 247-271.
- McLean RW, Ternouth JH (1994) The growth and phosphorus kinetics of steers grazing a subtropical pasture. *Australian Journal of Agricultural Research* 45, 1831-1845.
- McMeniman NP (1983) The toxic effect of some phosphate supplements fed to sheep. *Australian Veterinary Journal* 49, 150-152.
- Miller CP, Coates DB, Ternouth JH, White SJ (1998) Phosphorus management for breeding cattle in northern Australia. Final Report of Project DAQ093. Meat and Livestock Australia, Sydney.
- Miller CP, Fitzpatrick LA, White SJ, Coates DB, Ternouth JH (1996) Effects of phosphorus on the performance of grazing cows and calves. *Proceedings of the Australian Society of Animal Production* 21, 355.
- 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.
- Milton JTB, Ternouth JH, (1984) The effects of phosphorus upon in vitro microbial digestion. *Animal Production in Australia* 15, 472-475.
- Milton JTB, Ternouth JH, (1985) Phosphorus metabolism in ruminants. II. Effects of inorganic phosphorus concentration upon food intake and digestibility. *Australian Journal of Agricultural Research* 36, 647-654.
- Minson DJ (1990) Forage in Ruminant Nutrition. Academic Press, Harcourt Brace Jovanovich, pp. 230-264.
- Minson DJ, McDonald CK (1987) Estimating forage intake from growth of beef cattle. *Tropical Grasslands* 21, 116-122.
- Moir KM (1960) Nutrition of grazing cattle. 2. Estimation of phosphorus and calcium in pasture selected by grazing cattle. *Queensland Journal of Agricultural Science* 17, 373-383.

- Murray CA, Romyn AE (1937) The feeding of phosphorus supplements to growing cattle. *The Rhodesian Agricultural Journal* 34, 384-390.
- Müschen H, Petri A, Breves G, Pfeffer E (1988) Response of lactating goats to low phosphorus intake. 1. Milk yield and faecal excretion of P and Ca. *Journal of Agricultural Science, Cambridge* 111: 253–263.
- Penzhorn EJ, Meintjies JP (1972) Influence of pregnancy and lactation on the voluntary feed intake of Afrikaner heifers and cows. *Agroanimalia* 4, 83-92.
- Petri A, Muschen H, Breves G, Richter O, Pfeffer E (1988) Response of lactating goats to low phosphorus intake. 2. Nitrogen transfer from rumen ammonia to rumen microbes and proportion of milk protein derived from microbial amino acids. *Journal of Agricultural Science, Cambridge* 111, 265-271.
- Pfeffer E, Rodehutschord M, Breves G (1995) Effects of reducing dietary calcium and/or phosphorus on performance and body composition in male kids. *Journal of Animal Physiology and Animal Nutrition* 74, 243- 252.
- Pfeffer E, Rodehutschord M, Breves G (1996) Effects of varying dietary calcium and phosphorus on growth and on composition of empty bodies and isolated bones of male kids. *Archives of Animal Nutrition* 49, 243-252.
- Pfeffer E, Windhausen P, Rodehutschord M (1994) Changes in body composition of dairy goats caused by phosphorus depletion. *Journal of Animal Physiology and Animal Nutrition* 72, 65-70.
- Playne MJ (1994) Detrimental effect of phosphoric acid supplementation of beef cows in northern Australia. *Proceedings of the Australian Society of Animal Production* 10, 111.
- Poppi DP, McLennan SR (1995) Protein and energy utilization by ruminants at pasture. *Journal of Animal Science* 73, 278-290.
- Poppi DP, McLennan SR (2010) Nutrition research to meet future challenges. *Animal Production Science* 50, 329-338.
- Preston RL, Pfander WH (1964) Phosphorus metabolism in lambs fed varying phosphorus intakes. *Journal of Nutrition* 83: 369–378.
- Rajaratne AAJ, Scott D, Buchan W, Duncan A (1990) The effect of variation in dietary protein or mineral supply on calcium and phosphorus metabolism in lactating ewes. *British Journal of Nutrition* 64: 147–160.
