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H. C. BLOCK
Department of Animal Science, University of Nebraska, Lincoln

G. E. ERICKSON
Department of Animal Science, University of Nebraska, Lincoln

T. J. KLOPFENSTEIN
Department of Animal Science, University of Nebraska, Lincoln

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REVIEW: Re-evaluation of Phosphorus Requirements and Phosphorus Retention of Feedlot Cattle[1]

H. C. BLOCK, G. E. ERICKSON[2], PAS, and T. J. KLOPFENSTEIN
Department of Animal Science, University of Nebraska, Lincoln 68583-0908

Abstract

Phosphorus requirement recommendations for cattle are important for preventing over-feeding of P and excessive P excretion. Improved precision in managing P nutrition can reduce feedlot waste management concerns. Current beef recommendations (NRC, 1996) fail to account for absorption coefficient variation related to P source, whereas dairy recommendations (NRC, 2001) change absorption coefficients with P source. Maintenance and BW gain requirements for absorbed P do not represent underlying relationships. Maintenance P requirements reflect endogenous P loss arising from failure to reabsorb salivary P. Basing maintenance requirements on saliva P secretion and re-absorption rates should improve precision of maintenance requirement estimates. Gain requirement recommendations are from limited body composition data and relate P requirements to protein retention. However, metabolism and BW gain studies show uncoupled N and P retention. With extensive deposition of body P into skeletal tissues, basing gain requirements on skeletal tissue growth and mineralization should improve estimation of gain requirements. Cattle have extensive ability to buffer against P deficiency through mobilization of P reserves. The buffering ability causes P requirement for growth to be less than potential retention, complicating management of P nutrition. Improved estimates of P gain requirements may reduce P over-feeding, whereas separate retention estimates will allow accurate estimation of P excretion. Cattle are thought to excrete almost all P in feces. However, cattle on very high P diets saturate the fecal P excretion route and excrete an extensive proportion of P in urine. Future research should be directed at resolving deficiencies of current P nutritional recommendations and management to reduce environmental concerns.

(Key Words: Beef Cattle, Phosphorus, Requirement, Retention.)

Introduction

The impact of intensive livestock operations on the environment is a growing concern, particularly in regard to the management of animal manure. Manure from commercial feedlots is generally disposed of through land application (Freeze et al., 1999 and McKenzie et al., 2000, as cited by Whalen and Chang, 2001) and may result in continual application of manure to the land closest to feedlots (Whalen and Chang, 2001). Cattle feedlot manure has a lesser N:P ratio (2:1 to 3:1; Eghball and Power, 1994) than crop requirements (6:1 to 8:1), and application of manure based on crop N requirements provides P in excess of crop P requirements (Intensive Livestock Operations Committee, 1995, as cited by Whalen and Chang, 2001). Application of P in excess of requirements can result in accumulation of P in soils and increase the risk of P transport to water bodies through leaching, erosion, and runoff processes (Sharpley et al., 1994; Lennox et al., 1997). Lessening manure P content by reducing the amount of P excreted by cattle reduces the risk of P pollution. Wu et al. (2000, as cited by Wu et al., 2001) reported that 25 to 30% less manure P can be achieved with dairy cattle by reducing dietary P to better match requirements.

The objective is to review the P requirements of beef cattle with emphasis on predicting P retention and P excretion.

Review and Discussion

Recommended P Requirements for Cattle. The role of P in ruminant nutrition and metabolism has been extensively reviewed (Hemingway, 1967; Jacobson et al., 1972; Cohen, 1975; Braithwaite, 1976; Field, 1981; Scott and McLean, 1981; Horst, 1986; Minson, 1990; Ternouth, 1990;

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[2]To whom correspondence should be addressed: geericks@unlnotes.unl.edu

Winks, 1990; Karn, 2001). As such, P in ruminant nutrition and metabolism will only be discussed here as it relates to cattle P excretion and requirements.

Factorial P requirements for feedlot cattle have been published (NRC, 1996). Maintenance requirements are considered to be 16 mg of absorbed P/kg of BW and represent endogenous fecal losses when cattle are fed P at or near requirement (NRC, 1996). The P requirement for BW gain is 3.9 g of absorbed P/100 g of retained protein, determined by analysis of body composition data (Ellenberger et al., 1950) of dairy cattle (NRC, 1996).

The AFRC (1991) used a different approach to determining P requirements of cattle, which were adopted by the NRC (2001) for dairy cattle. The P requirement for maintenance has been related to DMI instead of BW, reflecting the importance of salivary P secretion in endogenous P losses. With this approach, the requirement for maintenance of growing cattle was set at 0.8 g of absorbed P/kg of DMI with an additional 0.002 g of absorbed P/kg of BW to account for endogenous urinary losses. The AFRC (1991) also developed an allometric relationship that utilizes BW, expected mature BW, and BW gain to estimate P requirements for gain:

$$P = (1.2 + (4.635 \times MW^{0.22})(BW^{-0.22})) \times WG$$

where P = P required for gain (g/d), MW = mature BW (kg), BW = BW (kg), and WG = BW gain (kg).

With both the beef (NRC, 1996) and dairy (NRC, 2001) recommendations, factorial P requirements are totaled and divided by a P absorption coefficient to determine dietary P requirements. The beef NRC (1996) recommendations use a P absorption coefficient of 0.68 for all feeds, whereas the dairy NRC (2001) recommendations use P absorption coefficients of 0.64 for forages and 0.70 for concentrates. The dairy NRC (2001) recommendations also use a variety of P absorption coefficients for various mineral sources of P (Table 1). The absorption coefficient has more potential influence on the dietary P requirement than any of the individual or combined absorbed P requirements (NRC, 2001).

TABLE 1. Phosphorus absorption coefficients used by the dairy NRC (2001) for mineral P sources.

Item	P Absorption coefficient
Ammonium phosphate (dibasic), $(NH_4)_2HPO_4$	0.80
Ammonium phosphate (monobasic), $NH_4H_2PO_4$	0.80
Bone meal, steamed	0.80
Calcium phosphate (monobasic), CaH_2PO_4	0.80
Curacao phosphate	0.85
Dicalcium phosphate (dibasic), $CaHPO_4$	0.75
Phosphate	0.65
Phosphate rock	0.30
Phosphate rock, low fluorine	0.30
Phosphoric acid	0.90
Sodium phosphate (monobasic) monohydrate, $NaH_2PO_4 \cdot H_2O$	0.90
Sodium tripolyphosphate (meta- and pyrophosphate), $Na_5P_3O_{10}$	0.75
Soft rock phosphate, colloidal clay	0.30

Problems with Recommended P Requirements. Erickson et al. (1999, 2002) conducted two feeding trials to evaluate the P requirements of steers brought into the feedlot as yearlings or calves. The yearling steer trial (Erickson et al., 1999) was a 2 × 5 factorial with Ca at 0.35 or 0.70% of DMI (39 or 76 g of Ca/d for each steer), and P at 0.14, 0.19, 0.24, 0.29, or 0.34% of DMI (16, 19, 26, 30, or 33 g of P/d for each steer). No effect (P>0.05) of P level was detected, suggesting that the P requirement of the yearlings was <0.14% of DMI (16 g of P/d). However, the beef NRC (1996) and dairy NRC (2001) recommendations for dietary P requirement were substantially greater at 0.20 and 0.26% of DMI (22 and 29 g of P/d, respectively).

