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# Differential effects of sodium and magnesium sulfate on water consumption by beef cattle<sup>1,2</sup>

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**ABSTRACT:** The existing guidelines for maximum sulfate (SO<sub>4</sub>) in cattle drinking water are based on Na<sub>2</sub>SO<sub>4</sub>, although many water sources contain greater concentrations of MgSO<sub>4</sub>. Two experiments compared the effect of different SO<sub>4</sub> salts on water consumption and fecal DM of cattle. In Exp. 1, 8 yearling heifers (initial BW = 345 ± 8 kg; mean ± SD) were watered twice daily with tapwater or water containing Na<sub>2</sub>SO<sub>4</sub> or MgSO<sub>4</sub> at target levels of 1,500, 3,000, or 4,500 mg of SO<sub>4</sub>/L for 2-d treatment periods separated by 2 d of access to tapwater. In Exp. 2, 16 yearling cattle (initial BW = 421 ± 24 kg) were watered twice daily with tapwater (16 mg of SO<sub>4</sub>/L) or water containing Na<sub>2</sub>SO<sub>4</sub> at target levels of 2,000 mg of SO<sub>4</sub>/L (low Na<sub>2</sub>SO<sub>4</sub>), MgSO<sub>4</sub> at 2,000 mg of SO<sub>4</sub>/L (low MgSO<sub>4</sub>), or MgSO<sub>4</sub> at 4,000 mg of SO<sub>4</sub>/L (high MgSO<sub>4</sub>) in 21-d treatment periods separated by 7-d periods on tapwater. The first 10 d of each period were allowed for adjustment to the treat-

ment, and the final 11 d was considered the treatment period for analysis purposes. Treatments were applied in an incomplete Latin square, where each animal was exposed to 3 of the 4 treatments. In Exp. 1, the average daily water consumption decreased linearly as the SO<sub>4</sub> concentration increased for MgSO<sub>4</sub> ( $P = 0.0001$ ) but not for Na<sub>2</sub>SO<sub>4</sub> ( $P = 0.39$ ). In Exp. 2, the average daily water consumption was less for cattle on the high-MgSO<sub>4</sub> treatment than for cattle on the low-MgSO<sub>4</sub> treatment ( $P = 0.0001$ ), and cattle on the low-MgSO<sub>4</sub> treatment tended ( $P = 0.09$ ) to drink less than those on the tapwater treatment. Fecal DM was greater for cattle on the high-MgSO<sub>4</sub> treatment than for those on the low-MgSO<sub>4</sub> treatment ( $P < 0.01$ ). These findings indicate that cattle reduce their consumption of water containing high ( $\geq 4,000$  mg of SO<sub>4</sub>/L) concentrations of MgSO<sub>4</sub>, even after a given time to adjust to the treatment; such reductions may be accompanied by an increase in fecal DM.

**Key words:** beef cattle, drinking behavior, sulfate, water intake, water quality

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## INTRODUCTION

Cattle grazing on rangeland often drink water that is contaminated with sulfate (SO<sub>4</sub>) salts. Water consumption by cattle begins to decrease at SO<sub>4</sub> levels of

2,500 to 3,000 mg/L (Weeth and Hunter, 1971; Harper et al., 1997) and declines further at greater concentrations (Embry et al., 1959). Over periods of >7 d, high-SO<sub>4</sub> water has also resulted in reduced feed consumption, lowered BW gains (Embry et al., 1959; Weeth and Hunter, 1971), scours (Embry et al., 1959), diuresis (Weeth and Hunter, 1971), and suboptimal production (Loneragan et al., 2001). High levels of dietary S, which can result from water containing SO<sub>4</sub>, have been implicated in reducing net energy values (Zinn et al., 1997), interference with mineral status (Smart et al., 1986; Ivancic and Weiss, 2001), and development of polioencephalomalacia (Olkowski, 1997).

