

# 10 Sulfur

Sulfur (S) occurs in nature as free S or combined with other elements in sulfides and sulfates. The most common form in water is the sulfate ( $\text{SO}_4^{2-}$ ) ion, although some sulfurous wells may contain relatively high concentrations of dissolved sulfides. The latter do not persist for long under surface conditions but may contribute to health problems while they are present. Sulfides in igneous and sedimentary rock are oxidized to sulfate ( $\text{SO}_4$ ) during the weathering process. The resulting sulfate salts are leached from soils by runoff and may be concentrated by evaporation in playas. Some aquifers are naturally very high in  $\text{SO}_4^{2-}$ . Once  $\text{SO}_4^{2-}$  is dissolved in water it cannot be removed unless it is reduced to sulfide by anaerobic organisms and precipitated in sediments, released as hydrogen sulfide ( $\text{H}_2\text{S}$ ) or incorporated into organic matter.<sup>587</sup> Reverse osmosis, distillation, and ion exchange may be used to remove  $\text{SO}_4^{2-}$  from water; however, none of these processes is cost-effective for livestock under normal conditions. Sulfur may also be present in organic compounds synthesized by aquatic biota; however, this form is usually a relatively minor component of the total water S content. In 1997, 11.5% of 454 forage/water pairs collected from around the United States yielded dietary S concentrations potentially hazardous for cattle. Thirty-seven % of these elevated pairs originated from the western United States, including Wyoming.<sup>588</sup>

## Essentiality

Sulfur is essential for health and, in fact, comprises about 0.15% of the total body in mammals, where it is a constituent of the amino acids methionine, cysteine, cystine, homocysteine, cystathionine, taurine, and cysteic acid. It is also a component of biotin, thiamin, estrogens, ergothionine, fibrinogen, heparin, chondroitin, glutathione, coenzyme A, and lipoic acid.<sup>589</sup> Calves deprived of dietary S had smaller livers, spleens, and testes, and larger brains and adrenals than controls.<sup>590</sup> Lactating dairy cows require between 0.17% and 0.20% total dietary S to remain in positive balance, as S constitutes an estimated 0.78% of milk proteins.<sup>591</sup> The nutritional S requirement of monogastric mammals must be provided as two amino acids – methionine and cystine. Ruminants can use either preformed amino acids or synthesize S-amino acids

from inorganic S; however, the efficiency of the latter process varies with other dietary conditions.<sup>592-594</sup>

## Metabolism

The first step in ruminal synthesis of S-amino acids from inorganic S is reduction of the latter to  $\text{H}_2\text{S}$ .<sup>595</sup> Not surprisingly,  $\text{SO}_4$  is converted to  $\text{H}_2\text{S}$  more efficiently than pre-formed S-amino acids. Halverson et al.<sup>596</sup> examined sulfide production from various S sources and found methionine produced one third the amount of sulfide as  $\text{SO}_4$ . Under normal circumstances, the reactive sulfide ion is combined with carbon by rumen microflora to create methionine, homocysteine, cystathionine, cysteine, and other S-amino acids. Under conditions of excessive S intake, however, significant quantities are reduced to  $\text{H}_2\text{S}$ , and the very toxic gas escapes from the rumen into the systemic circulation resulting in poisoning.<sup>597-601</sup>

Excess rumen sulfide may also interact with certain trace elements, especially Cu, decreasing bioavailability and possibly resulting in serious nutritional deficiencies.<sup>241,447,602-604</sup> In ruminants, S combines with Mo to form thiomolybdates. These, in turn, form unabsorbable complexes with Cu, which irreversibly bind to the solid phase of the digesta, resulting in Cu deficiency.<sup>241</sup> It has also been suggested that thiomolybdates interfere post-absorptively with Cu incorporation into the enzymes superoxide dismutase and cytochrome oxidase, compromising mitochondrial integrity and cell function.<sup>230,241,605</sup> Finally, it has been theorized that some of the effects of excess dietary Mo are actually due to Mo toxicity *per se* and not to hypocupremia.<sup>241</sup> Of the three elements, Cu, Mo, and S, S provides the most variation in nutritional outcomes due to its multiple metabolic pathways from the rumen. Sulfur exits the rumen principally as sulfide, but it can also leave as undegraded protein S or be incorporated into microbial protein. Inorganic S from diet, saliva, or degraded protein is the only form of S that will interact with Mo and Cu. Several factors affect protein degradation to S, including the supply of degradable nitrogen, the rate of ingestion, the specific population of rumen microbes, and the availability of readily fermentable carbohydrates.<sup>241</sup>

