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Effects of an aluminum-water treatment residual on performance and mineral status of feeder lambs☆

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Abstract

A 14-week experiment was conducted using 42 feeder lambs. Individual feeding was recorded between weeks 11 and 14. Diets, containing 0.25% P (as fed), included (1) control (10% sand), (2) (9.7% sand and 0.3% $AlCl_3$), (3) (2.5% water treatment residual (WTR) and 7.5% sand), (4) (5% WTR and 5% sand), (5) (10% WTR and 0% sand), and (6) (10% WTR, 0% sand, double the added quantities of the mineral–vitamin premix, and 1.29% dicalcium phosphate). The total Al varied from 910 to 8000 ppm among diets. Lambs fed the control and WTR had no decline in intake, body weight (BW), or average daily gain (ADG) which may be attributed to the non-available Al found in WTR. Whereas lambs fed $AlCl_3$ repeatedly had lower BW and intakes. During week 6, all treatments showed declines in plasma P, but the $AlCl_3$ treatment often declined the most, and during week 11, plasma P began to increase.

Accumulations of Al in the brain were greatest for lambs given 2000 ppm Al from $AlCl_3$ and increased incrementally when Al as WTR was fed at levels higher than 2000 ppm. With the exception of the brain, soft tissues did not accumulate large amounts of Al during this 14-week experiment.

Apparent P absorption from a 14-day metabolic study was positive (10.9–31.8%) for all lambs fed the control and various levels of WTR. However, lambs that received 2000 ppm Al via $AlCl_3$ had a negative P absorption of −12.9%. This was lower ($P < 0.05$) P absorption compared to all other treatments. Aluminum, as $AlCl_3$, fed at 2000 ppm reduced dietary P retention, but varying amounts of Al as WTR had no effect on P apparent absorption with similar absorption rates as the control. Therefore when dietary P is supplied in amounts of 0.25% or higher, Al (via WTR) fed to lambs in amounts as high as 8000 ppm did not negatively impact the feed intake, gain, BW, tissue P, plasma P, or P absorption.

Keywords: Lambs; Phosphorus; Water treatment residuals; Aluminum

1. Introduction

Ingestion of highly available dietary Al (e.g. $AlCl_3$) by livestock can result in Al toxicity, often observed as a P deficiency (Valdivia, 1977). Dietary Al suppressed sheep voluntary feed intake, feed efficiency, plasma P, growth, and gains (Rosa et al., 1982). When additional P was ingested, negative effects were less severe but were still evident.

Water treatment residuals are the by-products from a water purification procedure, and can contain high amounts of Al, Fe and Ca. The residual used in this experiment contained high amounts of Al and had a high

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P sorption capacity (O'Connor et al., 2002). Because Al is highly reactive and chemically binds P, the administration of WTR on manure containing soils could be a solution for P pollution of water systems by increasing soil P retention capabilities (Penn and Sims, 2002). Concerns exist regarding land application of WTR because of possible ingestion of WTR by grazing animals and the antagonistic reaction of Al to P within the animal.

Under grazing conditions, ruminants may consume 10–15% of their dry matter (DM) intake as soil (Field and Purves, 1964; Healy, 1967, 1968). Massive surface applications of WTR (~225 metric tonnes/ha) would cover the soil to a depth of about 2.54 cm and could constitute the entire 10% of "soil" consumed. Most situations require WTR rates of only 59.3 metric tonnes/ha (O'Connor et al., 2002), and would constitute correspondingly less exposure. Treatments containing 10% WTR were used herein for experimental observation.

The bioavailability of Al in WTR varies, but is generally low and thought to be harmless (O'Connor et al., 2002). No previous research has been conducted to determine the potential toxicity of WTR directly consumed by grazing ruminants.

The purpose of this study was to determine if feeding growing lambs a bioavailable source of Al ($AlCl_3$) versus a less available source of Al from a WTR would affect growth, feed intake, plasma P levels, tissue concentrations, and apparent P absorption.

2. Materials and methods

2.1. Animals, diets, and management

Forty-two, wethers (30) and ewes (12), 5–8-month-old lambs (22 Suffolk and 20 Suffolk-crosses) were utilized in a 111-day experiment at the University of Florida Sheep Nutritional Unit located in Gainesville, Florida. The experiment was conducted from 6 June 2004 until 25 September 2004. The lambs weighed between 22 and 39 kg at day 0. Lambs were shorn on day 42 to combat heat stress and to promote optimum feed intake. Prior to the experiment, lambs were vaccinated with clostridium C&D given as an injection of 2-mL, 4 weeks apart (Pfizer Animal Health, Exton, PA) and were dewormed with two 1-mL doses of ivermectin 2 weeks apart (Ivomec; Merial Ltd., Iselin, NJ). To prevent coccidiosis an amprolium solution was given as an oral drench. Lambs received 1-mL daily in a 6-day sequence (Corid 9.6%; Merial, Duluth, GA). On day 21 the animals were dewormed orally with 5 cc of fenbendazole (Panacur; Pfizer Animal Health, Exton, PA) and again drenched with 1-mL of Corid from days 21 to 26 (Corid 9.6%).