The subsequent steer calf trial (Erickson et al., 2002) provided similar results. Calves were fed diets with P at 0.16, 0.22, 0.28, 0.34, or 0.40% of DMI (14, 20, 23, 31, or 35 g of P/d for each steer). Plasma P level was affected quadratically (P<0.05) by dietary P level; however, the least plasma P level was considered adequate. As no other effects (P>0.05) of P level were observed, the P requirement for calves is suggested to be 0.16% of DMI (14 g of P /d) or less. In contrast, the beef NRC (1996) and dairy NRC (2001) recommendations for dietary P requirement were substantially greater at 0.22 and 0.27% of DMI (19 and 23 g of P/d, respectively).

Given the discrepancy between P requirements recommended by either of the NRC (1996, 2001) recommendations and those suggested by the feedlot trials of Erickson et al. (1999, 2002), the recommended P requirements of cattle are excessive. Other research data also suggest P requirement recommendations are in excess (Little, 1980; Call et al., 1986). This manuscript intends to evaluate the potential for improvements in recommending P requirements for feedlot cattle and evaluating P excretion.

P Absorption. The absorption of P from the digestive tract is known to vary in response to numerous factors (NRC, 2001). These include P source (Soares, 1995 and McDowell, 1997, as cited by Karn, 2001, and Lofgreen and Kleiber, 1953, 1954 and Martz et al., 1990, as cited by NRC, 2001), P intake level (Challa et al., 1989, as cited by NRC, 2001), DMI (Field et al., 1977; Braithwaite, 1984; and Challa et al., 1989, as cited by AFRC, 1991), Ca intake (Braithwaite, 1984, as cited by AFRC, 1991), age, other dietary minerals and fat, and physiological state (NRC, 2001). However, the AFRC (1991) concluded that experimentally determined P absorption coefficients largely reflect attributes of the feed and will be close to maximal available values. Sehested and Weisbjerg (2002) used in situ nylon bags to evaluate availability of P from different feedstuffs and found P availability to vary from 0.35 to 0.95 for forages, 0.38 to 0.98 for concentrates and byproducts, and 0.29 to 1.00 for minerals. Availability of P from forages was further found to be correlated (R^2 = 0.81) to DM availability (Sehested and Weisbjerg, 2002). Therefore, to improve recommendations of dietary P requirement, it appears necessary to discontinue use of a single P absorption coefficient for all feeds as is the case with the beef NRC (1996) guidelines and to make use of P absorption coefficients specific to the feed being used.

By comparing recommended requirements for P to dietary supply for the feedlot trials of Erickson et al. (1999, 2002), the P absorption coefficient required to prevent P deficiency at the least level of P intake can be calculated. For yearling steers (Erickson et al., 1999), the P absorption coefficient required to ensure adequate P absorption would be 0.93 for the beef NRC (1996) and 1.28 for the dairy NRC (2001) recommended absorbed P requirements, respectively. The calculated dairy NRC (2001) P absorption coefficient is not realistic, and the beef NRC (1996) P absorption coefficient is sufficiently greater than what would be suggested from a concentrate diet with no mineral P supplementation (~0.70). This strongly suggests that imprecise use of P absorption coefficients is not the sole explanation for observed P requirements being so much less than NRC (1996, 2001) recommended P requirements.

P Requirements for Maintenance. Erickson et al. (2002) reported that P requirements of cattle for maintenance have been well documented and results support NRC recommendations. Therefore, problems with estimation of maintenance requirements are most likely due to failure of recommendations to account for the underlying physiology. The P requirement of cattle for maintenance is based on the endogenous loss of P in the feces of cattle fed at or near requirements (NRC, 1996), although the dairy NRC (2001) also includes some minimal losses of P in urine.

Phosphorus is recycled through saliva into the rumen where it is incorporated into rumen microbes, including the microbial cell wall, which is not completely degradable (Van Soest, 1994). Endogenous loss of P in feces in ruminants results almost entirely from unabsorbed salivary P (Ternouth, 1989, as cited by Karn, 2001), although there is undoubtedly some P lost with sloughing of tissues into the digestive tract. The AFRC (1991) stated that P secreted in saliva is in the form of highly available salts but cited Field et al. (1983) as indicating animals with low dietary P absorptive efficiency also have low salivary P absorptive efficiency. When dietary P absorption ranged from 0.50 to 0.90, secreted P absorption was estimated to range from 0.65 to 0.95 (Field, 1981, as cited by AFRC, 1991). Allowing for the opinions of the AFRC (1991) on the causes of variation in absorptive efficiency, factors other than animal variation are of relatively minor importance, and individual animal variation is not readily accountable. Therefore, with the ability to assume relatively constant absorption coefficients for salivary P, endogenous loss of P in feces becomes a function of salivary P secretion.

That cattle require P for maintenance to replace losses caused by incomplete absorption of salivary P is not reflected in the current NRC (1996) beef recommendations, which express P requirements for maintenance as a function of BW. The relationship between BW, DMI, and subsequent saliva production can explain historic use of BW as an estimator of the maintenance requirement of cattle for P. Refinement in estimation of maintenance requirements for P will necessitate accounting for underlying physiological relationships.

Saliva secretion in ruminants is continuous but increases with eating and rumination. Total saliva flow is related to time spent eating and ruminating (Van Soest, 1994). For ruminants fed forage diets, the amount of DM ruminated each day is usually double or triple the amount of feed consumed per day (Owens and Goetsch, 1993). While high concentrate and pelleted forage diets are characterized by lesser net saliva flow (Bauman et al., 1971, as cited by Van Soest, 1994), saliva production increases with forage level in the diet (Fahey and Berger, 1993; Owens and Zinn, 1993). Cattle may produce 180 L of saliva/d or more when consuming high quality pasture (Church, 1993; Van Soest, 1994), and studies indicated a 10-fold range in saliva production as affected by the physical nature of feeds or type of feed (Church, 1993). Horst (1986). citing Wadsworth and Cohen (1977), suggested that saliva secretion in cattle ranges from 25 to 190 L/d and contributes 70 to 80% of total endogenous P. The AFRC (1991) approach to P requirements for maintenance attempts to account for the role of saliva production in endogenous fecal P losses by basing P requirements for maintenance on DMI. The AFRC (1991) approach fails to account for physiochemical properties of feed, such as moisture level and effective NDF (**eNDF**) as described by Pitt et al. (1996) who referenced Shiffen et al. (1992). However, Pitt et al. (1996) reported an equation for use in estimation of saliva production as related to rumen buffering that is based on both DMI and eNDF. Adaptation of this equation to determination of P maintenance requirements may improve accuracy of estimation.