Dietary S may also antagonize Cu metabolism in the absence of excessive Mo. Copper deficiencies occurred in cattle fed 0.3% total dietary S<sup>606</sup>, and 500 mg S/L water was hypothesized to cause secondary deficiency as it raised dietary S to 0.35%, both in the absence of excess Mo.<sup>230</sup> Sulfur inhibits the uptake of Zn. The interaction between Zn and S is further magnified if animals are fed a high fiber diet.<sup>603</sup> Sulfur also decreases the uptake of dietary Se.<sup>445,607</sup> High dietary concentrations of S are thought to reduce rumen pH, favoring the conversion of Se to biologically unavailable selenide.<sup>445,608</sup> Sulfur may also reduce incorporation of dietary Se into ruminal bacterial protein.<sup>447</sup> Interestingly, S has been shown to protect against Se intoxication under some circumstances.<sup>445,448</sup>

Monogastric animals lack the ability to produce S-amino acids from inorganic S and are thus somewhat less sensitive to the above-mentioned toxic effects of the sulfide ion. For example, the NRC “maximum tolerable” S concentration for range cattle is 0.5%, whereas 0.69% of diet is *optimal* in rats.<sup>589</sup> Although it is possible for a monogastric to generate toxic concentrations of H<sub>2</sub>S following ingestion of elemental S, the dosage required is much greater than in ruminants. To illustrate this, 14 horses were mistakenly fed between 0.2-0.4 kg of flowers of S (99% S) resulting in a dose between 333-666 mg/kg BW (corresponds to 11-22% dietary dry matter). The horses became ill within 12 hours, and two died after 48 hours. *Post mortem* examination of the two deceased animals revealed cranioventral consolidation of the lungs, hemorrhaging throughout the heart and GI, and congestion of the liver.<sup>609</sup> Toxic effect(s) of inorganic S salts (e.g. SO<sub>4</sub>) in monogastric species are usually related to abnormalities in water balance in the GI tract, explaining why clinical signs differ between monogastric and ruminant mammals. In swine, toxic effects are generally manifested as watery feces and have been shown to occur when ingesting water with concentrations as low as 600 mg SO<sub>4</sub><sup>2-</sup>/L, but they more commonly occur in water containing 1,600 mg SO<sub>4</sub>/L or higher.<sup>610-612</sup>

## Toxicity

As with all poisons, toxicity depends on dose, route of exposure, and form of the element. In this report, we are most interested in ingestion (oral exposure) and SO<sub>4</sub><sup>2-</sup>, as that is the form of S commonly found dissolved in water. Between 0.3-0.5% of dietary dry matter is the recommended maximum tolerable limit for total daily

S intake for ruminant animals.<sup>589</sup> The amount of S that water contributes to the diet depends on the amount of water an animal drinks as well as the concentration of S in the water. This varies drastically with environmental temperature, type of feed, and condition of the animal. In one published example, the amount of S contributed by 1,000 mg SO<sub>4</sub><sup>2-</sup>/L in drinking water varied from 0.1-0.27% under different conditions.<sup>613</sup>

Toxic S concentrations have been shown to reduce the feed intake, water intake, growth, and performance of animals. Cattle given water containing 1,219 mg SO<sub>4</sub><sup>2-</sup>/L in conjunction with a diet containing 0.16% S (0.29% total S intake), exhibited depressed dry matter intake (DMI).<sup>614</sup> Adding 0.72% SO<sub>4</sub> (0.24% dietary S) to cattle diets reduced weight gains by 50% after the first two weeks.<sup>615</sup> Concentrations of 0.35% or more dietary S resulted in diminished DMI in lactating dairy cows.<sup>591</sup> Water containing 5,000 mg sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>)/L and grass hay containing “0.75% SO<sub>4</sub>” reduced water intake by 35% and feed intake by 30% in cattle.<sup>574</sup> Decreases in average daily gain (ADG), feed efficiency, and dietary net energy were seen when heifers were fed 0.25% S as ammonium sulfate ((NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>).<sup>616</sup> Supplying heifers with water containing 2,814 mg SO<sub>4</sub>/L and hay containing “0.55% SO<sub>4</sub>” reduced hay intake by 12.4% during the summer months.<sup>617</sup> Water containing 3,087 mg SO<sub>4</sub>/L reduced ADG by 27%, DMI by 6.2%, and water intake by 6.1 L in steers, and it increased the incidence of polioencephalomalacia (PEM).<sup>618</sup> Cattle on a low plane of nutrition decreased their water intake when consuming water with 1,000 mg SO<sub>4</sub>/L, and cattle on a high plane of nutrition had a slight decrease in feed intake when consuming 2,000 mg SO<sub>4</sub>/L.<sup>619</sup> Concentrations of S greater than 0.4%, added as elemental S or Na<sub>2</sub>SO<sub>4</sub>, decreased gains in feeder lambs.<sup>594</sup> Approximately 0.5% S added to rations as calcium sulfate (CaSO<sub>4</sub>) or Na<sub>2</sub>SO<sub>4</sub> resulted in reduced feed intake and daily gains of 163 g/day and 191 g/day, respectively, compared to control lambs that gained 251 g/day.<sup>620</sup>

