Interrelationship of Dietary Phosphorus, Aluminum and Iron on Performance and Tissue Mineral Composition in Lambs

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INTERRELATIONSHIP OF DIETARY PHOSPHORUS, ALUMINUM AND IRON ON PERFORMANCE AND TISSUE MINERAL COMPOSITION IN LAMBS[1,2]

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Summary

A 76-d feeding trial was conducted with 24 wether lambs (31 kg, initially) to study the interrelationships among dietary P, Al and Fe. A 2 × 2 × 2 factorial arrangement of treatments included two concentrations of supplemental P (0 or .25%) with added P as NaH_2PO_4, two levels of supplemental Fe (0 or 760 ppm) with Fe added as ferric citrate and two levels of supplemental Al (0 or 1,450 ppm) with Al added as $AlCl_3 \cdot 6H_2O$. The basal diet contained .17% P, 40 ppm Fe and 168 ppm Al. Phosphorus increased ($P<.01$) feed consumption, but Fe ($P<.01$) and Al ($P<.05$) decreased intake. Dietary treatments affected average daily gain ($P<.01$), with added P improving and Fe or Al depressing gain. Additional P improved gain ($P<.05$) and intake ($P<.01$) in the presence of high Al and intake ($P<.05$) when dietary Fe was high. Serum P was increased ($P<.01$) by high dietary Fe and reduced ($P<.01$) by Al. High dietary P increased ($P<.05$) serum Mg. High dietary Fe increased ($P<.01$) hemoglobin and hematocrit and increased ($P<.01$) Fe storage in liver, kidney, spleen and muscle but decreased ($P<.01$) kidney Zn concentration. High dietary Al increased ($P<.01$) liver Fe and kidney Zn levels but decreased kidney P and Mg ($P<.05$) and bone ash and Mg ($P<.01$). Based on these studies, additional dietary P appeared beneficial in overcoming the adverse effects of high dietary Al or Fe.

(Key words: Aluminum, Phosphorus, Iron, Mineral Interrelationships, Tissue Mineral Concentrations, Sheep.)

Introduction

The P requirement of a ruminant is rarely met by forage diets, therefore, supplementation is necessary (Cohen, 1980). Furthermore, P utilization can be adversely influenced by factors including dietary Al and Fe. These elements can occur in relatively high concentrations in soil, which may be consumed by grazing ruminants (Healy, 1970; Valdivia, 1977).

High dietary Al has been suggested to interfere with P utilization in nonruminants by forming unabsorbable complexes in the gastrointestinal tract (Deobald and Elvehjem, 1935; Jones, 1938; Storer and Nelson, 1968). Likewise, high amounts of dietary Fe have been demonstrated to affect P absorption perhaps by forming insoluble phosphates in the digestive tract (O'Donovan et al., 1963; Standish et al., 1969). Although interference with P metabolism by Fe has been well demonstrated in ruminants, information concerning effects of high dietary Al is quite limited. Experiments with dietary Al up to 1,200 ppm have produced no adverse effects (Thompson et al., 1959; Valdivia et al., 1978). The present experiment was conducted to investigate further the interrelationships of dietary P, Al and Fe on performance and tissue mineral composition in growing lambs.

Experimental Procedure

Twenty-four 6-mo-old Florida native wether lambs, averaging 31 kg initially, were randomly assigned to eight groups with a

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2 × 2 × 2 factorial arrangement of treatments in a completely randomized design. The treatments consisted of a basal diet (table 1), in which cornstarch was partially replaced by minerals to provide the desired mineral concentrations (dry basis): .17 (basal) or .42% total P, supplemental P added as NaH_2PO_4; 0 or 760 ppm added Fe as ferric citrate (basal 40 ppm Fe) and 0 or 1,450 ppm added Al as $AlCl_3 \cdot 6H_2O$ (basal 168 ppm Al). Calcium was adjusted in all diets to provide a constant Ca to P ratio of 1.3:1. Animals were housed individually in elevated pens with slotted floors during a 76-d trial; experimental diets and tap water were supplied ad libitum. The water contained < 1 ppm Al and Fe and < 10 ppm P. Lambs were initially dewormed[5] and allowed to adjust to basal diets for 10 d. Individual weights were taken on two successive days at the beginning and end of the experiment. Blood samples were obtained via jugular puncture at the beginning and at the end of the experiment. At the end of the trial, all lambs were killed by exsanguination and liver, spleen, kidney, heart, longissimus muscle and metacarpal bone were removed and frozen for subsequent analysis.