The lambs were housed (seven/pen), in covered, earth-floored wooden pens (24 m^2), bedded with pine wood chips and provided *ad libitum* water and common salt. The University of Florida Institutional Animal Care and Use committee approved the experimental protocol (D231) used in this study.

A corn-based diet was formulated to meet NRC (1985) requirements for CP, TDN, vitamin, and minerals for lambs of this weight and age (Table 1). Prior to the experiment, during a 3-week adjustment period, lambs were fed the basal diet at 1200–1300 g/day per animal. During the experiment, the animals were fed once daily 1300–1600 g/day per lamb.

Lambs were stratified by sex and randomly assigned to six dietary treatments: (1) control (10% sand), (2) (9.7% sand and 0.3% $AlCl_3$), (3) (2.5% WTR and 7.5% sand), (4) (5% WTR and 5% sand), (5) (10% WTR and 0% sand), and (6) (10% WTR, 0% sand, plus double the quantities of the mineral–vitamin premix, and 1.29% dicalcium phosphate). The WTR used contained 7.8% total Al on a DM basis. Ten percent of each diet was either sand, WTR, $AlCl_3$ or a combination of the three. The diet concentrations of Al were 910, 2000, 2000, 4000, 8000, and 8000 ppm (DM basis), respectively, for the six diets.

On day 91 animals were placed into individual metabolic crates (1.4 m^2) to determine apparent digestibility of P. During a subsequent 21-day crate confinement, all animals were individually fed their respective experimental diets. Fresh feed was given *ad libitum* each morning. Orts were weighed back daily. Individual feed intake, average daily gain (ADG), and body weight (BW) differences from weeks 11 to 14 were evaluated.

2.2. Sample collection, preparation, and analyses

Blood samples (jugular venipuncture) and lamb weights were collected on day 0 and every 14 days thereafter. Blood was collected (10 mL) with a 20 gauge × 2.54 cm vacutainer needle (Vacutainer; Becton Dickinson, Franklin Lakes, NJ) into evacuated tubes containing sodium heparin. Immediately after collection, blood was centrifuged at 700 × *g* for 30 min, and plasma was collected and frozen at 0 °C. A 30 min thaw period was allowed so that plasma reached ambient temperature, the proteins were then separated using 10% trichloroacetic acid (Miles et al., 2001).

On day 91 wether lambs were fitted with cloth fecal collection devices for the study of apparent digestibility of P. Feces were collected daily for 14 days and composite samples were frozen at 0 °C. Each composite sample was sub-sampled and ground in a blender with stainless steel blades. Feces were then dried for 16 h at 105 °C to determine DM. Dried samples were ashed in a muffle furnace at 600 °C for 8 h, digested in HCl, filtered, and diluted for colorimetric P determination (Harris and Popat, 1954; MR7000 Microplate Reader, Dynatech Technologies Inc., Chantilly, VA).

On day 111, all animals were sacrificed at a USDA inspected facility. The following tissues were collected and analyzed for Al, Ca, Cu, Fe, Mg, Mn, P, and Zn contents: blood plasma, liver, heart, kidney, and brain, and Se was determined on the kidney. Samples were dried, weighed, ashed, and solubilized in HNO_3 acid (Miles et al., 2001). Bone was analyzed for P, Ca, and Mg. For all samples, P was analyzed using a colorimetric procedure

Table 1
Diet composition (as-fed) and analyses for average ($n = 18$) concentrations for macro- and micro-elements for treatments

Ingredient (%, as-fed)	Treatments[a]					
	1	2	3	4	5	6
Ground corn	41.1	41.1	41.1	41.1	41.1	39.9
Soybean hulls	12.5	12.5	12.5	12.5	12.5	12.5
Wet molasses, unfortified	10.0	10.0	10.0	10.0	10.0	10.0
Cottonseed hulls	8.0	8.0	8.0	8.0	8.0	8.0
Corn gluten meal, 60% CP	5.5	5.5	5.5	5.5	5.5	5.5
Alfalfa meal, 17% CP	5.0	5.0	5.0	5.0	5.0	5.0
Vegetable oil (soybean)	4.0	4.0	4.0	4.0	4.0	4.0
Sand[b]	10.0	9.3	7.5	5.0	–	–
Water treatment residual[c]	–	–	2.5	5.0	10.0	10.0
Aluminum chloride	–	0.7	–	–	–	–
Salt	1.0	1.0	1.0	1.0	1.	1.0
Urea	1.6	1.6	1.6	1.6	1.6	1.6
Ground limestone	0.7	0.7	0.7	0.7	0.7	0.7
Ammonium chloride	0.5	0.5	0.5	0.5	0.5	0.5
Flowers of sulfur	0.01	0.01	0.01	0.01	0.01	0.01
Mineral–vitamin premix[d]	0.01	0.01	0.01	0.01	0.01	0.02
Dicalcium phosphate	–	–	–	–	–	1.3
Analyses (ppm[e])						
Ca	7170	7120	7220	7440	7300	10,000
Mg	2780	2730	2700	2880	2870	3020
Na	4060	3240	3030	3000	3410	3110
K	4180	5210	3960	4560	4440	4380
P	2520	2490	2550	2480	2460	5020
Al	910	2320	2270	3970	7860	7790
Cu	31	33	33	32	34	42
Fe	66	65	67	66	66	70
Mn	11	13	13	13	14	19
Zn	74	70	71	70	67	79