Guidelines for maximum acceptable limits of SO<sub>4</sub> in cattle drinking water (CCREM, 1987) are based exclusively on work undertaken with Na<sub>2</sub>SO<sub>4</sub>. However, many water sources contain high levels of Mg as well as Na, and in these cases, response to the water may be influenced by the cation as well as by SO<sub>4</sub>. Ruminants have a recognized appetite for Na (Denton, 1982) and readily consume dissolved Na salts while avoiding

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comparable concentrations of Mg salts (Fraser and Reardon, 1980). Sodium is closely linked to thirst mechanisms, but there is no evidence that Mg plays a role in eliciting or satisfying thirst (Fitzsimons, 1979). Hence, there are good reasons to expect that cattle will respond differently to Mg than to Na and that water quality guidelines should distinguish between these cations. The objectives of this work were 1) to determine, using a "taste test" protocol, whether  $\text{Na}_2\text{SO}_4$  and  $\text{MgSO}_4$  differentially affect water consumption by cattle and 2) to examine whether any such differences, plus differences in fecal DM, would be maintained over a period long enough to incorporate adjustment to treatment.

## MATERIALS AND METHODS

Two experiments took place at Agriculture and Agri-Food Canada's Range Research Unit (Kamloops, British Columbia). Average maximum, minimum, and mean daily temperatures during Exp. 1 (August 2 to 29, 2001) were 28.3, 13.5, and 20.5°C, and average maximum and minimum relative humidity were 72 and 31%, respectively. There was 0.6 mm of precipitation during the experimental period, falling as 0.4 and 0.2 mm on 2 separate days. For Exp. 2 (June 13 to August 28, 2002), comparable temperatures were 28.7, 13.5, and 20.9°C, and average maximum and minimum relative humidities were 72.8 and 26.8%, respectively. During this experiment, 36.6 mm of precipitation occurred, nearly one-half (17.6 mm) of which fell in July. All experiments and animal use were approved by an institutional animal care committee according to the Canadian Council on Animal Care guidelines (CCAC, 1993).

### Exp. 1

This experiment was carried out as a "taste test" to determine whether yearling beef cattle responded differentially, under short periods of exposure, to 2 common  $\text{SO}_4$  salt compounds,  $\text{Na}_2\text{SO}_4$  and  $\text{MgSO}_4$ , at equal concentrations of  $\text{SO}_4$  up to 4,500 mg/L.

### Animals and Management

Eight barren yearling Angus heifers (initial BW =  $345 \pm 8$  kg; mean  $\pm$  SD) were studied. All heifers had been raised in the same environment with no known previous access to water contaminated with  $\text{SO}_4$  compounds. Heifers were housed in 2 groups of 4 in dirt floor pens that were 15 m wide  $\times$  13 m deep with concrete flooring in front of the 10-m feedbunk. Each pen had a covered shelter sufficiently large for all heifers to use at the same time.

Animals were fed orchardgrass hay (*Dactylis glomerata*; mean = 12.6% CP; DM basis) ad libitum, refreshed twice daily at 0700 to 0800 and 1400 to 1500. The hay contained Na, 0.03%; Mg, 0.20%; and S, 0.24% (DM basis). All heifers could eat from the feedbunk at the same time. Animals also had ad libitum access to

**Table 1.** Intended vs. actual  $\text{SO}_4$  concentrations for Exp. 1<sup>1</sup>

Cation	Intended	Actual	Na	Mg
	$\text{SO}_4$	$\text{SO}_4$		
	(mg/L)			
None (tapwater)	0	1.0	2.2	2.7
Na	1,500	1,558	704	2.2
	3,000	3,194	1,540	2.7
	4,500	4,804	2,340	2.7
Mg	1,500	1,609	2.7	418
	3,000	3,305	3.5	748
	4,500	4,662	5.2	1,152

<sup>1</sup>Values are treatment means based on samples taken at each drinking opportunity from each water container and pooled for each 2-d treatment period.

a Co-iodized stock salt block (NaCl, 99.5%; I, 200 mg/kg; Co, 100 mg/kg; The Canadian Salt Company Limited, Pointe Claire, QC, Canada) and to a mineral mix (Mg, 2%; Na, 10%; Ca, 12%; P, 12%; Zn, 5,000 mg/kg; Cu, 3,000 mg/kg; Co, 30 mg/kg; I, 160 mg/kg; vitamin A, 650,000 IU/kg; vitamin D<sub>3</sub>, 65,000 IU/kg; vitamin E, 650 IU/kg; Trail Blazer 1:1 Range Mineral; New-Life Feeds, Lethbridge, AB, Canada).