Kincaid (1993) reported the P content of saliva to be about 100 mg/dL, and Van Soest (1994) cited Kay (1960) with increased saliva secretion rate resulting in decreased P content. The concentration of P in ruminant saliva is generally low (Van Soest, 1994) but is a function of plasma P concentration (Horst, 1986, as cited by Karn, 2001). Plasma P concentration is under poor homeostatic regulation by cattle but is influenced by dietary Ca, P, Mg, and vitamin D levels (Kincaid, 1993). Mobilization of Ca from bone under conditions of dietary Ca deficiency results in large amounts of bone phosphate being released (Braithwaite, thereby elevating plasma P. Normal plasma P levels are 6 to 8 mg/dL in calves and decline with age to 4.5 to 6 mg/dL at maturity at 4 to 5 yr (Kincaid, 1993). Plasma P levels <4 mg/dL indicate possible deficiency (Kincaid, 1993) yet are not likely as long as adequate dietary P is available. Under conditions at or close to the P requirement of cattle for maintenance, plasma P level would be expected to be low and relatively constant and may have no effect on salivary P concentrations.

Determination of the net effects of changes in saliva secretion and resulting changes in P concentration on the net secretion of P are difficult but are discussed by the AFRC (1991). Secretion of P in saliva has a homeostatic role in ruminants (Horst, 1984 and Challa and Braithwaite, 1988, as cited by Karn, 2001; Vitti et al., 2000). Therefore, it would seem plausible that the P status of cattle would influence the effects and interaction that volume of saliva production and concentration of P in saliva have on net salivary P secretion. For cattle with high P status, it is expected that changes in saliva secretion would be opposed by changes in P concentration, resulting in relatively unchanged net salivary P secretion. For cattle with lesser P status, changes in

TABLE 2. Phosphorus retention relative to nitrogen retention in cattle.

Reference	Type of cattle	Treatment	n	Mineral retention P	Mineral retention Ca
				(g/100 g retained protein)	
Delaquis (1992) and Delaquis and Block (1995)	Dry Holstein cows	Cation-anion difference +481	11	0.54	4.74
		Cation-anion difference +327	10	0.51	4.67
Kegley et al. (1991); Trial 1	Hereford steers	Control, 0.3% Ca	2	0.96	6.29
		Control, 0.6% Ca	2	0.29	11.30
		Lysocellin, 0.3% Ca	2	4.36	16.36
		Lysocellin, 0.6% Ca	2	4.41	12.31
Kegley et al. (1991); Trial 2	Hereford steers	Control, 0.3% Ca	2	3.20	6.29
		Control, 0.6% Ca	2	4.40	13.21
		Lysocellin, 0.3% Ca	2	1.82	10.73
		Lysocellin, 0.6% Ca	2	3.69	7.79
Knowlton et al. (2001)	Lactating Holstein cows	Soybean and mineral	8	4.28	6.57
		Soybean and wheat bran	10	2.21	4.88
		Blood meal and mineral	9	3.40	5.07
		Blood meal and wheat bran	9	2.68	5.89
Rumsey et al. (1981,1985)	Hereford steers	Control	8	0.34	4.95
		Diethylstilbesterol	7	0.50	7.53
Rumsey (1982) and Rumsey et al. (1985)	Hereford steers	No Synovex[a], no kiln dust	6	0.05	0.61
		No Synovex[a], kiln dust	6	0.02	0.17
		Synovex[a], no kiln dust	6	0.22	3.19
		Synovex[a], kiln dust	6	0.15	2.99

[a]Synovex implants (Fort Dodge Animal Health, Overland Park, KS).

saliva production would be less effective at eliciting compensatory changes in P content of saliva, resulting in a greater influence on net salivary P secretion. Apparently no experimental data have been reported on the effects of level of saliva secretion and P content of saliva on net P secretion for cattle fed at or near maintenance. Therefore, caution must be used in combining data from different sources regarding saliva secretion and saliva P concentration.

P Requirements for Growth. As stated earlier, the P requirement for growth of beef cattle (NRC, 1996) is 3.9 g of P/100 g of retained protein and is based on analysis of compositional data of dairy cattle published by Ellenberger et al. (1950). This represents a relatively small change from much earlier recommendations of 4.32 g of P/100 g of retained protein (NRC, 1976), which were based on inadequate experimentally documented data (Shupe et al., 1988). Potential problems with expressing the P requirement in this fashion are related to the assumption of a constant relationship between the gain of P and protein. Relatively few studies have simultaneously measured P and protein or N retention in cattle. Values for retained P/100 g of retained protein obtained under simultaneous measurement have ranged from 0.02 to 4.41 g (Table 2). Coincidentally, these studies have also measured Ca retention and raise similar concerns with the Ca requirements of 7.1 g of Ca/100 g of retained protein recommended by the beef NRC (1996) guidelines. Measured Ca values ranged from 0.2 to 16.4 g of retained Ca/100 g of retained protein (Table 2). This large range in the ratio of retained P and Ca to protein suggests accumulation of P and Ca is not necessarily coupled to protein gain.

Because all of the data of Ellenberger et al. (1950) are reported, data were re-analyzed to evaluate retention of P and Ca in relationship to protein gain. Data were excluded from the analyzed data if they were obtained from fetuses or records were incomplete with regard to the empty body and skeletal tissues, which reduced the original data set of Ellenberger et al. (1950) from 132 animals to 103 animals. Phosphorus retention and protein gain were calculated by subtracting the average amount of P and protein in the newborn calves from each animal. The ratio of P and Ca retention to protein gain for all animals older than the newborn calves was then plotted against animal age (Figures 1 and 2). Average P retention for this reduced data set, including newborn calves, was 4.0 g/100 g of protein gain; Ca retention was 7.2 g/100 g of protein gain. These values are comparable with the beef NRC (1996) recommended P requirement for gain of 3.9 g of P/100 g of protein gain and Ca requirement for gain of 7.1 g of P/100 g of protein gain. Any difference between the values can be attributed to the reduction of the data set to exclude fetuses and animals for which complete data were unavailable. The data of Ellenberger et al. (1950) exhibited large variation in P