- Ramberg CF, Kronfeld DS, Wilson GDA (1975) Regulation of calcium metabolism in cattle during growth, gestation, and lactation and changes in diet. In: *Digestion and Metabolism in the Ruminant*. Eds I W McDonald and ACI Warner pp 231-242. The University of New England Publishing Unit, Armidale.
- Read MVP (1984) Animal performance from natural pastures and the effects of phosphorus supplementation. M. Sci. thesis. University of Stellenbosch, Republic of South Africa.
- 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.
- Riestra SP, Muir JP, Lambert BD, Tedeschi LO, Redmon LA (2010) Phosphorus and other nutrient disappearance from plants containing condensed tannins using the mobile nylon bag technique. *Animal Feed Science and Technology* 156, 19-25.
- Rodehutschord M, Heuvers H, Pfeffer E (2000) Effect of organic matter digestibility on obligatory faecal phosphorus loss in lactating goats, determined from balance data. *Animal Science* 70, 561-568.

- Rodehutsord M, Pauen A, Windhausen P, Brintrup R, Pfeffer E (1994a) Effects of drastic changes in P intake on P concentrations in blood and rumen fluid of lactating ruminants. *Journal of Veterinary Medicine* 41, 611-619.
- Rodehutsord M, Pauen A, Windhausen P, Pfeffer E (1994b) Balances of phosphorus and calcium in dairy goats during periods of phosphorus depletion and subsequent phosphorus repletion. *Journal of Animal Physiology and Animal Nutrition* 72: 54-64.
- Sanson DW, Walker GL, Clanton DC, Eskridge KM (1990) Relationship between phosphorus intake and blood or fecal phosphorus in gestating cows. *Journal of Range Management* 43, 238-241.
- Schneider KM, Boston RC, Leaver DD (1982) The metabolism of phosphorus and calcium in sheep during intravenous infusion of phosphorus. *Australian Journal of Agricultural Research* 33, 827-842.
- Scott D (1986) Control of phosphorus balance in ruminants. In: Aspects of digestive Physiology in Ruminants. Eds A Dobson and MJ Dobson. pp.156-174. Cornell University Press, Ithaca, USA.
- Sehested J (2004) Feeding phosphorus (P) to cattle: A new basis for Nordic recommendations. *Acta Agric. Scand., Sect. A, Animal Sci.* 54, 169-180.
- Ternouth JH (1991) The kinetics and requirements of phosphorus in ruminants. In: Recent Advances on the Nutrition of Herbivores. Eds YW Ho, HK Wong, N Abdullah, ZA Tajuddin. Malaysian Society of Animal Production.
- 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, Budhi SPS (1996) Effects of dietary phosphorus deficiency in pregnant and lactating ewes. *Australian Journal of Experimental Agriculture* 36, 137-144.
- Ternouth JH, Coates DB (1997) Phosphorus homeostasis in grazing breeder cattle. *Journal of Agricultural Science, Cambridge* 128, 331-337.
- Ternouth JH, McLachlan BP, Clarke JM, Thomas BJ (1993) Effects of dietary phosphorus and nitrogen deficiencies on the intake, growth and metabolism of lambs. *Journal of Agricultural Science, Cambridge* 121: 409-419.
- Ternouth JH, McLean RW, McDonald RN, Adamu A (1989) Field estimates of the phosphorus kinetics of grazing cattle. *Proceedings of the Australian Society of Animal Production* 18, 396-399.
- Ternouth JH, Sevilla CC (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 JH, Sevilla CC (1990b) Dietary calcium and phosphorus repletion in lambs. *Australian Journal of Agricultural Research* 41, 413-420.
- Theiler A, Du Toit PJ, Malan AI (1937) The influence of variations in the dietary phosphorus and in the Ca:P ratio on the production of rickets in cattle. *Onderstepoort Journal of Veterinary Science and Animal Industry* 8, 375-414.