Calcium, Mg, Fe, Cu, Zn and Mn in feed and tissues were analyzed by atomic absorption spectrophotometry[6] according to procedures recommended by the manufacturer (Perkin-Elmer, 1973). Phosphorus in feed and tissues was determined by the colorimetric method described by Harris and Popat (1954). Hemoglobin was determined by the hematin method (Cohen and Smith, 1919) and hematocrit by the microhematocrit method. Bones were cleaned of all soft tissue, dried at 100 C for 24 h, and defatted in a Soxhlet extractor for 48 h. Minerals were analyzed as described previously. Statistical evaluations of data were made by analysis of variance processed by computer programs of Statistical Analysis System (Barr et al., 1976) with the same basic model used for performance, tissue and blood data.

TABLE 1. COMPOSITION OF BASAL DIET

Item	%
Ingredient composition[a]	
Cornmeal (IFN 4-02-992)	44.0
Cottonseed hulls (IFN 1-01-599)	26.0
Cornstarch (IFN 4-02-889)	20.1
Corn oil (IFN 4-07-882)	3.0
Soybean meal (IFN 5-04-604)	2.0
Alfalfa meal (IFN 1-00-023)	2.0
Urea (281% equivalent protein)	1.5
Salt, trace mineralized[b]	1.0
Calcium carbonate (IFN 6-01-070)	.3
Sulfur, flowers	.1
Vitamin A and D[c]	+
Total	100.0
Chemical composition[d]	
Crude protein, %	12.0
P, %	.17
Ca, %	.23
Mg, %	.12
Al, ppm	168.0
Fe, ppm	40.0

[a] As-fed basis.

[b] Analysis in percentage as follows: NaCl, 96.0; Zn, .30; Mn, .24; Fe, .22; Cu, .025; I, .007; Co, .007.

[c] Vitamins added per kg of diet: 2,200 IU vitamin A palmitate, 440 IU vitamin D_3.

[d] Dry matter basis.

Results and Discussion

Animal Performance. Daily dry matter intake was increased (P<.01) by additional P (1,049 vs 1,259 g) but decreased by Fe (P<.01; 1,280 vs 1,027 g) and Al (P<.05; 1,224 vs 1,084 g; table 2). Phosphorus and Al interacted (P<.05) on voluntary feed intake, with additional P partially overcoming the adverse effect of high dietary Al. Addition of supplemental P to the basal diet improved (P<.01) average daily gain from 105 to 148 g. High dietary Fe and Al decreased (P<.01) average daily gain from 156 to 97 g and 159 to 95 g, respectively. There was a P × Al interaction (P<.05) on daily gain, with added dietary P counteracting the depressing effect of high dietary Al. There was also a P × Fe interaction (P<.05) on intake with added dietary P partially overcoming the depressing effects of Fe. There were no effects of dietary treatments on feed conversion.

The positive response to P probably can be attributed to a greater supply of P in a diet that is borderline or deficient in the element, because NRC (1975) recommends .23% dietary P for optimum performance in growing lambs. Thompson et al. (1959) reported no deleterious effects in lambs by feeding diets containing

[5] Levamisole, Pitman-Moore, Inc., Washington Crossing, NJ 08560.

[6] Perkin-Elmer 306, Perkin-Elmer Corp., Norwalk, CT 06850.

TABLE 2. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON FEED INTAKE, GAIN AND FEED CONVERSION IN LAMBS[a]

Treatment (added minerals)[b]			Avg initial weight, kg	Avg dry matter intake, g	Avg daily gain, g	Feed/unit gain
P, %	Fe, ppm	Al, ppm				
0	0	0	30.3 ± .9	1,326 ± 59	182 ± 22	7.4 ± .6
.25	0	0	33.0 ± 2.1	1,442 ± 127	187 ± 12	7.7 ± .6
0	760	0	29.7 ± .5	1,052 ± 81	132 ± 16	8.1 ± .4
.25	760	0	30.1 ± .5	1,077 ± 76	133 ± 13	8.1 ± .3
0	0	1,450	29.6 ± 1.0	1,073 ± 90	100 ± 19	11.0 ± 1.1
.25	0	1,450	32.5 ± 2.2	1,280 ± 24	157 ± 10	8.3 ± .6
0	760	1,450	30.1 ± .9	745 ± 68	5 ± 14	
.25	760	1,450	33.0 ± 2.2	1,237 ± 96	116 ± 12	10.7 ± .4
			Statistical significance[c]			
P				P<.01	P<.01	NS
Fe				P<.01	P<.01	NS
Al				P<.01	P<.05	NS
P × Fe				P<.05	NS	NS
P × Al				P<.01	P<.05	NS
Fe × Al				NS	NS	NS
P × Fe × Al				NS	NS	NS