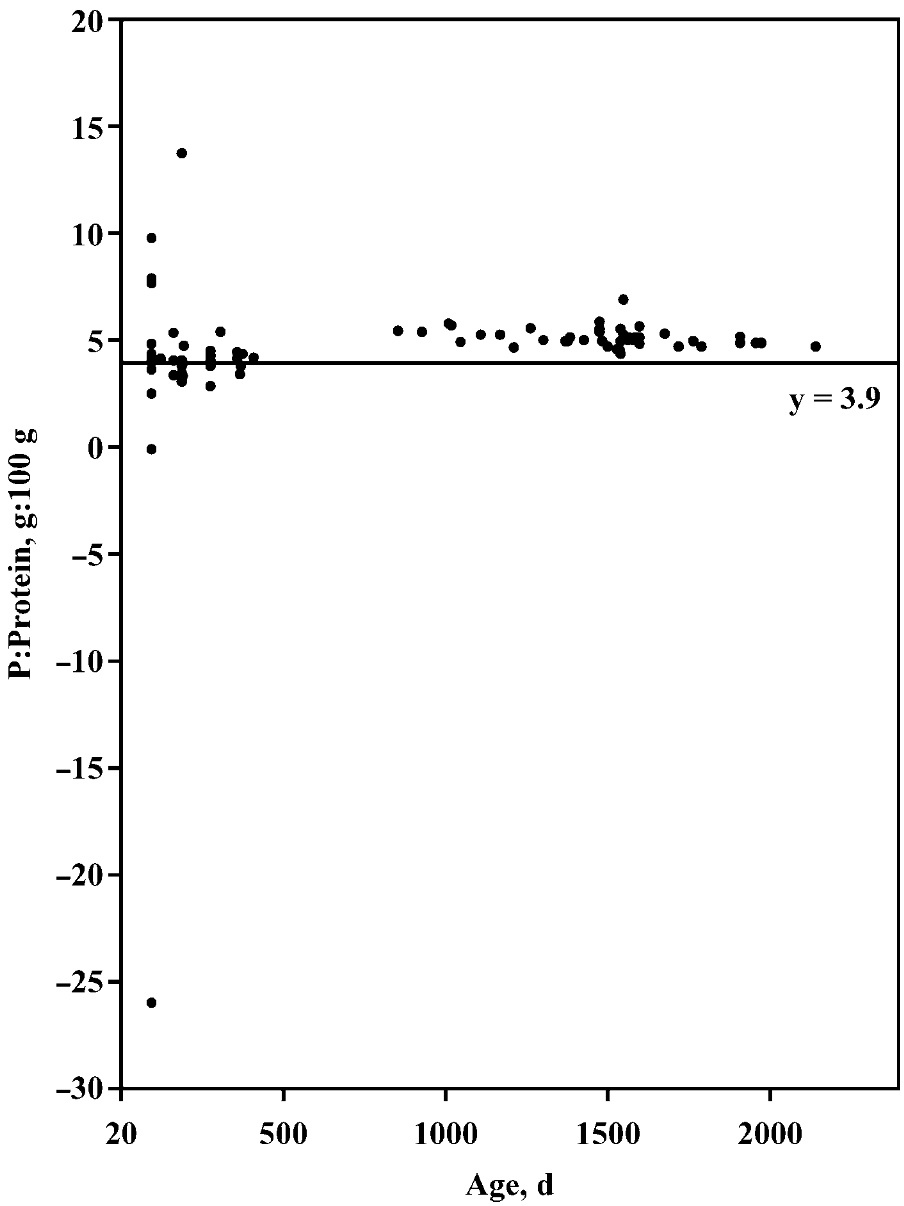

Figure 1. Phosphorus retention to protein gain over time. Data from Ellenberger et al. (1950).

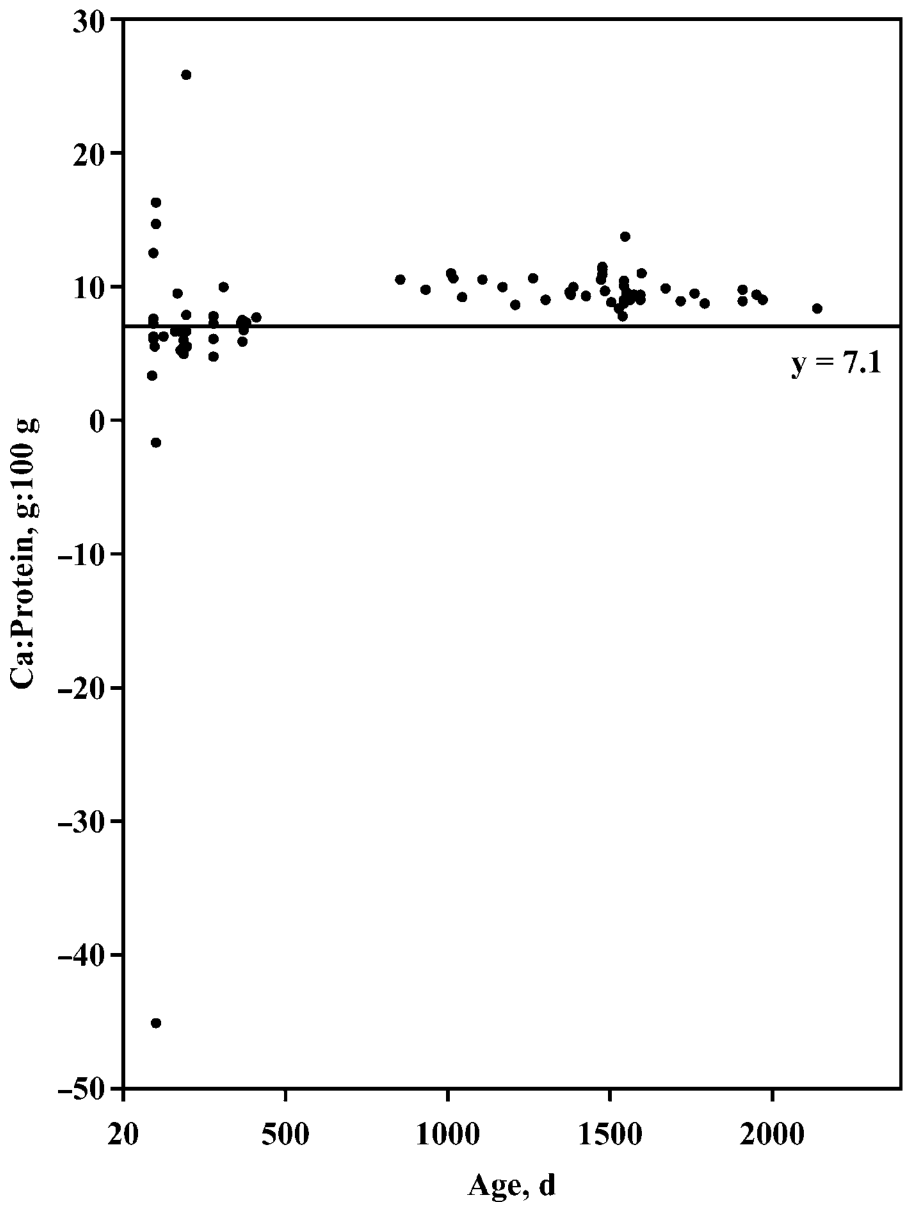

Figure 2. Calcium retention to protein gain over time. Data from Ellenberger et al. (1950).

and Ca retention relative to protein gain with young animals and decreased as animal age increased (Figures 1 and 2). Increased consistency with increasing animal age is more reflective of consistency in final body composition than of an inherent relationship between the retention of P or Ca and protein gain.