Water was provided twice daily, at 1030 to 1200 and 1530 to 1815, in 80-L polyethylene containers placed in the feedbunk. During these times, heifers were locked in the back of the pen and then released one at a time to drink from a single container. Containers were emptied every other day, scrubbed, and refilled. At the start of each treatment period (i.e., every fourth day), concentrated primary solutions were prepared gravimetrically with tapwater and ACS grade ( $\geq 99.0\%$  purity) anhydrous  $\text{Na}_2\text{SO}_4$  or  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (Anachemia Canada Inc., Lachine, QC, Canada). Treatment solutions were created daily by diluting the primary solutions to the intended  $\text{SO}_4$  concentration. Solutions were stirred before each drinking opportunity to prevent settling. The Na, Mg, and  $\text{SO}_4$  concentrations in the tapwater used to make up treatment solutions were 2.2, 2.7, and 1.0 mg/L, respectively (Table 1).

### Experimental Design and Data Collection

An experiment was conducted to determine the effects of offering  $\text{SO}_4$  concentrations of 1,500, 3,000, or 4,500 mg/L as either  $\text{Na}_2\text{SO}_4$  or  $\text{MgSO}_4$  in a Latin square design with a  $2 \times 3$  factorial arrangement of treatments. A reference treatment of tapwater (1 mg of  $\text{SO}_4$ /L) was employed. Eight heifers were tested; the first 7 heifers were randomly assigned to treatment without replacement, and the last one was provided a replicate sample for a randomly selected starting treatment. Animals remained on a treatment for 2 d (a total of 4 drinking opportunities). Each treatment was followed by 2 d on tapwater to minimize any residual effects between treatments and to ensure that the heifers remained well hydrated. Water consumption at each drinking opportunity was measured to the nearest 1 L.

Water evaporation from containers was negligible, and all treatments had similar exposure to sun and shade.

Hay samples were taken at each feeding (twice daily) and pooled in 4-d periods. The pooled samples were then analyzed for CP by micro-Kjeldahl (Nelson and Sommers, 1973), for Mg and Na content by flame atomic absorption spectrophotometry (Ivan et al., 1983), and for S in nitric-perchloric acid digests by inductively coupled plasma atomic emission spectrometry (McBride and Spiers, 2001). Water samples (50 mL) were taken at each drinking opportunity from each water container and were pooled for each 2-d treatment period across all 8 heifers, yielding one sample per treatment. The water samples were analyzed for  $\text{SO}_4$  by a turbidimetric method (AOAC, 1990) and for Na and Mg content by flame atomic absorption spectrophotometry (Ivan et al., 1983).

### Data Analysis

Water consumption per day was determined by taking mean daily values over the 2-d treatment period, thus yielding a single value per animal on each treatment. Data were analyzed using Proc Mixed of SAS (SAS Inst., Inc., Cary, NC) according to the model:

$$Y_{ijkl} = \mu + S_i + D_j + S_i \times D_j + P_k + H_l + \varepsilon_{ijkl},$$

where  $Y_{ijkl}$  is the individual observation,  $\mu$  is the overall mean,  $S_i$  is the effect of salt ( $i = \text{Mg}$  or  $\text{Na}$ ),  $D_j$  is the effect of dose ( $j = 1,500, 3,000, \text{ and } 4,500$ ),  $S_i \times D_j$  is the effect of the salt  $\times$  dose interaction,  $P_k$  is the effect of period ( $k = 1$  to  $6$ ; treated as a random effect),  $H_l$  is the effect of heifer ( $l = 1$  to  $8$ ; treated as a random effect), and  $\varepsilon_{ijkl}$  is the residual error term. The procedure included contrast statements, protected with a significant  $F$ -test for treatment, to test for linear and quadratic effects of dose for each salt.