[a]Each value represents the mean ± SE of three lambs.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

1.0% aluminum sulfate (810 ppm Al). Valdivia (1977) reported that inclusion of Al at 2,000 ppm in the diet of lambs depressed gain and feed intake. Addition of P, however, to the high Al diet improved intake and gain. Standish et al. (1969) observed depression of gain and feed intake in steers by as little as 400 ppm dietary Fe. Standish and Ammerman (1971) fed 1,600 ppm dietary Fe to lambs and observed an adverse effect of Fe on gain, which may have resulted from reduced dietary intake. In another trial with steers, Standish et al. (1971) reported the same adverse effect of high dietary Fe (1,000 ppm) on feed intake and gain. Feeding additional P (.23%) tended to counteract the adverse effects of high Fe but this was not statistically significant.

Blood Characteristics. Excess dietary Fe (760 ppm added) increased (P<.01) inorganic P in serum, while high dietary Al reduced (P<.01) serum P level (table 3). There was an Fe × Al interaction (P<.01) on serum P; the reduction in serum P caused by high dietary Al was counteracted partially by added dietary Fe. Serum Ca was not affected by dietary minerals, but serum Mg was increased (P<.05) when P was added to the diets. High dietary Al tended to depress serum Mg, but not significantly. Blood hemoglobin and hematocrit were increased (P<.01) by dietary Fe but other dietary treatments had no effect on these blood characteristics.

Similar increases in serum P related to high dietary Fe were reported to occur in chicks (Deobald and Elvehjem, 1935) and rats (Harmon et al., 1968). Standish et al. (1969), who observed a similar effect of high dietary Fe in steers, suggested that increased plasma P could be related more closely to a reduced feed intake. Standish et al. (1971) found a reduction in serum P of sheep by feeding 1,000 ppm Fe at the 45th d of a trial, but this effect was not apparent at the 77th d. The reduction in serum P caused by high dietary Al in the present study has been reported in previous studies with nonruminant animals (Jones, 1938; Street, 1942; Alsmeyer et al., 1963) and was attributed to a decreased P absorption resulting from P complexation with Al in the digestive tract. In ruminants, Thompson et al. (1959) reported no effect of 1.0% dietary aluminum sulfate on serum P and other characteristics studied in sheep. The authors suggested that ruminants were less susceptible to excess dietary Al than nonruminants due to considerable quantities

TABLE 3. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON SERUM MINERALS, HEMOGLOBIN AND HEMATOCRIT IN LAMBS[a]

Treatment (added minerals)[b]			Phosphorus		Calcium		Magnesium		Hemoglobin		Hematocrit	
P, %	Fe, ppm	Al, ppm	Final	Change	Final	Change	Final	Change	Final	Change	Final	Change
			mg/100 ml						g/100 ml		%	
0	0	0	6.3 ± .7	.63	8.1 ± .4	−.01	2.5 ± .12	.09	11.4 ± .4	−2.3	33.9 ± .9	−10.8
.25	0	0	6.1 ± .6	.06	8.4 ± .4	.30	2.5 ± .01	.03	12.6 ± .8	− .9	34.7 ± 1.7	− 6.2
0	760	0	6.4 ± .9	1.11	8.1 ± .1	.30	2.4 ± .13	.35	16.3 ± 1.2	3.2	46.6 ± 2.9	6.1
.25	760	0	7.6 ± .4	1.52	8.1 ± .1	.19	2.4 ± .07	.16	13.0 ± .2	−1.0	36.1 ± .5	− .5
0	0	1,450	1.7 ± .1	−2.57	9.1 ± .4	.26	2.3 ± .21	−.07	14.0 ± .6	.6	38.3 ± 2.0	− 2.7
.25	0	1,450	5.6 ± .6	.95	8.8 ± .1	.20	2.3 ± .02	.34	12.5 ± .4	− .8	34.7 ± .4	− 5.1
0	760	1,450	1.5 ± .2	−1.96	9.1 ± .4	.34	1.8 ± .16	−.54	15.4 ± .5	.9	45.5 ± 3.0	3.6
.25	760	1,450	5.1 ± .8	− .22	8.2 ± .4	−.02	2.1 ± .07	−.11	15.0 ± 1.6	.7	41.6 ± 4.5	− 2.7
			Statistical significance[c]									
P			NS		NS		P<.05		P=.08		NS	
Fe			P<.01		NS		NS		P<.01		P<.01	
Al			P<.01		NS		P=.06		NS		NS	
P X Fe			NS		NS		NS		P=.08		P=.09	
P X Al			NS		NS		NS		NS		NS	
Fe X Al			P<.01		NS		NS		NS		NS	
P X Fe X Al			P=.08		NS		NS		P=.07		NS	