With bone containing 80 to 90% of body P and 99% of body Ca, and 60 to 85% of body protein in soft tissues (Ellenberger et al., 1950), including skeletal muscle, any alteration in the relative growth and maturation of muscle and bone could uncouple the relationship between P retention and protein gain. A common difference between breeds of cattle is the ratio of muscle to bone in the body. This is illustrated by data from Kempster et al. (1982), which confirmed a changing ratio of lean to bone in the carcasses of cattle as related to breed of sire. Dairy breeds have a lean-to-bone ratio of <3.4; many common beef breeds will have ratios of 3.6 to 4.0. Based on this difference, it would be expected that the P retained during growth would decline as the ratio of lean to bone increased; therefore, the P requirement for growth of beef cattle should be <3.9 g of P/100 g of protein recommended by NRC (1996) for beef cattle.

Bone is an earlier maturing tissue than muscle (Pálsson, 1955), resulting in a continual increase in the carcass muscle-to-bone ratio from 2:1 at birth to 4:1 at maturity (Kempster et al., 1982; Robelin and Tulloh, 1992). A changing ratio for the rates of gain of bone and soft tissue in the body is the reason for adopting the allometric equation developed by the AFRC (1991). Allometric equations are useful for modeling the changing rates of growth for portions of the body relative to the whole (Berg and Butterfield, 1976). However, the equation developed by AFRC (1991) and adopted by the dairy NRC (2001) was partially based on the data of Ellenberger et al. (1950) and may not be suitable for use with beef cattle.

In comparison with calf-fed cattle, which receive a high level of nutrition at an early age, yearling cattle are maintained on low levels of nutrition for extended periods prior to entry into the feedlot. Lessening the level of nutrition will impair the development of tissues, and later-maturing tissues, fat, and muscle, will be most strongly affected (Pomeroy, 1977). There is the possibility for nutritional management of growing cattle to affect the P requirement of gain when expressed as a portion of the retained protein, i.e., yearling cattle would have a lesser P requirement because of greater skeletal maturity upon entry into the feedlot. Therefore, determination of the P requirements of feedlot cattle for growth are complicated by the fact that most retained P is partitioned into skeletal tissue, which is a small and variable portion of total BW gain, and by 'maturity of mineralization' of cattle at the initiation of the feeding period (AFRC, 1991).

Maturity of mineralization is subject not only to stage of growth, but also to previous nutrition. Karn (2001) cited Little et al. (1978), indi-

TABLE 3. Relationship between P and other body components in soft and skeletal tissues (Ellenberger et al., 1950).

		Linear equation			
Item	R^2	Slope	SE of slope	Intercept	SE of intercept
Soft tissue					
DM	0.9308	0.003[a]	0.000	64.533[a]	5.643
Protein	0.9866	0.007[a]	0.000	14.193[a]	2.914
Fat	0.8121	0.005[a]	0.000	112.937[a]	7.972
Ash	0.9561	0.176[a]	0.004	–2.222	5.631
Ca	0.7681	3.482[a]	0.190	47.987[a]	11.713
Skeletal tissue					
DM	0.9872	0.077[a]	0.000	–135.707[a]	22.272
Protein	0.9611	0.252[a]	0.005	–330.188[a]	42.581
Fat	0.9063	0.262[a]	0.008	17.171	58.069
Ash	0.9986	0.178[a]	0.000	2.357	6.908
Ca	0.9989	0.460[a]	0.002	30.747[a]	5.994

[a]Value is different from zero ($P<0.01$).

cating that cattle rib bone P can be reduced by 17 to 42% during deficiency. Karn (2001) also cited Ternouth (1990), suggesting up to 30% of total bone P can be reabsorbed. Furthermore, the swine NRC (1998) guidelines indicated the amount of P required to optimize animal growth is substantially less than the amount of P required for maximum skeletal mineralization. There is no performance benefit from maximizing bone mineralization with the harvest of feedlot cattle at the end of the feeding period. Therefore, partial depletion of body P status during the feeding period would be acceptable, and the P requirement for growth and the potential retention of P by cattle are different, as cattle are capable of retaining more P within the body than is necessary to support cattle growth.

P Retention Estimation. With uncoupled P retention and protein gain, because of the majority of body P being in skeletal tissues while the majority of protein is in soft tissues, improved P retention estimation requires accounting for both skeletal growth and mineralization and soft tissue gain. Further evaluation of the data of Ellenberger et al. (1950; Table 3) shows that P in soft tissues is most highly correlated to protein (R^2 = 0.9866) and P in skeletal tissues is most highly correlated to Ca (R^2 = 0.9989). The high degree of relationship between skeletal Ca and P is not unexpected as the two minerals have extensive extracellular storage in skeletal tissue as hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$; Wasserman et al., 1993), calcium phosphate, and calcium carbonate (Hays and Swenson, 1993) functioning to provide structural strength and acting as a mineral reserve. Whereas almost all of the body Ca is in bone and reflects the degree of mineralization, body Ca should provide information on the retention of P in skeletal tissues and improve accounting of P retention. Protein gain would still be of use in accounting for the P retained in soft tissues.

Operating under the hypothesis that body P could be best estimated through its relationship to Ca in skeletal tissues and protein in soft tissues, regression analysis using the data of Ellenberger et al. (1950) was conducted. The resulting equation has an R^2 of 0.9990, and all estimates except the intercept were different ($P<0.01$) from zero. The equation is:

$$P = 15.1736\ (\pm 8.2200) + 0.4192\ (\pm 0.0087)\ Ca + 0.0094\ (\pm 0.0009)\ protein$$

where P = P content of the empty body (g), Ca = Ca content of the empty body (g), protein = protein content of the empty body (g), and SE for the estimates are presented in brackets.