### Exp. 2

Substantial declines in water consumption over the 2-d treatment periods of Exp. 1, where treatments were applied in a "taste test" manner, suggested that, at least in the short term, cattle responded adversely to water containing  $\text{MgSO}_4$ . The longer treatment periods of this experiment tested whether initial responses to water containing  $\text{MgSO}_4$  were maintained once cattle were given time to adjust to treatment; emphasis was placed on exploring the relationship among high levels (4,000 mg of  $\text{SO}_4/\text{L}$ ) of  $\text{MgSO}_4$ , water consumption, and fecal DM.

### Animals and Management

Sixteen yearling Hereford and Hereford  $\times$  Angus steers and bred heifers (initial BW =  $421 \pm 24$  kg) were used, including 8 animals of each sex. All cattle had been raised as part of the same breeding herd and had

spent the previous summer with their dams on rangeland where some natural water sources contain high levels of  $\text{SO}_4$ . All animals had previous exposure to water containing  $\text{SO}_4$  at concentrations ranging from 0 to approximately 5,000 mg/L as either  $\text{Na}_2\text{SO}_4$  or  $\text{MgSO}_4$ .

Animals were housed in 2 groups, split according to sex, in the same pens described in Exp. 1. Cattle were fed as described in Exp. 1, except that the orchardgrass hay contained a mean of 9.7% CP, 0.03% Na, 0.14% Mg, and 0.20% S on a DM basis.

Each pen was equipped with Calan headgates (American Calan Inc., Northwood, NH), and each animal was fitted with a neck collar carrying a transponder that corresponded to one specific headgate within the pen. Containers had marks on their sides denoting 2-L increments of volume. Access to water was limited to 2 drinking opportunities daily at 1000 to 1130 and 1630 to 1730. The length of access during each drinking opportunity was not predetermined; instead, a drinking opportunity was considered to have ended when all cattle had stopped drinking and left the area of the headgates and water containers. Once this happened, headgates were locked and covers were put on the containers to prevent further access to water until the next scheduled drinking opportunity. After each drinking opportunity, water consumption was noted to the nearest 1 L, and containers were refilled to the 30-L mark with the appropriate water treatment. Containers were emptied, scrubbed, and refilled every second day. Treatment solutions were prepared according to the method described in Exp. 1, but with fresh primary solutions made up every second day.

### Experimental Design and Data Collection

Two animals of each sex were randomly allocated to each of the 4 treatments: tapwater,  $\text{Na}_2\text{SO}_4$  at 2,000 mg of  $\text{SO}_4/\text{L}$  (low  $\text{Na}_2\text{SO}_4$ ),  $\text{MgSO}_4$  at 2,000 mg of  $\text{SO}_4/\text{L}$  (low  $\text{MgSO}_4$ ), or  $\text{MgSO}_4$  at 4,000 mg of  $\text{SO}_4/\text{L}$  (high  $\text{MgSO}_4$ ). Cattle were adapted to treatments for 10 d followed by 11 d of data collection and were provided tapwater for 7 d in between periods to minimize residual effects. This cycle was repeated for a total of 3 times, so that each animal was exposed to 3 of the 4 potential treatments in an incomplete Latin square design.

Fecal samples were taken by rectal grab sampling on d 11 and 21 of each treatment period at approximately the same time in the morning, before the first drinking opportunity of the day. Large samples (250 to 500 g) were mixed thoroughly, and a representative subsample of approximately 60 g spread in a thin layer was dried at  $60^\circ\text{C}$  for 48 h.