[a]Each value represents the mean ± SE of three lambs.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

of organic acids in the rumen, which would complex Al, preventing, at least partially, P precipitation in the digestive tract. Valdivia et al. (1978) reported no changes in plasma P of steers by the feeding of up to 1,200 ppm Al. In an experiment with sheep, however, Valdivia (1977) reported a significant decrease in plasma P when 2,000 ppm Al (as chloride) were supplied in the diet.

The increase in blood hemoglobin and hematocrit by feeding high dietary Fe is in agreement with results reported for swine (Furugouri, 1972) and calves (Thomas et al., 1954; Koong et al., 1970). Standish et al. (1969, 1971) and Standish and Ammerman (1971) reported no effect of up to 1,600 ppm dietary Fe on blood hemoglobin and hematocrit in steers and sheep.

Tissue Minerals. Iron was the only mineral in liver that was affected by dietary treatments (table 4). High dietary Fe increased (P<.01) Fe concentration in liver. Added dietary P reduced (P<.01) hepatic Fe levels while high dietary Al increased (P<.01) liver Fe concentration. Phosphorus interacted (P<.01) with Fe by depressing Fe accumulation in the liver resulting from high dietary Fe. An interaction (P<.01) between Fe and Al was manifested by the dietary excess of both elements combining to produce an increase in liver Fe. Again, antagonistic dietary effects of P and Al were indicated (P<.01), with high dietary P depressing liver Fe accumulation induced by excess dietary Al. A three-way interaction (P<.01) was also detected with high Fe and Al producing an increase in liver Fe and high dietary P antagonizing this effect.

High dietary Al depressed (P<.05) P concentration in kidney (12,204 vs 11,491 ppm; table 5). Kidney Mg was decreased (P<.01) by high Al diets. Either high dietary P or Fe decreased kidney Mg in the presence of low dietary concentrations of the other element and this effect was reversed when both elements were present at high concentrations (P × Fe interaction, P<.05). The addition of P or Fe to the diet decreased (P<.01) kidney Zn, but high dietary Al increased (P<.01) kidney Zn concentration. High dietary Al increased Zn concentration in kidney in the presence of low dietary P, but added dietary P reversed this effect (P × Al interaction, P<.01). Iron concentration in kidney was increased (P<.01) by dietary Fe from 349 to 678 ppm. Kidney Cu was increased (P<.01) by addition of dietary Al and there was also

TABLE 4. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON LIVER MINERAL COMPOSITION IN LAMBS[a]