[a] Dietary treatments were created by additions to a corn based diet as follows: (1) (control) 10% sand; (2) 9.3% sand + 0.7% $AlCl_3$; (3) 7.5% sand + 2.5% WTR; (4) 5% sand + 5%WTR; (5) 10% WTR; (6) 10% WTR + two times the added amount of mineral–vitamin premix + 1.29% dicalcium phosphate. Treatments 2 and 3 were formulated to contain 2000 ppm Al, treatment 4 was formulated to contain 4000 ppm Al, and treatments 5 and 6 were formulated to contain 8000 ppm Al.

[b] Sand contained 0.2% Fe, 0.01% Al, 0.09% Ca, 0.03% Mg, 0.1% P, 0.005% Mn, 0.004% Cu, and 0.001% Zn.

[c] Water treatment residuals contained 0.30% Fe, 7.8% Al, 0.11% Ca, 0.024% Mg, 0.3% P, 0.004% Mn, 0.73% S, 0.006% Cu, and 0.002% Zn.

[d] Mineral–vitamin premix contained 8.0% Mg (as oxide), 0.70% Fe (as sulfate), 2.40% S (as sulfate), 1.9% Cu (as sulfate), 6.0% Mn (as oxide), 0.47% I (as iodate), 0.075% Se (as sodium selenite), 4.5% Zn (as oxide and sulfate), 133,363.4 IU/kg Vitamin A supplement, 412,272.7 IU/kg Vitamin D_3 supplement, 259.1 IU/kg Vitamin E supplement, rice mill by-product, and stabilized fat as a vitamin carrier.

[e] Dry matter basis.

(Harris and Popat, 1954). Kidney Se was determined using a fluorometric procedure (Whetter and Ullrey, 1978). Calcium, Fe, Mg, Cu, Mn, and Zn in tissues and feed samples were analyzed by flame atomic absorption spectrophotometry (Perkin-Elmer Model 5000, Perkin-Elmer Corp., Norwalk, CT). Aluminum concentrations were analyzed in diets, heart, brain, liver, and kidney by atomic absorption spectrophotometry using nitrous oxide-acetylene flame (Varian SpectrAA 220 FS; Varian Inc., Walnut Creek, CA).

2.3. Statistical analysis

Soft tissue, fecal, and feed intake data were analyzed for treatment effects using PROC GLM in SAS (SAS for Windows v9; SAS Inst. Inc., Cary, NC) in a completely randomized design. PROC MIXED of SAS was used to analyze treatment effects on BW, ADG, and plasma P as repeated measures with a variance component covariance structure in respect today and subplot of animal nested within treatment. Significance was declared at $P < 0.05$ and tendencies were discussed when $P < 0.10$.

3. Results

Six animals died during the experiment. The cause of death was determined to be parasite infestation of the gastrointestinal tract, and was deemed unrelated to

Table 2
Effects of dietary Al concentration and source on body weight (BW) of feeder lambs[a]

Week	Treatment[b] (BW, kg)						S.E.
	1	2	3	4	5	6	
0	32.6	31.4	33.1	31.1	32.2	31.7	1.5
2	32.8 cd	31.6 c	34.6 cd	34.4 cd	37.5 d	33.6 cd	1.9
4	34.3 cd	31.6 c	37.7 de	35.8 cde	41.3 e	35.2 cd	2.3
6	38.4 d	32.3 c	40.7 d	39.3 d	41.2 d	34.7 cd	2.6
11	41.4 cd	36.8 c	46.7 d	45.1 d	48.1 d	42.9 cd	2.5
14	49.3 cd	45.9 c	52.8 d	50.3 d	53.3 d	49.7 cd	1.9

Means within rows lacking a common letter differ ($P < 0.05$).
[a] Data represent least-square means; $n = 7$ per treatment.
[b] Dietary treatments were created by additions to a corn based diet as follows: (1) (control) 10% sand; (2) 9.3% sand + 0.7% $AlCl_3$; (3) 7.5% sand + 2.5% WTR; (4) 5% sand + 5%WTR; (5) 10% WTR; (6) 10% WTR + two times the added amount of mineral–vitamin premix + 1.29% dicalcium phosphate. Treatments 2 and 3 were formulated to contain 2000 ppm Al, treatment 4 was formulated to contain 4000 ppm Al, and treatments 5 and 6 were formulated to contain 8000 ppm Al.

