CHAPTER

45

Forage-induced Animal Disorders

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Forages are a major source of nutrients for herbivores around the world. In the United States and Canada about 110 million cattle, 7.4 million sheep, 1.4 million goats, and 7.4 million horses depend on forages for all or part of their nutritional needs (Table 45.1). Sometimes the balance of nutrients or presence of some constituent in the forage will have negative effects on animal health. This chapter presents some of these forage-induced health problems, including bloat, milk fever, grass tetany, laminitis, nitrate poisoning, mineral imbalances, and effects of toxic secondary compounds.

Pasture Bloat

Description

Pasture bloat occurs when gas production in the rumen of cattle or sheep exceeds the animal's ability to expel the gas produced by fermentation. With some legume forages such as alfalfa, fermentation in the rumen is very rapid, providing for bacterial blooms and producing large quantities of gas. For example, steers fed fresh alfalfa can produce 2 L of gas per minute. Under normal conditions this gas collects in the free space at the top of the rumen and is then expelled by eructation, or belching. In pasture bloat the gas is trapped in small bubbles such that the eructation mechanism is inhibited by frothy rumen contents (Fig. 45.1). The gas and bubbles remain trapped in the rumen fluid, and the frothy contents inflate the rumen (Fig. 45.2), increasing pressure against the lungs.

Receptors in the rumen wall sense that the area is exposed to liquid rather than free gas, so the esophagus remains closed, preventing belching. The study of this process is facilitated with the presence of an artificial port or fistula in the rumen. The severe distension is followed by an exceptional release of frothy rumen contents when the cannula plug is removed from rumen-fistulated cattle (Figs. 45.3 and 45.4). When the gas cannot be released, severe distension occurs, compressing the lungs and preventing inhalation; death is likely caused by suffocation.

Risk among Forages

When fed fresh alfalfa, the concentration of chloroplast fragments in the rumen of cattle was associated with the occurrence of bloat (Majak et al., 1983). This led to a general theory that attributes frothy bloat to an excess of small feed particles that contribute to bubbles or froth in combination with a readily digestible feedstuff that contributes to rapid gas production. The concentration of small particles can directly increase the rate of passage of digesta (Majak et al., 1986).

Forages are classified as bloat causing, low risk, or bloat safe (Table 45.2). However, even so-called bloat-safe forages have been known to cause bloat under certain conditions. Grasses are usually bloat safe if not overly lush or immature. Common forage legumes such as alfalfa and clovers may not be bloat safe. Several less-common legumes have been pastured intensively without causing bloat. In a 3-yr study, bloat occurred five times more often with alfalfa (39 cases) than with berseem clover (8

Table 45.1. Census of domestic cattle, sheep, goats, and horses in the United States (2002–2003) and Canada (2001)

	Number of animals (in millions)	
Animal	United States[a]	Canada[b]
Cattle	96.0	15.6
Dairy	9.1	1.2
Beef	87.0	14.4
Sheep	6.3	1.2
Goats	1.2	0.2
Horses	6.9	0.5

[a]US data are from 2002–2003 USDA Agricultural Census and horse data are from html://www.horsecouncil.org/ahcstats.html.

[b]Canadian Agricultural Census, 2001.

cases) and four times more often with alfalfa (64 cases) than with persian clover (15 cases) when the freshly harvested forages were fed to cattle (W. Majak, unpublished data). Bloat potential of a species is related to the ease with which it is digested by rumen microbes. Bloat-causing forages are digested rapidly, whereas bloat-safe forages are digested more slowly (Fay et al., 1980). The bloat potential of alfalfa has been reduced by selecting for a low initial rate of digestion (Berg et al., 2000).

Forage Management

Stage of growth or crop maturity is the most important factor in preventing pasture bloat. The risk of bloat is highest at the vegetative (or prebud) stage, decreasing progressively as the plant matures to full bloom. Alfalfa harvested at the vegetative stage caused the highest incidence of bloat (129 cases in 2 yr) compared with the bud (20 cases) or bloom stage, which had no cases (Thompson et al., 2000). Leaf-to-stem ratio also decreased as the forage matured, which would decrease chloroplast particles in the rumen. A leaf-to-stem ratio of < 1:2 (on a dry weight basis) could be used as an indicator of a low potential for bloat in alfalfa. The importance of forage maturity should also be considered when managing grass–legume mixtures because cattle may select one component over another. Generally, the incidence is reduced to bloat safe if the bloat-causing legume is less than 50% of a legume–grass mixture. Alfalfa bloat can be prevented with as little as 25% orchardgrass (on a dry matter, or DM, basis) in the herbage diet (Majak et al., 2003a).