Treatment[b]			Mineral concentration (ppm dry matter basis)						
P, %	Fe, ppm	Al, ppm	P	Ca	Mg	Zn	Fe	Cu	Mn
0	0	0	8,301 ± 1,333	128 ± 18	422 ± 68	91 ± 8	162 ± 9	296 ± 31	7.4 ± 1.7
.25	0	0	8,729 ± 843	122 ± 16	407 ± 47	88 ± 7	164 ± 13	312 ± 25	6.7 ± .5
0	760	0	9,588 ± 639	126 ± 14	463 ± 52	104 ± 7	1,306 ± 206	360 ± 94	6.5 ± .2
.25	760	0	8,187 ± 1,064	117 ± 10	410 ± 49	105 ± 18	1,091 ± 201	272 ± 43	6.9 ± 1.2
0	0	1,450	8,206 ± 1,102	124 ± 12	474 ± 38	105 ± 11	185 ± 25	361 ± 18	5.8 ± .3
.25	0	1,450	8,357 ± 967	121 ± 15	443 ± 55	88 ± 7	188 ± 50	394 ± 88	5.9 ± .5
0	760	1,450	9,530 ± 187	124 ± 7	536 ± 32	112 ± 9	3,652 ± 383	431 ± 101	5.9 ± .4
.25	760	1,450	9,376 ± 1,309	138 ± 14	473 ± 30	103 ± 21	1,057 ± 420	384 ± 45	7.0 ± .9
			Statistical significance[c]						
P			NS	NS	NS	NS	P<.01	NS	NS
Fe			NS	NS	NS	NS	P<.01	NS	NS
Al			NS	NS	NS	NS	P<.01	NS	NS
P × Fe			NS	NS	NS	NS	P<.01	NS	NS
P × Al			NS	NS	NS	NS	P<.01	NS	NS
Fe × Al			NS	NS	NS	NS	P<.01	NS	NS
P × Fe × Al			NS	NS	NS	NS	P<.01	NS	NS

[a]Each value represents the mean ± SE of three animals.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

a P × Al interaction (P<.05) in which additional P overcame the increase in kidney Cu brought about by dietary Al.

Skeletal muscle exhibited an efficient homeostatic mechanism for minerals (table 6); however, there was an increase (P<.01) of Fe in muscle from 65 to 81 ppm when high Fe diets were fed. Also, a P × Fe interaction (P<.05) on muscle Fe was detected, with high dietary P decreasing Fe accumulation resulting from excess dietary Fe. The remaining minerals analyzed in the muscle were not affected (P>.10) by dietary treatments. Cardiac muscle, like skeletal muscle, is known to possess a rather efficient mechanism for controlling mineral accumulation when excesses are supplied in the diet (table 7). The only effect of dietary treatment on heart minerals was a decrease (P<.05) in heart Mn concentration caused by added dietary P.

High dietary Fe decreased (P<.01) Ca concentration in spleen from 223 to 198 ppm (table 8). Magnesium and Mn concentrations in spleen were not affected (P>.10) by dietary treatments. Added dietary P decreased (P<.05) spleen Zn. Iron storage in spleen was increased (P<.01) by high dietary Fe, from 981 to 7,510 ppm. Dietary Fe also increased (P<.05) Cu concentration from 4.3 to 5.8 ppm. An interaction (P<.05) of P × Al on Cu in spleen was observed, with added dietary P decreasing spleen Cu concentrations resulting from high dietary Al.

Dietary P produced a 3.9% increase (P<.01) in bone ash (table 9). Conversely, high dietary Al caused a 2.3% reduction (P<.01) in that characteristic. Phosphorus content in bone ash was increased (P<.01) by dietary P from 16.8 to 17.2%. High dietary Al had a tendency to depress bone P percentage, but this effect was not significant. An interaction (P<.05) of P × Al was detected, with added dietary P increasing bone Ca, while high Al in the diet antagonized this effect. Bone Mg was increased (P<.01) by high dietary P but decreased (P<.01) by dietary Al. An interaction (P<.01) between P and Al on bone Mg was observed and manifested by high dietary P partially counteracting the adverse effect of added Al.

Doyle and Spaulding (1978) suggested that Fe in excess of requirements for metabolic processes in the animal body is stored in several tissues, with highest concentrations in liver,

TABLE 5. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON KIDNEY MINERAL COMPOSITION IN LAMBS[a]