dietary treatment. Body weights increased for all treatments for weeks 0–14 (Table 2). Average daily gains and feed intakes (Table 3) also increased with time ($P < 0.05$). Throughout the experiment, lambs fed 2000 ppm Al via $AlCl_3$ consistently had lower BW than all other treatments. During week 6, lambs fed 2000 ppm Al via $AlCl_3$ had lower BW than control animals and lambs fed 2000 ppm Al, 4000 ppm Al or 8000 ppm Al from WTR ($P < 0.05$). Lambs receiving 2000 ppm, 4000 ppm and 8000 ppm Al via WTR were heavier than animals consuming 2000 ppm Al via $AlCl_3$ during week 11 ($P < 0.05$). Body weights during week 11 differed by 11.3 kg ($P < 0.05$) between those animals consuming 2000 ppm Al via $AlCl_3$ and those fed 8000 ppm Al via WTR; the difference between these two groups at week 14 was 7.4 kg ($P < 0.05$).

During week 2, ADG of lambs given 8000 ppm Al from WTR exceeded animals given 2000 ppm Al via $AlCl_3$ ($P < 0.05$). Lambs receiving 4000 ppm Al from WTR tended ($P = 0.11$) to gain more than lambs fed 2000 ppm Al via $AlCl_3$. During week 4, lambs receiving the control, 2000 ppm Al via WTR and 8000 ppm Al via WTR treatments gained more than lambs in the treatment given 2000 ppm Al via $AlCl_3$ ($P < 0.05$). During week 6, lambs consuming the control, and 4000 ppm Al from WTR diets gained more than lambs consuming 2000 ppm Al from $AlCl_3$ ($P < 0.05$). Additionally, during week 6, all treatments, except 2000 and 4000 ppm Al via WTR had gains much lower than the control ($P < 0.05$).

During week 11, animals began a 3-week individual feeding regime to determine feed intake. From weeks 11 to 14, lambs fed the control, 2000 ppm, and 4000 ppm Al via WTR ($P < 0.05$) consumed more than those fed 8000 ppm Al via WTR.

Plasma P during week 4 (Table 4) in animals receiving 2000 ppm Al via WTR were greater than all other treatments, except those receiving 8000 ppm Al via WTR plus double the minerals and vitamins ($P < 0.05$). The

Table 3
Effect of dietary Al concentration and source on feed intake of feeder lambs[a]

Week	Treatment[b] (intake, g $lamb^{-1}$ d^{-1})						S.E.
	1	2	3	4	5	6	
2	827	959	1170	1120	1100	1020	–
4	1410	876	1150	1150	1070	1120	–
6	954	1110	1150	1200	1210	1210	–
11	1610	1460	1790	1550	1910	1940	–
14	1940 c	1870 cd	1900 c	1940 c	1270 d	1570 cd	54.6

Lambs were individually fed for 3-week ending at week 14; means within rows lacking a common letter differ ($P < 0.05$).
[a] Data represent means of intake during weeks 0–11 and least-square means during week 14; $n = 7$ per treatment.
[b] Dietary treatments were created by additions to a corn based diet as follows: (1) (control) 10% sand; (2) 9.3% sand + 0.7% $AlCl_3$; (3) 7.5% sand + 2.5% WTR; (4) 5% sand + 5%WTR; (5) 10% WTR; (6) 10% WTR + two times the added amount of mineral–vitamin premix + 1.29% dicalcium phosphate. Treatments 2 and 3 were formulated to contain 2000 ppm Al, treatment 4 was formulated to contain 4000 ppm Al, and treatments 5 and 6 were formulated to contain 8000 ppm Al.

Table 4
Effect of dietary Al concentration and source on plasma P of feeder lambs[a]

Week	Treatment[b] (μg/mL)						S.E.
	1	2	3	4	5	6	
0	48.7	44.6	51.2	40.8	45.6	43.8	3.7
2	48.3	44.7	50.5	41.5	45.7	44.1	5.3
4	54.3 d	54.2 d	64.4 c	49.8 d	39.7 e	58.5 cd	4.6
6	39.2 c	25.2 d	27.9 d	28.5 d	26.2 d	27.0 d	2.5
8	33.8 c	19.6 d	19.9 d	26.3 cd	21.9 d	28.1 cd	2.3
11	36.2 cd	22.2 e	46.3 c	30.0 de	29.0 de	29.3 de	5.0
14	38.3 c	34.0 cd	34.9 cd	28.0 de	24.5 de	24.9 e	3.6

Means within rows lacking a common letter differ ($P < 0.05$).

[a] Data represent least-square means; $n = 7$ per treatment.