The data presented (Table 2) were used to evaluate the ability of the slopes of this equation to estimate P retention. Results of this evaluation, as compared with the previous NRC (1996) recommended growth requirement of 3.9 g of P/100 g of retained protein, are presented as residuals in Table 4. Despite lower average residual and maximum residuals, minimum residual was worsened for the new equation with limited overall improvement in residuals (Table 4) with the new equation as opposed to the NRC (1996) equation; therefore, the new equation is not well suited to the purpose of accounting for P retention. Use of Ca and protein in the equation should account for differences in lean-to-bone ratio, changing composition of gain, and variation in mineralization of skeletal tissues. However, the equation has been derived from body composition data, not composition of gain data. Values for body composition data are sufficiently greater in magnitude than daily retention values. Therefore, small changes in precision will have a greater impact on retention values (g/d) compared with body composition data (expressed in kg). Additionally, the equation requires knowledge of Ca retention, for which accurate estimation may be more difficult than accurate estimation of P.

Testing the same hypothesis with the data used in Tables 2 and 4 yielded different results than those observed with data from Ellenberger et al. (1950). Three methods of estimating P retention were evaluated. Phosphorus retention was related to protein retention, Ca retention, or protein and Ca retention. The results of this evaluation are presented in Table 5. In contrast to the evaluation with the body composition data of Ellenberger et al. (1950), the fit of these equations is much poorer, with R^2

TABLE 4. Comparison of P retention residuals (predicted – observed) from beef NRC (1996) equation and equation developed from data of Ellenberger et al. (1950) using Ca and protein.

Reference	Type of cattle	Treatment	n	Protein (NRC)	
				Ca	Protein (Ellenberger)
Delaquis (1992) and Delaquis and Block (1995)	Dry Holstein cows	Cation-anion difference +481	11	21.22	15.07
		Cation-anion difference +327	10	20.54	14.46
Kegley et al. (1991); Trial 1	Hereford steers	Control, 0.3% Ca	2	2.76	2.45
		Control, 0.6% Ca	2	2.46	3.67
		Lysocellin, 0.3% Ca	2	–0.25	1.89
		Lysocellin, 0.6% Ca	2	–0.50	1.65
Kegley et al. (1991); Trial 2	Hereford steers	Control, 0.3% Ca	2	0.66	0.35
		Control, 0.6% Ca	2	–0.34	1.41
		Lysocellin, 0.3% Ca	2	1.15	1.99
		Lysocellin, 0.6% Ca	2	0.20	0.50
Knowlton et al. (2001)	Lactating Holstein cows	Soybean and mineral	8	–1.60	–2.47
		Soybean and wheat bran	10	6.21	2.85
		Blood meal and mineral	9	1.29	–0.84
		Blood meal and wheat bran	9	3.19	1.91
Rumsey et al. (1981, 1985)	Hereford steers	Control	8	3.77	2.83
		Diethylstilbesterol	7	4.59	4.86
Rumsey (1982) and Rumsey et al. (1985)	Hereford steers	No Synovex[a], no kiln dust	6	3.77	1.12
		No Synovex[a], kiln dust	6	3.14	0.80
		Synovex[a], no kiln dust	6	3.68	2.06
		Synovex[a], kiln dust	6	4.43	2.41
		Average residual	4.02	2.95	
		Maximum residual	21.22	15.07	
		Minimum residual	–1.60	–2.47	

[a]Synovex implants (Fort Dodge Animal Health, Overland Park, KS).

TABLE 5. Equations relating retention of P to protein retention, Ca retention, or protein and Ca retention.

Intercept		Protein slope		Calcium slope		
Estimate	SE	Estimate	SE	Estimate	SE	R^2
	1.092	1.290	0.012[a]	0.005	—	0.2486
–0.097	1.225	—	—	0.322[a]	0.088	0.4246
–0.311	1.186	–0.017	0.011	0.641[a]	0.220	0.4993

[a]Value is different from zero (*P*<0.05).

ranging from 0.2486 to 0.4993; protein gain was only a predictor of P retention when Ca retention data were unavailable.

Based on these limited attempts to estimate P retention in cattle, it appears that adequate data are not yet available for accurate estimation of P retention and that improvement in future estimation will demand estimation of skeletal growth and mineralization. Past efforts in modeling composition of gain have focused on the retention of lean and fat tissues in re-

TABLE 6. Diet composition for heifer metabolism trial.

Item	Dietary DM (%)
Dry rolled corn	57.800
Wet corn gluten feed	30.000
Alfalfa hay	10.000
Limestone	1.800
Sodium chloride	0.300
Trace mineral premix[a]	0.050
Rumensin premix[b]	0.019
Tylan premix[c]	0.014

[a]Trace mineral premix contains 13.00 to 15.00% Ca, 12.00% Zn, 8.00% Mn, 10.00% Fe, 1.50% Cu, 0.20% I, and 0.10% Co on a DM basis.

[b]Premix contained 176 g/kg, and diet was formulated to contain 30 mg/kg monensin.

[c]Premix contained 88 g/kg, and diet was formulated to contain 10 mg/kg tylosin.

lationship to their importance in energy and protein requirements for gain and are of limited use for estimation of mineral retention. Furthermore, it is necessary to realize that the P requirement for gain may be substantially less than the ability of cattle to retain P, a factor that will complicate the use of nutrient requirement recommendations in estimation of P excretion.

Route of P Excretion. Although P is normally thought to be excreted primarily in the feces of ruminants with only limited urinary excretion (Tölgyesi, 1972; Morse et al., 1992, Knowlton et al., 2001), several reports of substantial urinary P excretion exist (Reed et al., 1965; Field, 1981; Challa et al., 1989). The contribution of urinary P to net P excretion and homeostasis in cattle has not been clearly resolved. Excretion of P in urine of cattle has been investigated at the University of Nebraska.

Heifers (n = 6) involved in a metabolism trial were catheterized for urine collection over 5 d. Diet composition data are presented in Table 6, with P content of diet ingredients determined by analysis or beef NRC (1996) feed composition tables. Total urine excreted over 2-h periods was collected and sampled. Composite urine samples were constructed from 12 sequential 2-h period samples in proportion to 2-h urine excretion and analyzed for inorganic P (Fiske and SubbaRow colorimetric method, Sigma Procedure No. 670, Sigma Diagnostics, St. Louis, MO). Catheter failure resulted in lost samples, reducing the number of 24-h composite samples that could be constructed for the heifers. No 24-h composite samples could be constructed for one heifer, resulting in her exclusion from the reported data. Body weight, DMI, and urinary P excretion data for the heifers are reported in Table 7. There was a wide range, 3.4 to 18.2 g/d, in the average amount of P excreted in urine for each of the five heifers, with P in urine representing 8.6 to 45.3% of daily P intake. As stated earlier, there have been other reports of substantial urinary P excretion in cattle (Reed et al., 1965; Field, 1981, Challa et al., 1989). However, other researchers (Tölgyesi, 1972; Morse et al., 1992, Knowlton et al., 2001) have indicated that urinary excretion of P in cattle is minimal. It is important to determine the reason behind these conflicting reports regarding route of P excretion in cattle.