Treatment (added minerals)[b]			Mineral concentration (ppm dry matter basis)						
P, %	Fe, ppm	Al, ppm	P	Ca	Mg	Zn	Fe	Cu	Mn
0	0	0	12,104 ± 216	475 ± 57	830 ± 23	96 ± 5	289 ± 19	11.9 ± .8	3.3 ± .07
.25	0	0	12,208 ± 441	487 ± 62	793 ± 17	102 ± 17	349 ± 24	13.1 ± 1.7	3.2 ± .13
0	760	0	12,049 ± 174	360 ± 19	818 ± 5	91 ± 5	566 ± 48	12.0 ± 3.3	3.4 ± .30
.25	760	0	12,454 ± 544	633 ± 162	833 ± 43	88 ± 5	569 ± 67	13.4 ± .9	3.1 ± .17
0	0	1,450	11,761 ± 345	477 ± 91	802 ± 42	174 ± 14	395 ± 8	18.9 ± 1.9	3.3 ± .20
.25	0	1,450	11,368 ± 450	441 ± 57	763 ± 16	106 ± 5	364 ± 58	13.6 ± .9	3.1 ± .14
0	760	1,450	11,104 ± 257	381 ± 18	715 ± 26	134 ± 2	1,087 ± 357	14.7 ± 1.5	2.8 ± .29
.25	760	1,450	11,731 ± 458	463 ± 86	792 ± 6	99 ± 5	489 ± 41	14.2 ± .4	3.7 ± .21
			Statistical significance[c]						
P			NS	NS	NS	P<.01	NS	NS	NS
Fe			NS	NS	NS	P<.01	P<.01	NS	NS
Al			P<.05	NS	P<.01	P<.01	NS	P<.01	NS
P × Fe			NS	NS	P<.05	NS	NS	NS	P=.08
P × Al			NS	NS	NS	P<.01	P=.08	P<.05	P<.05
Fe × Al			NS	NS	NS	NS	NS	NS	NS
P × Fe × Al			NS	NS	NS	P<.05	NS	NS	P<.05

[a]Each value represents the mean ± SE of three animals.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

TABLE 6. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON MUSCLE MINERAL COMPOSITION IN LAMBS[a]

Treatment (added minerals)[b]			Mineral concentration (ppm dry matter basis)						
P, %	Fe, ppm	Al, ppm	P	Ca	Mg	Zn	Fe	Cu	Mn
0	0	0	5,951 ± 628	132 ± 7	821 ± 66	94 ± 11	63 ± 4	4.2 ± .15	.59 ± .08
.25	0	0	6,424 ± 259	149 ± 9	853 ± 38	100 ± 3	70 ± 5	4.1 ± .26	.51 ± .01
0	760	0	6,807 ± 288	139 ± 5	885 ± 52	92 ± 11	87 ± 2	3.9 ± .45	.54 ± .03
.25	760	0	6,902 ± 114	138 ± 8	908 ± 25	116 ± 17	72 ± 2	4.6 ± .41	.59 ± .01
0	0	1,450	6,673 ± 241	142 ± 6	934 ± 25	126 ± 19	64 ± 4	4.5 ± .35	.51 ± .04
.25	0	1,450	6,817 ± 197	142 ± 2	949 ± 24	110 ± 6	62 ± 8	5.1 ± .35	.53 ± .02
0	760	1,450	7,079 ± 345	154 ± 3	919 ± 47	95 ± 10	85 ± 2	4.4 ± .54	.52 ± .04
.25	760	1,450	6,711 ± 182	153 ± 8	897 ± 22	120 ± 16	78 ± 5	4.6 ± .36	.60 ± .01
			Statistical significance[c]						
P			NS	NS	NS	NS	NS	NS	NS
Fe			P=.08	NS	NS	NS	P<.01	NS	NS
Al			NS	P=.09	P=.06	NS	NS	P=.09	NS
P X Fe			NS	NS	NS	NS	P<.05	NS	NS
P X Al			NS	NS	NS	NS	NS	NS	NS
Fe X Al			NS	NS	NS	NS	NS	NS	NS
P X Fe X Al			NS	NS	NS	NS	NS	NS	NS

[a]Each value represents the mean ± SE of three lambs.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

TABLE 7. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON HEART MINERAL COMPOSITION IN LAMBS[a]