[b] Dietary treatments were created by additions to a corn based diet as follows: (1) (control) 10% sand; (2) 9.3% sand + 0.7% $AlCl_3$; (3) 7.5% sand + 2.5% WTR; (4) 5% sand + 5%WTR; (5) 10% WTR; (6) 10% WTR + two times the added amount of mineral–vitamin premix + 1.29% dicalcium phosphate. Treatments 2 and 3 were formulated to contain 2000 ppm Al, treatment 4 was formulated to contain 4000 ppm Al, and treatments 5 and 6 were formulated to contain 8000 ppm Al.

animals receiving 8000 ppm Al via WTR had the lowest plasma P of all groups of animals ($P < 0.05$). In weeks 6–11, the lambs receiving 2000 ppm Al via $AlCl_3$ had lower plasma P than controls ($P < 0.05$). During week 11, lambs from both the control and those receiving 2000 ppm Al via WTR had higher plasma P than animals receiving 2000 ppm Al via $AlCl_3$ ($P < 0.05$). Analyses of plasma P during week 14 showed that controls had higher P concentrations than lambs receiving 4000 ppm Al via WTR, 8000 ppm Al via WTR or 8000 ppm Al via WTR plus two times the amount of added mineral–vitamin premix, and 1.29% dicalcium phosphate ($P < 0.05$). Plasma evaluations of all other minerals showed no differences among treatments, which included the following (μg/mL): Ca 87–101, Mg 17–21, Cu 1.3–1.5, Fe 0.9–2.0, Mn 0.05–0.06, and Zn 0.3–1.6.

Tissue mineral concentrations (Table 5) among treatments were deemed not to be hazardous to animal health. With the exception of Cu, tissue mineral concentrations remained within normal ranges (Miles et al., 2001). Liver Cu concentrations were high for all treatments. The mineral–vitamin premix used inadvertently contained excess Cu in relation to sheep requirements. Levels of P showed no differences among treatments except that animals given 4000 ppm Al from WTR deposited more P in the kidney than those animals receiving 8000 ppm Al from WTR ($P < 0.05$). No differences ($P < 0.05$) were observed in soft tissue or bone Ca concentrations. Aluminum was deposited in smaller amounts in the brain in lambs fed 2000 ppm Al via WTR than all other treatments except the control ($P < 0.05$). Kidney Al deposits were greater in lambs receiving 2000 ppm Al via $AlCl_3$ than those receiving 8000 ppm Al via WTR ($P < 0.05$), and those receiving 8000 ppm Al via WTR plus two times the added amount of mineral–vitamin premix, and 1.29% dicalcium phosphate ($P < 0.05$). Concentrations of Mg showed no differences in soft tissue deposition. Differences in Fe deposition were observed in liver ($P < 0.05$), with lambs consuming the $AlCl_3$ treatment having lower Fe concentrations than those receiving the two treatments of 8000 ppm Al as WTR. Variations in heart and kidney Mn concentrations seemed unrelated to Al source or quantity.

Apparent P absorption ranged from −12.9 to 31.8% (Fig. 1). The control and all WTR treatment lambs had a greater apparent P absorption (10.9–31.89%) than the

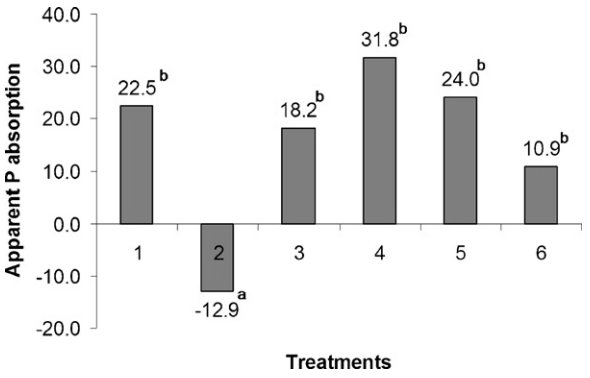

Fig. 1. Effect of dietary Al source on apparent P absorption. Dietary treatments were created by additions to a corn based diet as follows: (1) (control) 10% sand; (2) 9.3% sand + 0.7% $AlCl_3$; (3) 7.5% sand + 2.5% WTR; (4) 5% sand + 5%WTR; (5) 10% WTR; (6) 10% WTR + two times the added amount of mineral–vitamin premix + 1.29% dicalcium phosphate. Treatments 2 and 3 were formulated to contain 2000 ppm Al, treatment 4 was formulated to contain 4000 ppm Al, and treatments 5 and 6 were formulated to contain 8000 ppm Al. The SE for treatments is 8.23. [ab]Means lacking a common superscript differ ($P < 0.05$).

Table 5
Tissue mineral composition resulting from experimental diets[a]