Pasture Mixes

Seeding rates, fertilization, and grazing management can help maintain a 50:50 mixture of grass and alfalfa. Nitrogen fertilization promotes grass growth at the expense of alfalfa. Although alfalfa–grass mixtures may be seeded to promote the desired proportion, selective grazing may still allow excessive intake of alfalfa, resulting in

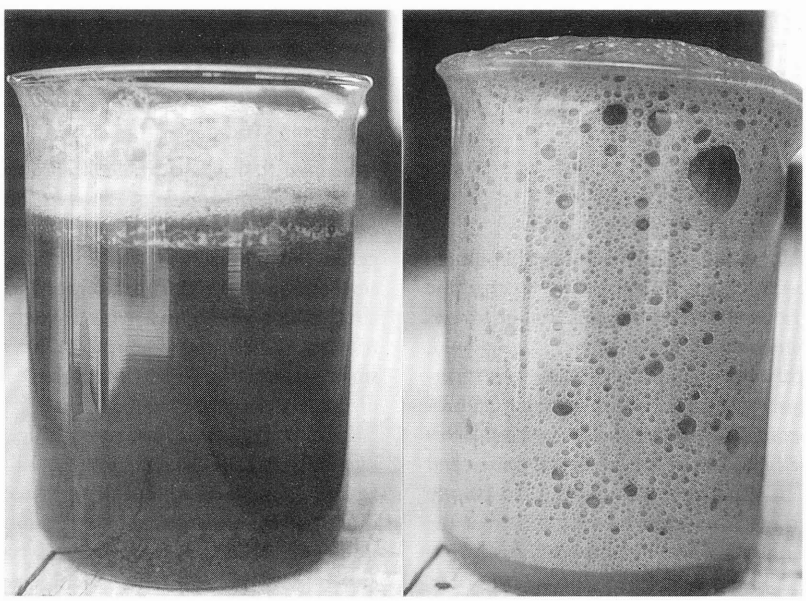

FIG. 45.1. An example of normal rumen fluid *(left),* where gases are expelled, and frothy rumen fluid *(right)* showing trapped fermentation gases.

FIG. 45.2. An example of severe distension of the rumen resulting from the inability to expel microbial fermentation gases. The animal is shown before *(left)* and after *(right)* the onset of frothy bloat.

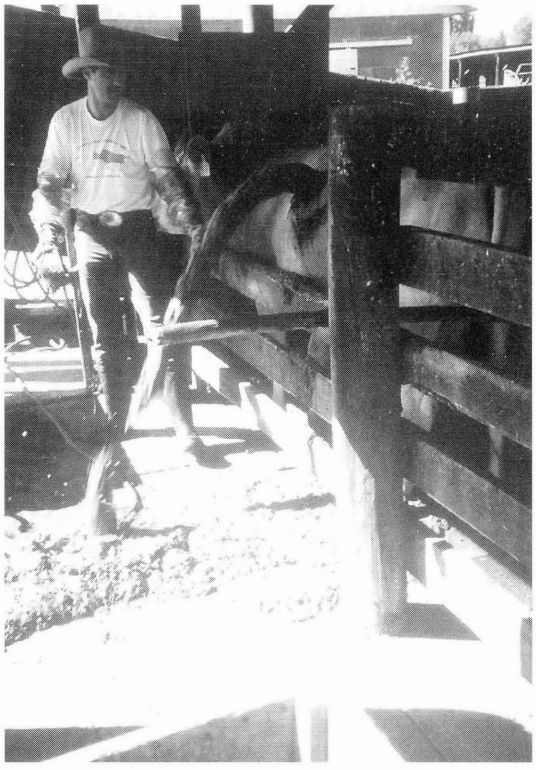

FIG. 45.3. The release of frothy rumen contents of alfalfa when the cannula is removed from a bloated cow. The degree of bloat was 3 on a scale of 1–5 (Majak et al., 1995).

bloat. The ideal companion grass should have the same seasonal growth pattern and regrowth characteristics as alfalfa. The principles of competition in mixtures of grass and alfalfa have been thoroughly reviewed by Chamblee and Collins (1988).