- Theiler A, Green HH, Du Toit PJ (1928) Studies in mineral metabolism. III. Breeding of cattle on phosphorus deficient pasture. *Journal of Agricultural Science, Cambridge* 18, 369-371.
- Tuen AA, Wadsworth JC, Murray M (1984) Absorption of calcium and phosphorus by growing cattle during dietary protein deficiency. *Proceedings of the Nutrition Society of Australia* 9, 144-147.
- Turner AW, Kelley RB, Dann AT (1935) Peg-leg of cattle in north Queensland. *Journal of the Council for Scientific and Industrial Research* 8, 120-136.
- Valk H, Sebek LBJ, Beynen AC (2002) Influence of phosphorus intake on excretion and blood plasma and saliva concentrations of phosphorus in dairy cows. *Journal of Dairy Science* 85, 2642-2649.
- Van Niekerk BDH, Jacobs GA (1985) Protein, energy and phosphorus supplementation of cattle fed low quality forage. *South African Journal of Animal Science* 15, 133-136.

- Van Schalkwyk A, Lombard PE (1969) The influence of phosphorus supplementation on body function and growth of young steers. *Agroanimalia* 1, 45-52.
- Vitti DMSS, Kebreab E, Lopes JB, Abdalla AL, De Carvalho FFR, De Resende KT, Compton LA, France J (2000) A kinetic model of phosphorus metabolism in growing goats. *Journal of Animal Science* 78, 2706-2712.
- 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.
- Ward HK (1968) Supplementation of beef cows grazing on veld. *Rhodesian Journal of Agricultural Research* 6, 93-101.
- Williams SN, Lawrence LA, McDowell LR, Warnick AC, Wilkinson NS (1990) Dietary phosphorus concentrations related to breaking load and chemical bone properties in heifers. Criteria to evaluate bone mineralization in cattle. *Journal of Dairy Science* 73, 1100-1106
- Williams SN, Lawrence LA, McDowell LR, Wilkinson NS, Ferguson PW, Warnick AC (1991) Criteria to evaluate bone mineralization in cattle. I. Effect of dietary phosphorus on chemical, physical, and mechanical properties. *Journal of Animal Science* 69, 1232-1242.
- Winks L (1990) Phosphorus and beef production in northern Australia. 2. Responses to phosphorus by ruminants: a review. *Tropical Grasslands* 24, 140-158.
- Winks L, Laing AR (1972) Urea, phosphorus and molasses supplements for grazing beef weaners. *Proceedings of the Australian Society of Animal Production* 9, 253-257.
- Winks L, Laing AR, O'Rourke PK, Wright GS (1979) Factors affecting the response to urea-molasses supplements by yearling cattle in tropical Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* 19, 522-529.
- Winks L, Laing AR, Wright GS, Stokoe J (1976) Effects of nitrogen, phosphorus and molasses on the performance of weaner cattle during the dry season in north Queensland. *Journal of the Australian Institute of Agricultural Science* 42, 246-251.
- Winks L, Lamberth FC, Moir KW, Pepper PM (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 FC, O'Rourke PK (1977) The effect of a 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 WH (1988) Supplementation of steers grazing *Stylosanthes hamata* pastures at Katherine, Northern Territory. *Australian Journal of Experimental Agriculture* 28, 669-682.
- Winter WH, Coates DB, Hendricksen RE, Kerridge PC, McLean RW, Miller CP (1990) Phosphorus and beef production in northern Australia. 4. The response of cattle to fertilizer and supplementary phosphorus. *Tropical Grasslands* 24, 170-184.
- Yano F, Yano H, Breves G (1991) Calcium and phosphorus metabolism in ruminants. In: Tsuda, T., Sasaki, T. Y. & Kawashima, R. (eds.), *Physiological aspects of digestion and metabolism in ruminants*. pp.277-295. Academic Press, Inc., London.
- Young VR, Lofgreen GP, Luick JR (1966) The effects of phosphorus depletion, and of calcium and phosphorus intake, on the endogenous excretion of these elements by sheep. *British Journal of Nutrition* 20, 795-805.