	Treatment[b]						S.E.
	1	2	3	4	5	6	
Macro elements (%)							
Ca							
Heart	0.01	0.01	0.01	0.01	0.01	0.02	0.004
Kidney	0.06	0.04	0.08	0.08	0.06	0.05	0.02
Liver	0.05	0.04	0.04	0.05	0.04	0.05	0.01
Bone	39.9	39.4	38.1	39.5	37.0	37.7	18.3
Mg							
Heart	0.15	0.13	0.15	0.14	0.12	0.13	.019
Kidney	0.11	0.11	0.11	0.13	0.10	0.10	0.02
Liver	0.066	0.062	0.066	0.070	0.062	0.064	0.004
Bone	0.79 c	0.70 cd	0.79 c	0.79 c	0.73 cd	0.61 d	0.04
P							
Heart	1.16	1.03	1.16	1.16	1.09	1.01	0.14
Kidney	1.12 c	1.15 cd	1.21 cd	1.17 c	1.15 d	1.14 cd	0.087
Liver	1.07	1.17	1.07	1.09	1.05	1.01	0.18
Bone	14.2	14.4	14.6	15.4	14.1	15.1	0.63
Micro elements (mg/kg)							
Al							
Brain	43.1 cd	52.0 d	33.9 c	50.4 d	47.5 d	48.2 d	4.10
Heart	6.9 cd	5.1 def	6.1 cdef	7.4 c	7.0 cd	4.5 ef	0.79
Kidney	7.2 cd	9.4 c	7.1 cd	7.5 cd	5.4 d	5.4 d	1.03
Liver	15.4 c	22.3 cd	16.7 c	20.9 cd	25.3 d	18.5 cd	2.75
Cu							
Heart	8.7	12.7	9.8	14.4	10.3	7.4	2.07
Kidney	38.0	37.3	46.9	36.1	31.2	27.9	9.79
Liver	4090	4570	3080	3930	3270	3900	713
Fe							
Heart	152	143	154	146	162	134	10.9
Kidney	443	442	425	447	434	434	66.4
Liver	212 cd	141 d	208 cd	162 cd	262 c	226 c	27.8
Mn							
Heart	1.6 cd	1.4 d	1.80 c	1.31 d	1.57 cd	1.50 cd	0.13
Kidney	18.3 cd	23.2 cd	16.4 c	23.2 d	23.9 cd	18.4 cd	2.4
Liver	12.8	11.4	14.1	10.2	11.9	11.4	2.0
Se							
Kidney	1.1	1.2	1.3	1.1	1.1	1.2	0.07
Zn							
Heart	71.5	63.6	65.7	69.1	59.8	61.2	6.65
Kidney	83.9	110	120	110	85.1	95.2	15.0
Liver	48.5	48.4	44.8	43.5	36.8	46.3	6.91

Means within rows lacking a common letter differ ($P < 0.05$).

[a] Data represent least-square means; $n = 5, 5, 7, 7, 5$, and 6 for the control and treatments 1–5, respectively.

[b] Dietary treatments were created by additions to a corn based diet as follows: (1) (control) 10% sand; (2) 9.3% sand + 0.7% $AlCl_3$; (3) 7.5% sand + 2.5% WTR; (4) 5% sand + 5%WTR; (5) 10% WTR; (6) 10% WTR + two times the added amount of mineral–vitamin premix + 1.29% dicalcium phosphate. Treatments 2 and 3 were formulated to contain 2000 ppm Al, treatment 4 was formulated to contain 4000 ppm Al, and treatments 5 and 6 were formulated to contain 8000 ppm Al.

negative absorption (−12.9%) of lambs fed 2000 ppm Al via $AlCl_3$ ($P < 0.05$).

4. Discussion

Increases in BW, ADG and intakes were observed for all treatments and can be logically attributed to increased appetite which occurs in growing animals. The previous studies at the University of Florida conducted by Valdivia et al. (1978, 1982) observed an increase in feed intake from 1.03 to 1.20 kg/day, and an increase in BW gain as dietary P was increased from 0.15 to 0.29% in diets that contained 1200–2000 ppm Al as $AlCl_3$. Valdivia et al. (1978) and Rosa et al. (1982) concluded that the increase in P was able to overcome the clinical signs normally observed with Al toxicosis. Diets in the present study contained approximately 0.25% P as fed (Table 1), which exceeds the requirements (0.23% dietary P) of lambs of this age and breed (NRC, 1985; McDowell, 2003). Our study showed no major losses in weight or intakes regardless of treatment, which can be attributed to the proper amounts of dietary P (0.25%) supplied. This concurs with the work of Valdivia et al. (1978) and Rosa et al. (1982).

The control lambs, which received 910 ppm Al from sand, and lambs receiving treatments containing WTR had no declines in intake. This is attributed to the low bioavailability of Al in WTR and sand (O'Connor et al., 2002; Dayton et al., 2003). A low bioavailable Al source should not depress intake because the Al would not readily react with the P in the gastrointestinal tract.

Aluminum from $AlCl_3$ is an available source and has been shown to depress intakes in various species including: sheep (Valdivia et al., 1978; Rosa et al., 1982), broilers and chicks (Fethiere et al., 1990), humans (Chappard et al., 2003; Rengel, 2004) and rats (Gómez-Alonso et al., 1996). An Al toxicity results in a P deficiency (McDowell, 1997), which can lead to serious tissue damage, lower intakes and gains. Williams et al. (1990, 1991a,b, 1992) induced a P deficiency in heifers and observed an 11% decrease in feed intake. In the present study, there was a decrease in feed intake for the lambs that were fed 2000 ppm Al via $AlCl_3$. This is expected, as $AlCl_3$ is considered to be a bioavailable source of Al (Valdivia et al., 1978; Rosa et al., 1982), and thus may induce a P deficiency and depress feed intake.