Hay samples were taken daily, pooled by 21-d treatment period, and then analyzed as in Exp. 1. Water samples (10 mL) were taken the morning of every second day after containers had been refilled and were pooled according to treatment within animal. Samples

were analyzed according to the methods outlined for Exp. 1.

Cattle were monitored daily for changes in their health status through visual observation for signs of excessive weight loss and symptoms of polioencephalomalacia such as "star-gazing," head pressing, and loss of coordination (Hamlen et al., 1993; Niles et al., 2000). A review of the literature suggested that cattle similar to those used in this trial can fully recover from 4 d of water deprivation (Weeth et al., 1967). Therefore, to maintain animal health, daily water consumption was closely monitored, and on the one occasion when an animal failed to consume the offered water for 3 d (6 drinking opportunities), it was offered tapwater and discontinued on that treatment.

**Data Analysis.** Data were pooled for the last 11 d of each treatment period to give a single mean daily water consumption value for each animal on each treatment. A mean fecal DM value per animal on each treatment was generated similarly, by pooling data from d 11 and 21 (start and end of treatment period, respectively). Data were analyzed as an incomplete Latin square design using the Proc Mixed procedure of SAS (SAS Inst., Inc.) according to the model:

$$Y_{ijk} = \mu + T_i + P_j + A_k + \varepsilon_{ijk},$$

where  $Y_{ijk}$  is the individual observation,  $\mu$  is the overall mean,  $T_i$  is the effect of treatment ( $i = 1, 2, 3,$  and  $4$ ),  $P_j$  is the effect of period ( $j = 1, 2,$  and  $3$ ; treated as a random effect),  $A_k$  is the effect of animal ( $k = 1$  to  $12$ ; treated as a random effect), and  $\varepsilon_{ijk}$  is the residual error term.

Because of the incomplete design, each animal was exposed to 3 of the 4 treatments, yielding 12 animals per treatment and 8 animals for each pair-wise comparison of treatments. To reduce the likelihood of spurious significant differences owing to a large number of comparisons, only 3 specific treatment comparisons were tested: 1) tapwater vs. low  $MgSO_4$ , 2) low  $MgSO_4$  vs. high  $MgSO_4$ , and 3) low  $Na_2SO_4$  vs. low  $MgSO_4$ . The first 2 comparisons tested whether  $MgSO_4$  affects water consumption and fecal DM of cattle after time is allowed for adjustment to treatment. The low- $Na_2SO_4$  treatment was included as a reference point because  $Na_2SO_4$  is the source of  $SO_4$  in the majority of previous published work in this area; the final comparison tested the null hypothesis that  $MgSO_4$  and  $Na_2SO_4$  have similar effects on water consumption and fecal DM at approximately 2,000 mg of  $SO_4/L$ .

## RESULTS

### Exp. 1

Actual  $SO_4$  concentrations of the test solutions were within 10% of the intended values (Table 1). Cattle did not respond ( $P = 0.39$ ) to increasing  $Na_2SO_4$  concentra-

**Table 2.** Effect of  $Na_2SO_4$  and  $MgSO_4$  on water consumption (L/d) for the 6 treatments in Exp. 1<sup>1</sup>

Source	$SO_4$			SE <sup>2</sup>	P-value <sup>3</sup>
	1,500 mg/L	3,000 mg/L	4,500 mg/L		
$Na_2SO_4$ , L/d	37.4	34.5	30.3	4.1	0.39
$MgSO_4$ , L/d	39.8	28.2	12.6	4.1	<0.001

<sup>1</sup>Eight heifers were used in a Latin square experiment. Salt treatments were mixed in the drinking water, and the heifers were allowed individual access twice daily. Water consumption periods lasted for 2 d (4 drinking opportunities) followed by 2 d of tap water between periods.

<sup>2</sup>Pooled SE.