On the other hand, when 0.75% S was added as CaSO<sub>4</sub> to the concentrate portion of the diet (0.477% total dietary S) of six Hereford cattle, no statistically significant changes in serum enzyme activity, Se concentrations, weight gains, or general health were noticed.<sup>621</sup> The study, however, was designed to look at S-Se interactions and lacked statistical power to examine growth, ADG, or other measures of performance, and one of the animals died of PEM at the end of the experiment. Cattle offered water containing 2,500 mg SO<sub>4</sub>/L showed no changes

in feed or water consumption. The animals consumed an average of 3.9 kg of hay, 3.1 kg concentrate, and 33.1 kg water per day, suggesting this level as a safe tolerable limit.<sup>585</sup> As with the previous study, the number of animals tested was very small. Sublimed S added to the diet of steers for 10 weeks at 0.42% did not affect feed intake but did at 0.98%.<sup>622</sup> Qi et al.<sup>623</sup> added various amounts of CaSO<sub>4</sub> to the diet of goats and concluded that optimum feed performance occurred between 0.2-0.28% S.<sup>623</sup> Pendlum et al.<sup>624</sup> fed up to 0.3% elemental S to steers without adverse effects.

The most dramatic manifestations of S toxicity in ruminants are sudden death, with no lesions, and/or PEM. Polioencephalomalacia is a neurological disease of cattle and sheep, resulting in seizures, ataxia, blindness, and recumbency as the main clinical signs. It is usually fatal. Seven hundred of 2,200 ewes grazing a pasture previously sprayed with elemental S began showing signs of abdominal discomfort within two hours of exposure, and 220 ewes died within five days. Lesions of PEM were found only in the sheep that had survived for five days.<sup>625</sup> Animals ingesting water with 4,564 mg SO<sub>4</sub>/L and feed containing 0.17% S had a 47.6% incidence of PEM and a 33% mortality rate.<sup>626</sup> Six of 110 cows drinking 7,200 mg Na<sub>2</sub>SO<sub>4</sub>/L water developed PEM.<sup>627</sup> Eighteen of 21 herds fed supplements containing 2% inorganic SO<sub>4</sub> developed PEM. This supplement provided approximately 0.16% S beyond what was in the rest of the diet.<sup>628</sup> Water containing 2,000 mg SO<sub>4</sub><sup>2-</sup>/L produced PEM in one of nine steers.<sup>597</sup> Three of 21 steers fed 3,780 mg SO<sub>4</sub><sup>2-</sup>/L developed PEM and died. Feeding thiamin did not prevent S-toxicity.<sup>629</sup> Four steers died of PEM on a feedlot in Alberta, Canada, after consuming water with 5,203 mg SO<sub>4</sub>/L while the temperature was 30 C.<sup>630</sup> Four of 40 animals developed PEM after ingesting hay with 0.39% S and water containing 2,250 mg SO<sub>4</sub>/L.<sup>631</sup> All 10 experimental animals offered water with 5,540 mg S/L or 7,010 mg S/L showed signs of PEM.<sup>632</sup> The incidence of death from PEM in a beef feedlot varied dramatically with environmental temperature, from none in the winter to 0.8% per month in the summer. The increase also corresponded with a 2.4-fold increase in water intake as a result of summer weather, raising total dietary S intake to 0.67%.<sup>633</sup> Cows in Canada were stricken with PEM when exposed to 3,400 mg SO<sub>4</sub><sup>2-</sup>/L water; no new cases occurred after the water was replaced.<sup>634</sup> Sixty-nine animals were affected with PEM after ingesting a protein supplement containing "1.5% organosulfate" and water containing 1,814 mg SO<sub>4</sub>/L.<sup>205</sup>

Experimentally feeding 0.477% total dietary S resulted in one of 12 heifers developing PEM three days after termination of the experiment.<sup>621</sup> Polioencephalomalacia has been diagnosed in wild ruminants.<sup>635,636</sup> Tests were not conducted to confirm SO<sub>4</sub> as the cause of these cases, but surface waters in the area where the animals were found are naturally high in SO<sub>4</sub>, and exposure to these waters was considered likely.<sup>637</sup>

Sulfate waters are quite unpalatable, and, when given a choice, animals will discriminate against them. A taste test was conducted between waters containing 1,450 mg/L and 2,150 mg/L SO<sub>4</sub> and tap water. The cattle discriminated against the water containing 1,450 mg/L and rejected the water containing 2,150 mg/L, opting for tap water instead.<sup>617</sup> Despite the unpalatability, if no other water is available, animals will reluctantly drink water with higher SO<sub>4</sub> concentrations resulting in potential toxicity.