Ingestion of Al as $AlCl_3$ by ruminants decreases bone density, plasma P levels, feed intakes and gains (Rosa et al., 1982; Valdivia et al., 1982; Ammerman et al., 1984). Animals receiving the $AlCl_3$ diet repeatedly had lower BW and feed intakes than animals fed other sources of Al. Lower intakes and gains can be attributed to greater Al availability; similar observations occurred when 0.75% aluminosilcate was fed to laying hens and feed intake was significantly depressed (Fethiere et al., 1990).

One of the objectives of the present study was to compare the availability of Al in WTR to Al in $AlCl_3$ and a control when fed to ruminants. During week 11, body weights ranged from 36.8 kg for lambs fed 2000 ppm Al via $AlCl_3$ diet to 48.1 kg for lambs fed 8000 ppm Al via WTR. Thus, lambs receiving 8000 ppm Al from WTR, on average, had BW that were 11.2 kg heavier than those fed 2000 ppm Al from $AlCl_3$ despite the four fold difference in total Al administered. The group fed 8000 ppm Al from WTR had the highest amount of Al and the largest percentage of WTR (10% of the diet as fed). Differences observed in BW, between lambs fed 8000 ppm Al via WTR and 2000 ppm Al via $AlCl_3$ validates previous studies which showed Al in Al-WTR to be high in a non-available source of Al (O'Connor et al., 2002; Novak and Watts, 2004) and that $AlCl_3$ is available for uptake in the small intestine (Valdivia et al., 1978; Rosa et al., 1982). It is thought that grazing ruminants can consume up to 10–15% of their total DM intake as soil (Healy, 1967, 1968). It has also been shown that soil Al is often consumed by grazing ruminants in amounts as high as 10% of the soil consumed. Aluminum ingested from soil sources has not been shown to reduce performance. Ammerman et al. (1984) fed sheep varying soils types, from Latin America, containing as much as 16,600 ppm Al. They concluded that the soil Al sources had no significant effect on BW, gains, and intakes of the sheep which consumed them. The soils contained various levels of Al or Fe oxides, which are similar to the chemical form of Al in Al-WTR. The additions of high Fe and Al soils had no harmful effects on P utilization, feed intake, or gains.

Differences, in general, between treatments were limited throughout the trial. Lambs receiving diets containing Al via WTR at varying levels showed no differences in BW from the control ($P < 0.05$). Additions of WTR in amounts as high as 10% of the diet, and representing 8000 ppm Al in the diet, do not negatively impact growing lambs in relation to BW, ADG, and feed intakes when dietary P is at least 0.25%. Thus, under natural grazing conditions [where 10% of the DM intake is of soil (Field and Purves, 1964; Healy, 1967, 1968)], even high rates of surface applied WTR are not expected to harm animal performance.

During week 14, the ADG of treatments plateaued, consistent with a natural sigmoidal growth curve. Prior to week 14, animals were gaining at rates between 463 and 593 g/day. The rate declined during week 14 to only

207–244 g/day, but the decline is not attributed to dietary treatments. Animals appeared healthy with notable accumulations of body fat. Lambs in both the control and $AlCl_3$ treatment continued to gain larger amounts of weight during week 14, because they had not reached a maintenance weight. Lambs fed 2000 ppm Al via $AlCl_3$ had lowered growth, intake and BW throughout the trial and did not reach a growth plateau by week 14. The control animals during week 6 experienced an illness which was attributed to parasite infestations which suppressed ADG means thereafter. In previous studies, similar declines in ADG were observed with $AlCl_3$ additions, and animal growth peaked at later dates than those not receiving an Al source (Valdivia et al., 1978; Rosa et al., 1982; Fethiere et al., 1990).

Feed intakes, regardless of treatment, increased with time. Constituents added to the basal diets did not cause any animal to become anorexic, a common clinical sign of Al toxicity, or P deficiency (Williams et al., 1992; McDowell, 2003). Differences in intakes were evaluated individually in a 3-week period between weeks 11 and 14. Prior to this date, lambs had been group fed. Individual intake data were similar to those reported by Rosa et al. (1982), and Valdivia et al. (1978). Lambs fed diets containing 2000 ppm Al from $AlCl_3$ consumed less than the control ($P > 0.05$), which can again be attributed to the high bioavailability of $AlCl_3$. Intakes were the lowest for animals consuming 8000 ppm Al from WTR. During week 14, these animals had the highest BW, but a decline in ADG from week 11 (480 g) to week 14 (207.0 g), which was the lowest gain for that period. Intakes for lambs receiving 8000 ppm Al from WTR were lower than the control, 2000 and 4000 ppm Al from WTR ($P < 0.05$), but higher than lambs receiving 2000 ppm from $AlCl_3$ or 8000 ppm Al from WTR with additional minerals and vitamins ($P > 0.05$). Prior to week 14, lambs fed 8000 ppm Al from WTR showed adequate performance in relation to gains, intake and BW. Therefore, the cause of these declines seen in lambs receiving 8000 ppm Al via WTR are unknown and could be related to normal growing patterns, an unknown parasite infestation, Cu toxicities, Al toxicities, or other various environmental interactions.