<sup>3</sup>P-value for linear contrasts.

tions by changing their water consumption (Table 2). However, a negative linear response was apparent ( $P = 0.0001$ ) as the concentration of  $MgSO_4$  increased. A wide range was observed in the response of cattle to water containing both  $SO_4$  salts; several heifers drastically reduced their water consumption at high  $SO_4$  concentrations, but others responded with only modest decreases in consumption. For example, when given water at 4,500 mg of  $SO_4/L$  as  $MgSO_4$ , average daily water consumption ranged between 3.5 and 31.8 L/d (CV = 79.6%). When given water at 4,500 mg of  $SO_4/L$  as  $Na_2SO_4$ , cattle consumed between 5.0 and 52.3 L/d (CV = 58.2%).

### Exp. 2

Actual  $SO_4$  concentrations in the test solutions were 16, 1,958, 2,012, and 4,060 mg/L for the tapwater, low- $Na_2SO_4$ , low- $MgSO_4$ , and high- $MgSO_4$  treatments, respectively. The 3 planned pair-wise comparisons showed that average daily consumption of low- $Na_2SO_4$  and low- $MgSO_4$  water was not different ( $P = 0.61$ ); however, consumption of low- $MgSO_4$  water tended ( $P = 0.092$ ; Table 3) to be lower than that of tapwater. Animals consumed only 75% as much water when provided high- vs. low- $MgSO_4$  water ( $P < 0.001$ ).

Fecal DM content was greater ( $P = 0.0001$ ) for cattle consuming high- $MgSO_4$  water (16.4%) than for cattle consuming low- $MgSO_4$  water (12.8%); this difference was not apparent between any of the other treatments (Table 3). No instances of compromised animal health were recorded during this study. However, one animal was removed from the high- $MgSO_4$  treatment on d 10, after 6 consecutive drinking opportunities where consumption was <3 L per drink. Upon receiving tapwater, this animal's average daily consumption rose to 42 L/d.

## DISCUSSION

The decline in water consumption with rising  $SO_4$  levels observed in both Exp. 1 and 2 is consistent with existing literature (Harper et al., 1997; Lonergan et al., 2001). Similarly, the 44 to 57% decline in water

**Table 3.** Effect of Na<sub>2</sub>SO<sub>4</sub> and MgSO<sub>4</sub> on water consumption and fecal DM values in Exp. 2<sup>1</sup>

Treatment	SO <sub>4</sub>	Avg. water consumption	Fecal DM
	(mg/L)	(L/d)	(%)
Tapwater	16	42.7	13.0
Low Na <sub>2</sub> SO <sub>4</sub>	1,958	38.9	14.4
Low MgSO <sub>4</sub>	2,012	39.7	12.8
High MgSO <sub>4</sub>	4,060	29.7	16.4
Pooled SE		1.5	0.7
Preplanned comparisons		P-value	
Tapwater vs. low MgSO <sub>4</sub>		0.092	0.792
Low MgSO <sub>4</sub> vs. high MgSO <sub>4</sub>		<0.001	0.001
Low MgSO <sub>4</sub> vs. low Na <sub>2</sub> SO <sub>4</sub>		0.614	0.106

<sup>1</sup>Eight steers and 8 bred heifers were used in a replicated Latin square in which 2 steers and 2 heifers received each water treatment for 21 d (10 d of adaptation and 11 d of sample collection) with 7 d on tapwater between each period. This cycle was repeated 3 times, and each animal was exposed to 3 of the 4 treatments. Therefore, values are based on 12 animals per treatment, and preplanned comparisons were tested using 8 animals per pair. Daily water consumption estimates and fecal values were averaged over the 11-d collection period, resulting in one value per animal for each period.

consumption at high SO<sub>4</sub> levels ( $\geq 4,000$  mg/L) is similar to the reduction in water consumption noted by Weeth and Hunter (1971) at 3,493 mg of SO<sub>4</sub>/L (35%) and Harper et al. (1997) at 4,000 mg of SO<sub>4</sub>/L (40%).