Treatment (added minerals)[b]			Mineral concentration (ppm dry matter basis)						
P, %	Fe, ppm	Al, ppm	P	Ca	Mg	Zn	Fe	Cu	Mn
0	0	0	9,038 ± 39	228 ± 14	993 ± 19	79 ± 4	184 ± 10	17.1 ± .6	1.6 ± .17
.25	0	0	8,155 ± 587	198 ± 19	893 ± 64	79 ± 1	161 ± 12	16.8 ± .2	1.5 ± .01
0	760	0	8,297 ± 587	193 ± 14	929 ± 24	75 ± 4	190 ± 15	15.8 ± .7	1.3 ± .05
.25	760	0	8,773 ± 416	210 ± 9	964 ± 58	76 ± 5	190 ± 5	16.1 ± 1.0	1.3 ± .10
0	0	1,450	8,672 ± 388	206 ± 8	952 ± 40	77 ± 4	193 ± 10	14.7 ± 1.3	1.7 ± .11
.25	0	1,450	8,707 ± 366	220 ± 9	939 ± 35	77 ± 3	181 ± 11	15.6 ± 1.0	1.3 ± .14
0	760	1,450	8,572 ± 248	235 ± 17	988 ± 17	80 ± 11	200 ± 21	16.1 ± .2	1.6 ± .17
.25	760	1,450	9,008 ± 505	221 ± 17	977 ± 29	76 ± 3	204 ± 5	15.5 ± .5	1.4 ± .20
			Statistical significance[c]						
P			NS	NS	NS	NS	NS	NS	P<.05
Fe			NS	NS	NS	NS	NS	NS	NS
Al			NS	NS	NS	NS	P=.09	NS	NS
P X Fe			NS	NS	NS	NS	NS	NS	NS
P X Al			NS	NS	NS	NS	NS	NS	NS
Fe X Al			NS	NS	NS	NS	NS	NS	NS
P X Fe X Al			NS	NS	NS	NS	NS	NS	NS

[a]Each value represents the mean ± SE of three lambs.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

TABLE 8. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON SPLEEN MINERAL COMPOSITION IN LAMBS[a]

Treatment (added minerals)[b]			Mineral concentration (ppm dry matter basis)						
P, %	Fe, ppm	Al, ppm	P	Ca	Mg	Zn	Fe	Cu	Mn
0	0	0	10,538 ± 746	201 ± 9	744 ± 26	105 ± 9	800 ± 25	3.4 ± 1.0	.95 ± .10
.25	0	0	12,857 ± 288	239 ± 5	828 ± 27	107 ± 3	849 ± 41	4.8 ± .4	1.08 ± .04
0	760	0	11,192 ± 255	215 ± 6	755 ± 35	108 ± 4	8,686 ± 1,969	5.1 ± .1	.99 ± .04
.25	760	0	11,429 ± 273	191 ± 12	791 ± 32	104 ± 7	6,063 ± 876	5.2 ± .2	.99 ± .08
0	0	1,450	11,176 ± 556	239 ± 10	802 ± 3	122 ± 2	1,348 ± 192	5.7 ± .6	1.06 ± .07
.25	0	1,450	11,352 ± 1,108	213 ± 20	778 ± 51	104 ± 8	929 ± 115	3.5 ± .4	.91 ± .08
0	760	1,450	10,265 ± 232	196 ± 3	755 ± 25	115 ± 4	6,704 ± 1,872	6.3 ± 1.6	.94 ± .06
.25	760	1,450	10,729 ± 473	191 ± 10	754 ± 33	100 ± 2	8,586 ± 1,069	5.3 ± .1	.95 ± .07
			Statistical significance[c]						
P			P=.06	NS	NS	P<.05	NS	NS	NS
Fe			NS	P<.01	NS	NS	P<.01	P<.05	NS
Al			NS	NS	NS	NS	NS	NS	NS
P X Fe			NS	NS	NS	NS	NS	P=.09	NS
P X Al			NS	NS	NS	P<.05	NS	P<.05	NS
Fe X Al			NS	NS	NS	NS	NS	P=.08	NS
P X Fe X Al			NS	NS	NS	NS	NS	NS	NS

[a]Each value represents the mean ± SE of three lambs.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS=P>.10.

TABLE 9. EFFECT OF DIETARY PHOSPHORUS, IRON AND ALUMINUM ON BONE COMPOSITION IN LAMBS[a]

Treatment (added minerals)[b]				Mineral concentration (% ash basis)		
P, %	Fe, ppm	Al, ppm	Ash, %	P	Ca	Mg
0	0	0	35.9 ± .38	16.8 ± .25	32.8 ± .70	.72 ± .01
.25	0	0	39.8 ± .07	17.1 ± .20	33.9 ± .21	.70 ± .03
0	760	0	36.5 ± 1.14	17.1 ± .18	33.0 ± .58	.68 ± .01
.25	760	0	39.2 ± .14	17.2 ± .02	34.3 ± .26	.73 ± .01
0	0	1,450	34.4 ± .98	16.5 ± .18	33.6 ± .33	.59 ± .02
.25	0	1,450	38.0 ± .10	17.2 ± .08	33.8 ± .39	.67 ± .01
0	760	1,450	32.2 ± .04	16.6 ± .06	34.3 ± .21	.56 ± .02
.25	760	1,450	37.4 ± .11	17.1 ± .08	33.5 ± .11	.66 ± .01
			Statistical significance[c]			
P			P<.01	P<.01	NS	P<.01
Fe			NS	NS	NS	NS
Al			P<.01	P=.09	NS	P<.01
P X Fe			NS	NS	NS	NS
P X Al			NS	NS	P<.05	P<.01
Fe X Al			NS	NS	NS	NS
P X Fe X Al			NS	NS	NS	NS