Animal variation in fractional absorption of secreted and dietary P can explain the variation in route of P excretion (Field, 1981). Field (1981) stated that with high P absorption, required P secretion will exceed salivary gland secretion capacity and surplus P will be excreted in urine. Ligation of both parotid salivary glands in sheep resulted in increased excretion of P in urine with a proportionate decrease in fecal P (Tomas and Somers, 1974, as cited by Scott and McLean, 1981). When sheep were fed grass or pelleted hay diets, Scott and McLean (1981) observed a slight increase in the threshold for urine P excretion in relationship to plasma inorganic P for sheep fed the pelleted hay diet. Greater saliva P secretion might have occurred with the pelleted hay diet, reducing the need for urinary excre-

TABLE 7. Body weight, intake, and urine P excretion for metabolism study heifers.

	Heifer ear tag number				
Item	4048	4201	4218	4241	4245
Initial BW, kg	543	525	535	536	522
Intake[a], kg/d (as-fed)	8.45	8.17	8.32	8.34	8.12
P intake[b], g/d	40.1	38.8	39.5	39.6	38.6
n[c]	3	3	5	5	3
Average urine P, g/d	18.2	6.6	3.4	5.2	8.3
Coefficient of variation, %	4.95	18.57	49.64	15.57	11.43
Average urine P, % of intake	45.3	17.0	8.6	13.1	21.5

[a]Heifer as-fed intake was restricted to 2.00% of initial BW.

[b]Diet contained 0.48% P (DM basis).

[c]Number of 24-h periods that were constructed and analyzed for each heifer.

tion of P. Factors that reduce salivary flow divert endogenous P excretion from saliva to urine (Tomas, 1974, as cited by Horst, 1986). Karn (2001) cited Challa et al. (1989) and others as reporting that urinary P excretion occurs when plasma P concentrations exceed a renal threshold value of between 6 and 9 mg/dL.

Implications

The recommended P requirements (NRC, 1996) for feedlot cattle appear excessive and contribute to over-feeding of P, thereby elevating the risk of P pollution of surface water. Improvement in estimating requirements by use of more appropriate P absorption coefficients, basing maintenance requirements on salivary P secretion, and requirements for gain on skeletal growth and mineralization will reduce over-feeding of P and risk of P pollution. Furthermore, it is important to realize that the ability of cattle to retain P is greater than the requirement for P to support gain. Accurate estimation of P retention, not P requirement, will allow prediction of P excretion for management of P in animal waste. Although cattle excrete all non-retained P consumed, the route of excretion can vary. Incomplete re-absorption of salivary P allows ruminants use of salivary P secretion as a means of P excretion. However, the capacity of saliva P secretion may be exceeded with high P diets or low saliva secretion, resulting in increased urinary P excretion. For feedlot cattle consuming grain-based diets with highly available P, substantial excretion of P in urine is likely.

Literature Cited

AFRC. 1991. Technical Committee on Response to Nutrients, Agriculture and Food Research Council, Report 6. A Reappraisal of the calcium and phosphorus requirements of sheep and cattle. Nutr. Abstr. Rev. (Ser. B). 61:573.

Berg, R. T., and R. M. Butterfield. 1976. New Concepts of Cattle Growth. Sydney Univ. Press, Sydney, Australia.

Braithwaite, G. D. 1976. Calcium and phosphorus metabolism in ruminants with special reference to parturient paresis. J. Dairy Res. 43:501.

Call, J. W., J. E. Butcher, J. L. Shupe, J. T. Blake, and A. E. Olson. 1986. Dietary phosphorus for beef cows. Am. J. Vet. Res. 47:475.

Challa, J., G. D. Braithwaite, and M. S. Dhanoa. 1989. Phosphorus homeostasis in growing calves. J. Agric. Sci. (Camb.) 112:217.

Church, D. C. 1993. Salivary function and production. In The Ruminant Animal: Digestive Physiology and Nutrition. D. C. Church (Ed.). Waveland Press, Inc., IL.

Cohen, R. D. H. 1975. Phosphorus for grazing beef cattle. A. M. R. C. Rev. Aust. Meat Res. Commun. 23:1.

Delaquis, A. M. 1992. The effects of dietary cation-anion balance, stage of lactation and ration ingredients on acid base metabolism and productivity of dairy cows. Ph.D. Thesis, McGill Univ. Montréal, Québec.

Delaquis, A. M., and E. Block. 1995. Acid-base status, renal function, water, and macromineral metabolism of dry cows fed diets differing in cation-anion difference. J. Dairy Sci. 78:604.

Eghball, B., and J. F. Power. 1994. Beef cattle feedlot manure management. J. Soil Water Conserv. 49:113.

Ellenberger, H. B., J. A. Newlander, and C. H. Jones. 1950. Composition of the bodies of dairy cattle. Univ. Vermont Agric. Exp. Stn. Bull. No. 558. Univ. Vermont, Burlington.

Erickson, G. E., T. J. Klopfenstein, C. T. Milton, D. Brink, M. W. Orth, and K. M. Whittet. 2002. Phosphorus requirement of finishing feedlot calves. J. Anim. Sci. 80:1690.

Erickson, G. E., T. J. Klopfenstein, C. T. Milton, D. Hanson, C. Calkins. 1999. Effect of dietary phosphorus on finishing steer performance, bone status, and carcass maturity. J. Anim. Sci. 77:2832.

Fahey, Jr., G. C., and L. L. Berger. 1993. Carbohydrate nutrition of ruminants. In The Ruminant Animal: Digestive Physiology and Nutrition. D. C. Church (Ed.). Waveland Press, Inc., IL.

Field, A. C. 1981. Some thoughts on dietary requirements of macro-elements for ruminants. Proc. Nutr. Soc. 40:267.

Hays, V. W., and M. J. Swenson. 1993. Minerals and bones. In Dukes Physiology of Domestic Animals. (11th Ed.). M. J. Swenson and W. O. Reece (Eds.). Cornell Univ. Press, Ithaca, NY.

Hemingway, R. G. 1967. Phosphorus in the ruminant. Outlook Agric. 5:172.

Horst, R. L. 1986. Regulation of calcium and phosphorus homeostasis in the dairy cow. J. Dairy Sci. 69:604.

Jacobson, D. R., R. W. Hemken, F. S. Button, and R. H. Hatton. 1972. Mineral nutrition, calcium, phosphorus, magnesium, and potassium interrelationships. J. Dairy Sci. 57:935.

Karn, J. F. 2001. Phosphorus nutrition of grazing cattle: A review. Anim. Feed Sci. Technol. 89:133.

Kegley, E. B., R. W. Harvey, and J. W. Spears. 1991. Effects of lysocellin and calcium level on mineral metabolism, performance and ruminal and plasma characteristics of beef steers. J. Anim. Sci. 69:782.