During week 4, lambs receiving 2000 Al from WTR had the highest concentration of plasma P and differed from the control, those receiving 2000 ppm Al from $AlCl_3$, 8000 ppm Al from WTR. ($P < 0.05$). Huff et al. (1996) administered 3.7% aluminum sulfide to broiler chicks and observed declines in serum P after a 3-week period. Plasma P levels declined in the lambs from 54.2 to 19.6 μg/mL between weeks 4 and 8. Additionally, all treatments showed declines in plasma P during this period, but the $AlCl_3$ treatment declines were most often the greatest. During weeks 11 and 14, plasma P concentrations began to increase in all treatments. One could conclude that plasma P concentrations declined to levels which demanded the use of body stores of P (Williams et al., 1990; McDowell, 2003). Bone mineral content was evaluated in the long bones, with no differences among treatments and no evidence of a mineral depression; yet research has shown that the ribs and the vertebrae are first to become depleted in mineral concentrations (Williams et al., 1990, 1991a; McDowell, 2003). Therefore the possibility exists that increases in plasma P levels during weeks 11–14 occurred from bone mineral resorption. This is reasonable, but unlikely, because within a long time frame of 8 weeks (between weeks 6 and 14) bone loss most likely would have been observed in the long bone of the leg which was analyzed. Previous experimental data have not demonstrated similar increases in plasma P after a decline. Therefore, observations are speculative at this time and further research is needed to validate this theory.

Tissue mineral concentrations analyzed for this study were in the normal ranges for lambs of this breed and age (Miles et al., 2001; McDowell, 2003). Previous research found differences in kidney, bone, liver and spleen concentrations of Al, Fe, P Mg and Zn (Rosa et al., 1982) and Ca (Rosa et al., 1982; Zafar et al., 2004) when various amounts of Al were fed. In the present study, Al concentrations differed in brain, heart, liver, and kidney, Mg in bone, and Fe in the liver. Absorption of Al in monogastrics is approximately 0.1% (Rengel, 2004) and is thought to be even lower in ruminants (Valdivia, 1977; Valdivia et al., 1978). Aluminum accumulation occurs most readily in the brain. The exact mechanism is unknown but Al can cross the blood–brain barrier (Rengel, 2004). In the kidney, the highest concentrations of Al were detected when lambs were fed 2000 ppm Al from $AlCl_3$, and differed from both treatments receiving 8000 ppm Al from WTR and from the control and 2000 ppm Al via WTR ($P < 0.05$). Rosa et al. (1982) observed increases in Al tissue concentration as Al consumption increased, which was not consistently observed in our study. Additionally, soft tissues, except brain matter, that have been evaluated in past studies have not been shown to accumulate large amounts of Al during short time periods (Rengel, 2004), and may not prove to be useful for determination of differences of any Al sources and levels.

Apparent P absorption from a 14-day fecal collection showed differences among all five treatments versus the treatment containing 2000 Al via $AlCl_3$. Studies by Valdivia et al. (1982) observed a marked decrease in P

absorption and net P retention in lambs fed 2000 ppm Al as $AlCl_3$. Negative apparent P absorptions were observed in all groups except those given high P with low Al. When 0.29% P was fed with no dietary Al, the mean apparent absorption was unaffected. In our study, the control had an apparent absorption of 22.5%, and the mean for all the WTR groups was 21.2%. This suggests that Al in WTR did not negatively impact or reduce dietary P absorption. Valdivia et al. (1982) found a negative apparent P absorption (−10.7%) when 0.29% dietary P and 2000 ppm Al as $AlCl_3$ were fed to sheep. Additionally, Martin et al. (1969) conducted P retention studies using dietary applications of a hydrated Al source and discovered that P decreased linearly as Al fed increased. Similar results were observed in our study when 2000 ppm Al was added via $AlCl_3$ to the basal diet containing 0.25% P. The apparent P absorption averaged −12.9% at week 14 and suggested a negative impact on dietary P utilization with added Al as $AlCl_3$.

5. Conclusion

Dietary administration of $AlCl_3$ has negative impacts on average daily gain, body weight, feed intake, apparent absorption of P, and plasma phosphorus concentrations. Lambs fed aluminum-water treatment residuals had apparent P absorption percentages that were similar to the control and were higher than the $AlCl_3$ treatment. Water treatment residuals are not harmful when consumed in amounts up to 8000 ppm aluminum when P is supplied in amounts of 0.25%, and do not negatively affect gain, feed intake, body weight, or P availability. Additionally, the consumption of water treatment residuals in amounts as high as 10% by grazing livestock would require massive amounts of water treatment residuals (∼225 metric tonnes/ha) as a top dressing (∼2.54 cm thickness). Most situations would require 56 metric tonnes/ha. Therefore, water treatment residual applied to pastures to control environmental P issues is safe at normal, and even extreme rates to grazing small ruminants.

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