## Summary

In ruminants, high dietary S may cause acute death, PEM, trace mineral (especially Cu) deficiencies, and/or chronic, as-yet-poorly-defined ailments that decrease production efficiency. All dietary sources of S (water, forage, concentrates, feed supplements) contribute to total S intake and thus to potential toxicity. The S contribution of water, usually as the SO<sub>4</sub><sup>2-</sup> ion, varies dramatically with environmental conditions as water consumption goes up and down.

From a strictly theoretical standpoint, the NRC maximum tolerable dose of S for cattle is 0.5% of the total diet (0.3% for feedlot animals).<sup>589</sup> Wyoming grasses are reported to contain between 0.13%-0.48% S.<sup>638</sup> Assuming forage S concentrations of 0.2% and water consumption typical of young, rapidly growing cattle at summer temperatures (30 C), a water SO<sub>4</sub> concentration of 1,125 mg/L will meet or exceed the NRC's maximum tolerance limit for S in cattle. Adult bulls, which consume half as much water, could theoretically be impacted by 2,250 mg/L, and lactating cows would fall somewhere in between. In practice, water SO<sub>4</sub> concentrations as low as 2,000 mg/L have caused PEM and/or sudden death in cattle. This observation is supported by many field cases investigated by the WSVL and other regional diagnostic labs since 1988. It *seems* to be contradicted by some of the early studies mentioned above, notably Digesti and Weeth<sup>585</sup>, but both probability and the morbidity of poisoning increase with progressively larger SO<sub>4</sub> concentra-

tions; thus, studies with small numbers of animals easily overlook marginally toxic doses. Anecdotal data also indicate cattle are able to adapt to elevated S concentrations *if* introduced gradually to potentially toxic waters over a period of several days to weeks. The details (i.e. how rapidly dietary S can change) of this process and the effect(s) of other dietary factors such as energy and protein on the process are still a matter of conjecture.

Waterborne  $\text{SO}_4$  is reported to decrease Cu uptake at concentrations as low as 500 mg S/L as  $\text{SO}_4^{2-}$ .<sup>602,606</sup> Whether overt Cu deficiency results depends upon the dietary concentration of Cu, and excess dietary Cu may compensate for some or all of the effect of  $\text{SO}_4^{2-}$ .<sup>308</sup> Unfortunately, most Wyoming forages are marginally to drastically deficient in Cu for cattle. Elevated dietary S also interferes with the uptake of Zn and Se. Trace element deficiencies are multifactorial diseases that do not normally manifest themselves unless animals are exposed to other stressors such as bacterial pathogens, bad weather, shipping, etc. Therefore, it is difficult, if not impossible, to settle upon a single number that consistently results in deficiency or guarantees safety; however, the NRC recommends “the sulfur content of cattle diets be limited to the requirement of the animal, which is 0.2% dietary sulfur for dairy and 0.15% in beef cattle and other ruminants.”<sup>589</sup>

Relatively low S concentrations (equivalent to 500-1,500 mg  $\text{SO}_4^{2-}$ /L in water) have also impacted performance (e.g. ADG, feed efficiency) in feedlot and range cattle via a variety of mechanisms not completely understood.<sup>614,616,639,640</sup> Loneragan et al.<sup>597</sup> suggested that  $\text{H}_2\text{S}$  produced from  $\text{SO}_4^{2-}$ , eructated and then inhaled, resulted in pulmonary damage and increased susceptibility to respiratory infections. Elevated  $\text{SO}_4^{2-}$  also results in decreased water intake under experimental conditions. Finally, it is possible some, as yet unrecognized, interactions with other dietary components result in decreased utilization and feed efficiency. These effects have obvious implications for animal health, but they are difficult to quantify under field conditions.

Monogastrics, such as horses, are at less risk of S effects that involve ruminal generation of sulfide. In these species, the principle effect of elevated drinking water  $\text{SO}_4$  seems to be diarrhea resulting from the osmotic attraction of water into the gut. The relative contributions of the  $\text{SO}_4^{2-}$  ion and its associated cation are unclear, but the literature indicates the effect 1) is transient and not life-threatening and 2) probably only occurs at concentra-

tions considerably in excess of those toxic in ruminants. Therefore, concentrations that are safe in ruminants should provide adequate protection for horses.

***Assuming normal feedstuff S concentrations, keeping water  $\text{SO}_4^{2-}$  concentrations less than 1,800 mg/L should minimize the possibility of acute death in cattle. Concentrations less than 1,000 mg/L should not result in any easily measured loss in performance.***