Kempster, A. J., A. Cuthbertson, and G. Harrington. 1982. Carcase evaluation. In Livestock Breeding, Production and Marketing. Granada Publishing Ltd., Great Britain.

Kincaid, R. 1993. Macro elements for ruminants. In The Ruminant Animal: Digestive Physiology and Nutrition. D. C. Church (Ed.). Waveland Press, Inc., IL.

Knowlton, K. F., J. H. Herbein, M. A. Meister-Weisbarth, and W. A. Wark. 2001. Nitrogen and phosphorus-partitioning in lactating Holstein cows fed different sources of dietary protein and phosphorus. J. Dairy Sci. 84:1210.

Lennox, S. D., R. H. Foy, R. V. Smith, and C. Jordan. 1997. Estimating the contribution from agriculture to the phosphorus load in surface water. In Phosphorus Loss from Soil to Water. H. Tunney, O. T. Carton, P. C. Brookes, and A. E. Johnston (Eds.). CAB Int., NY.

Little, D. A. 1980. Observations on the phosphorus requirement of cattle for growth. Res. Vet. Sci. 28:258.

Minson, D. J. 1990. Forage in Ruminant Nutrition. Academic Press, San Diego, CA.

Morse, D., H. H. Head, C. J. Wilcox, H. H. Van Horn, C. D. Hissem, and B. Harris, Jr. 1992. Effects of concentration of dietary phosphorus on amount and route of excretion. J. Dairy Sci. 75:3039.

NRC. 2001. Nutrient Requirements of Dairy Cattle. (7th Rev. Ed.). Natl. Acad. Sci., Washington, DC.

NRC. 1996. Nutrient Requirements of Beef Cattle. (7th Rev. Ed.). 2000 Update. Natl. Acad. Sci., Washington, DC.

NRC. 1998. Nutrient Requirements of Swine. (10th Rev. Ed.). Natl. Acad. Sci., Washington, DC.

NRC. 1976. Nutrient Requirements of Beef Cattle. (5th Rev. Ed.). Natl. Acad. Sci., Washington, DC.

Owens, F. N., and A. L. Goetsch. 1993. Ruminal fermentation. In The Ruminant Animal: Digestive Physiology and Nutrition. D. C. Church (Ed.). Waveland Press, Inc., IL.

Owens, F. N., and R. A. Zinn. 1993. Protein metabolism of ruminant animals. In The Ruminant Animal: Digestive Physiology and Nutrition. D. C. Church (Ed.). Waveland Press, Inc., IL.

Pálsson, H. 1955. Conformation and body composition. In Progress in the Physiology of Farm Animals. J. Hammond (Ed.). Butterworths Scientific Publications, London, England.

Pitt, R. E., J. S. Van Kessel, D. G. Fox, A. N. Pell, M. C. Barry, and P. J. Van Soest. 1996. Prediction of ruminal volatile fatty acids and pH within the net carbohydrate and protein system. J. Anim. Sci. 74:226.

Pomeroy, R. W. 1977. Historical and general review of growth and development. In Patterns of Growth and Development in Cattle. H. De Boer and J. Martin (Eds.). Commission of the European Communities, Luxembourg.

Reed, W. D. C., R. C. Elliott, J. H. Topps. 1965. Phosphorus excretion of cattle fed on high-energy diets. Nature 208:953.

Robelin, J., and N. M. Tulloh. 1992. Patterns of growth of cattle. In Beef Cattle Production. R. Jarrige and C. Béranger (Eds.). Elsevier, Amsterdam, The Netherlands.

Rumsey, T. S. 1982. Effect of Synovex-S implants and kiln dust on tissue gain by feedlot beef steers. J. Anim. Sci. 54:1030.

Rumsey, T. S., A. S. Kozak, and H. F. Tyrrell. 1985. Mineral deposition in diethylstilbesterol- and Synovex-treated steers. Growth 49:354.

Rumsey, T. S., H. F. Tyrrell, D. A. Dinius, P. W. Moe, and H. R. Cross. 1981. Effect of diethylstilbesterol on tissue gain and carcass merit of feedlot beef steers. J. Anim. Sci. 53:589.

Scott, D., and A. F. McLean. 1981. Control of mineral absorption in ruminants. Proc. Nutr. Soc. 40:257.

Sehested, J., and M. R. Weisbjerg. 2002. Release of phosphorus from feedstuffs for cattle. J. Anim. Sci. 80(Suppl. 1):364. (Abs.)

Sharpley, A. N., S. C. Chapra, R. Wedepohl, J. T. Sims, T. C. Daniel, and K. R. Reddy. 1994. Managing agricultural phosphorus for protection of surface waters: Issues and options. J. Environ. Qual. 23:437.

Shupe, J. L., J. E. Butcher, J. W. Call, A. E. Olson, and J. T. Blake. 1988. Clinical signs and bone changes associated with phosphorus deficiency in beef cattle. Am. J. Vet. Res. 49:1629.

Sniffen, C. J., J. D. O'Connor, P. J. Van Soest, D. G. Fox, and J. B. Russell. 1992. A net carbohydrate and proetin system for evaluating cattle diets: II. Carbohydrate and protein availability. J. Anim. Sci. 70:3562.

Ternouth, J. H. 1990. Phosphorus and beef production in northern Australia. 3. Phosphorus in cattle: A review. Trop. Grassl. 24:159.

Tölgyesi, G. 1972. Renal phosphorus excretion of cattle and its relationship with calcium supply. Acta Vet. Acad. Sci. Hung. 22:25.

Van Soest, P. J. 1994. Nutritional Ecology of the Ruminant. (2nd Ed.). Cornell Univ. Press, Ithaca, NY.

Vitti, D. M. S. S., E. Kebreab, J. B. Lopes, A. L. Abdalla, F. F. R. De Carvalho, K. T. De Resende, L. A. Crompton, and J. France. 2000. A kinetic model of phosphorus metabolism in growing goats. J. Anim. Sci. 78:2706.

Wasserman, R. H., F. A. Kallfelz, and G. Lust. 1993. Bones, joints, and synovial fluid. In Dukes Physiology of Domestic Animals. (11th Ed.). M. J. Swenson and W. O. Reece (Eds.). Cornell Univ. Press, Ithaca, NY.

Whalen, J. K., and C. Chang. 2001. Phosphorus accumulation in cultivated soils from long-term annual applications of cattle feedlot manure. J. Environ. Qual. 30:229.

Winks, L. 1990. Phosphorus and beef production in northern Australia. 2. Responses to phosphorus by ruminants: A review. Trop. Grassl. 24:140.

Wu, Z., L. D. Satter, A. J. Blohowiak, R. H. Stauffacher, and J. H. Wilson. 2001. Milk production, estimated phosphorus excretion, and bone characteristics of dairy cows fed different amounts of phosphorus for two or three years. J. Dairy Sci. 84:1738.