Although cattle clearly find SO<sub>4</sub> aversive at high levels, the differential response to the associated cation (Na vs. Mg) appears not to have been reported previously. These experiments demonstrate that MgSO<sub>4</sub> and NaSO<sub>4</sub> have different effects on the water consumption of cattle as shown by the presence of a dose response to increasing concentrations of MgSO<sub>4</sub> and the lack of a similar dose response to increasing concentrations of Na<sub>2</sub>SO<sub>4</sub> in Exp. 1.

Differences in acceptability between Na<sub>2</sub>SO<sub>4</sub> and MgSO<sub>4</sub> are not surprising given the distinct functions of these ions in the body. Specifically, Na is the principal extracellular cation (Fitzsimons, 1979), plays an important role in homeostasis, and is involved in active transport through the Na<sup>+</sup>/K<sup>+</sup> pump, whereas Mg plays a critical role in the derivation of energy from ATP (Frandsen and Spurgeon, 1992). Differences in palatability of Na and Mg, as observed in humans (Bruvold and Gaffey, 1969) and moose (Fraser and Reardon, 1980), may contribute to the different responses by cattle. Differences in postingestive consequences (CCREM, 1987) could also play a role in the acceptability of the 2 cations. For example, although both Mg and SO<sub>4</sub> are known purgatives (Harvey and Read, 1973), the effect of Na is less clear. High levels of Mg have also been implicated in central nervous system impairment (Fraser et al., 1991).

The unique physiological system that causes a specific appetite for Na could also affect the acceptability of this cation (Denton, 1982). In some circumstances, Na appetite might override aversions to high levels of SO<sub>4</sub>, and although Mg-specific appetite has been sug-

gested to occur in the rat, particularly under conditions of deficiency (McCaughy and Tordoff, 2002), it has not yet been demonstrated that this appetite is sufficiently strong to ameliorate SO<sub>4</sub> aversion. Bitter taste is an attribute of several compounds including MgSO<sub>4</sub> (Frank et al., 2004), and there appears to be large variation in species and individual responses to these bitter substances (Lindemann, 1996). The decrease in consumption of water containing MgSO<sub>4</sub> observed in the taste test (Exp. 1) suggests that an aversion to bitterness observed in other species is also prevalent in cattle. In the present studies, because cattle had ample access to Na, no Na appetite would be expected, but there may still be a tolerance or positive response to Na that does not occur with Mg. Further, Na is linked to thirst mechanisms through complex regulatory systems (Fitzsimons, 1979; Blair-West et al., 1989), and animals need to make up both lost water and Na when they become dehydrated (Rolls and Rolls, 1982).

Of particular interest was the wide variation between animals in response to SO<sub>4</sub>, regardless of associated cation, suggesting differences in individual aversion thresholds to SO<sub>4</sub> in water. Aversion thresholds can be defined as the concentration at which an animal demonstrates that they find a compound to be unpalatable by altering their behavior, either by reducing water consumption or discriminating against it in a preference test (Digesti and Weeth, 1976). Such phenomena have been described elsewhere as taste discrimination (Bell and Williams, 1959), taste quality (Bruvold and Gaffey, 1969), behavioral taste thresholds (Goatcher and Church, 1970a,b), and discrimination and rejection thresholds (Weeth and Capps, 1972). Aversion thresholds are known to vary in humans (Zoeteman, 1980), and similar differences may well occur in cattle. Goatcher and Church (1970a) demonstrated a trend in variability of aversion thresholds in ruminants offered water containing acetic acid, where response varied by as much as 71% between 2 groups of sheep. Variation in response to SO<sub>4</sub> water might also have been influenced by the Calan gates, which can interfere with social interactions (Sowell et al., 1999). At rangeland watering sites where cattle can drink as a group, it is possible that social facilitation (Clayton, 1978; Ralphs and Provenza, 1999) might reduce individual variation in water consumption.

Aversion thresholds for various compounds can be influenced by species, age, sex, physiological status, and diet composition (McKee and Wolf, 1963; Goatcher and Church, 1970b). The influence of these factors can largely be ruled out in these experiments, as the animals were uniform in these characteristics. Previous experience with the compounds in question can also play a role in taste response (Provenza and Balph, 1987), but in these experiments, preliminary analysis suggested that response to SO<sub>4</sub> was similar for cattle with and without previous exposure. Bell and Williams (1959) used monozygotic twin calves to demonstrate that aversion thresholds may be genetically controlled.