[a]Each value represents the mean ± SE of three lambs.

[b]Basal diet contained .17% P, 40 ppm Fe and 168 ppm Al.

[c]NS = P>.10.

spleen and red bone marrow. In investigations with ruminants, Standish et al. (1969, 1971) and Standish and Ammerman (1971) consistently observed an increased Fe content in liver, spleen and kidney when high dietary Fe was supplied to steers or sheep. High dietary Fe also increased Fe concentrations in heart and muscle in steers and in heart in sheep. Iron increases in liver of steers were threefold with 1,600 ppm dietary Fe (Standish et al., 1969), and 10-fold in sheep fed the same concentration of dietary Fe (Standish and Ammerman, 1971). An antagonism between Fe and P was evidenced in certain tissues: addition of P to the high Fe diets reduced Fe concentration in liver to about one-half. In spleen, however, the second most important site of Fe accumulation in this study, P did not affect Fe concentration.

Decreased liver Fe concentration related to high dietary P is in agreement with findings of several authors and related to the observation by Brock and Diamond (1934) that Fe combines with P in the intestinal tract to form compounds that are difficult to absorb. A metabolic antagonism between P and Fe characterized by reduced liver Fe accumulation has been reported by Harmon et al. (1968) in rats and by Standish et al. (1971) in steers.

The synergistic effect between Al and Fe can be related to the metabolic antagonism of both elements with P. Because it is well established that P can combine with either Al or Fe and make them unavailable for absorption and vice versa, it seems reasonable to infer that increasing either Fe or Al in a diet high in P would permit more of each element to be available for absorption in the digestive tract. Valdivia (1977) reported increased Fe in liver and spleen of sheep when high dietary Al (2,000 ppm) was fed, even though concentrations of dietary Fe were in a range considered normal. In our study a depressing effect of high dietary Al on concentrations of P and Mg in kidney was observed. A depression of Mg concentration in kidney of sheep was also related to high dietary Al (2,000 ppm; Valdivia, 1977). In the present study high dietary P or Fe decreased Zn concentration in kidney, while high dietary Al had the opposite effect. Zinc concentration was reduced in spleen by diets high in P. Similar results were reported by Valdivia (1977) who observed a reduction in kidney Zn by increasing dietary P and an increase in Zn concentration in kidney and liver when high dietary Al was fed. Standish et al. (1971) reported that reduced Zn concentrations in liver and increased concentrations in spleen of steers were related to high dietary Fe (1,000 ppm). High dietary Al decreased ($P<.01$) Mg concentration in bone and kidney. Similarly, Valdivia (1977) reported a reduction of Mg in kidney and serum when high dietary Al was fed. These findings are of importance in view of a recent report (Allen et al., 1980) on the presence of high concentrations of Al in pasture influencing the occurrence of grass tetany.

When high dietary Al (1,450 ppm) was provided, bone ash as well as bone Mg were reduced. Valdivia (1977) observed decreased bone ash percentage in sheep fed 2,000 ppm dietary Al. In the present study, antagonistic effects between P and Al were observed on bone Mg, Ca and P, which were depressed by high dietary Al. Iron interference with P utilization, manifested by low bone ash and bone P, has been reported for nonruminants (O'Donovan et al., 1963; Furugouri, 1972). In the present experiment, a similar effect on bone composition was not detected with the relatively low concentration of Fe utilized (760 ppm) as compared with concentrations used with nonruminants (above 2,000 ppm).

These findings suggest that excessive levels of dietary Al or Fe increase the dietary requirement for P and that elevated levels of dietary P help alleviate the adverse effects of excessive Al and Fe. This may have special importance under grazing conditions in which quantities of soil are consumed.

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