Associations of taste with negative postingestive consequences may also be genetically fixed (Fischer, 1967) and, thus, could result in varying aversion thresholds between different genetic lines of cattle; this factor was not controlled in either of the experiments under discussion.

Individual variability in aversion thresholds coupled with small sample size ( $n = 8$  and  $16$  for Exp. 1 and 2, respectively) might account for the lack of treatment differences at lower (i.e.,  $\leq 3,000$  mg/L)  $\text{SO}_4$  concentrations in both experiments. Once the  $\text{SO}_4$  concentration increased to approximately  $4,000$  mg/L, the water became sufficiently unpalatable to elicit a more dramatic rejection. Treatment differences may also have been obscured by an interaction between salinity and thirst. Ingestion of saline water (i.e., containing a surplus of ions) increases the demand for water (Silanikove et al., 1997) and could result in a continuous feedback loop whereby the saline water increased thirst, overriding the low palatability of saline water.

According to the NRC (1996), cattle similar to those used in this research require approximately  $41$  L of water daily, depending on animal and environmental factors. This is in close agreement with average daily water consumption values for tapwater in all 3 experiments. At approximately  $4,500$  mg of  $\text{SO}_4/\text{L}$  (Exp. 1), average daily water consumption during the 2-d treatments dropped well below this level for  $\text{Na}_2\text{SO}_4$  ( $30.3$  L/d) and even lower for  $\text{MgSO}_4$  ( $12.6$  L/d); similarly, in Exp. 2, average daily water consumption at approximately  $4,000$  mg of  $\text{SO}_4/\text{L}$  as  $\text{MgSO}_4$  was only  $29.7$  L/d for the 11-d treatments. Large stores of rumen water (Hecker et al., 1964) and the ability to withstand several days of water deprivation without long-term consequences (Weeth et al., 1967) might have allowed the cattle to maintain low water consumption for the short duration of Exp. 1. Several potential mechanisms could be responsible for the results observed here. A likely scenario is that cattle had time to adapt to both the flavor of water containing  $\text{MgSO}_4$  and the metabolic consequences of increased  $\text{MgSO}_4$  intake. Alternatively, the animals might not have adjusted but might have been able to sustain such low consumption over the 21-d periods of Exp. 2 without becoming dehydrated, and the longer treatment periods forced the cattle to increase their consumption of the poor quality water (Weeth and Capps, 1972) despite any metabolic consequences.

It was expected that the purgative properties of  $\text{SO}_4$  salts, and particularly  $\text{MgSO}_4$  (McKee and Wolf, 1963; Harvey and Read, 1973; Fraser et al., 1991), would result in an increase in fecal moisture. Embry et al. (1959) observed scouring in cattle given high- $\text{SO}_4$  water. However, fecal DM content was greater ( $P = 0.0001$ ) in cattle exposed to high  $\text{MgSO}_4$  compared with low  $\text{MgSO}_4$  in Exp. 2. When cattle experience water restriction or deprivation, one of the first physiological responses noted is a decrease in fecal water content (Thornton and Yates, 1968; Little et al., 1976). The

reduction in water consumption by cattle on the high- $\text{MgSO}_4$  treatment might have reduced fecal moisture sufficiently to outweigh any purgative effects of  $\text{MgSO}_4$ . Further work investigating the interaction between consumption of purgative salts and decreased water consumption is warranted.

Finally, readers should regard the results of Exp. 1 with some caution, as the animals received treatments in a set order, and the analysis showed an effect of treatment order ( $P < 0.05$ ). However, when these results are considered with those of Exp. 2, in which treatments were applied randomly in the style of a Latin square, it is clear that increasing concentrations of  $\text{MgSO}_4$  in drinking water can potentially reduce water consumption by cattle.

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