Birdsfoot trefoil, annual lespedeza, sericea lespedeza, and sainfoin do not cause bloat. These plants contain tannins, which at low concentrations complex with the cytoplasmic proteins and prevent their ability to foam. Lespedeza and trefoils often contain sufficiently high tannin levels to inhibit animal performance by reducing feed intake and protein digestibility. Although saponins are foaming agents that occur in most bloat-producing legumes, earlier studies suggested they did not have a significant role in bloat (Majak et al., 1980), but this has been disputed more recently (Mathison et al., 1999). Alfalfa saponins were determined during 10-d periods of high bloat and low bloat, but significant differences in saponin levels were not detected between the two periods (Majak, unpublished data).

Alfalfa bloat is reduced but not eliminated when sainfoin, a bloat-free legume, makes up 10%–20% of the grazing diet (McMahon et al., 1999). Sainfoin did not compete well with alfalfa. The reduction in bloat by sainfoin additions was attributed to condensed tannins. However, bloat incidence with alfalfa was not reduced by feeding a commercially available condensed tannin (extract of *Schinopsis quebracho-colorado*) administered either in drinking water (5 g L^{-1}) or when sprinkled on top of the hay (75 g $head^{-1}$ d^{-1}) (Majak et al., 2004a).

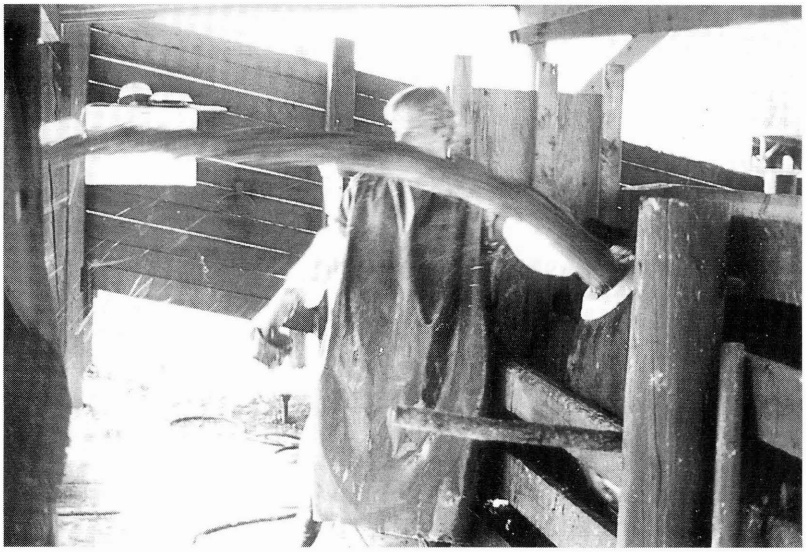

FIG. 45.4. Alfalfa bloat with a degree of 4, which could rapidly escalate to a degree of 5. Through diligent animal care, extreme cases of bloat were avoided to prevent animal distress.

Table 45.2. Bloat-causing, low-risk, and bloat-safe forages used as pasture

Bloat-causing	Low-risk	Bloat-safe
Alfalfa	Arrowleaf clover	Sainfoin
Sweetclover	Spring wheat	Birdsfoot trefoil
Red clover	Oats	Cicer milkvetch
White clover	Rape (canola)	Crownvetch
Alsike clover	Perennial ryegrass	Lespedeza
Winter wheat	Berseem clover	Fall rye
	Persian clover	Most perennial grasses

Note: Classification is based on published reports that are consistent. Species not listed do not have enough data for assessment.

Dry Matter Intake

Maintaining uniform and regular DM intake is the key to managing cattle on legume-dominated pastures. Bloat is less likely to occur if animals are turned out to legume-dominated pasture in the afternoon rather than in the morning (Hall and Majak, 1995). This is partly due to avoiding the morning dew. Animals should be fed coarse hay before being introduced to a legume-dominated pasture. This practice prevents them from gorging and overeating on the lush legume forage. If the legume pasture remains highly bloat potent, the animals should be removed from the pasture until the alfalfa matures. Furthermore, bloat is often associated with interrupted grazing such as the overnight removal of animals from legume pastures. Factors that alter normal grazing habits generally result in more intensive, shorter feeding periods that may increase the incidence of bloat (Majak et al., 1995). Grazing alfalfa that has been swathed and wilted reduces risk of bloat. Compared with feeding a fresh swath, wilting a swath for 24–48 hr can significantly reduce the incidence of bloat and may even eliminate bloat if the moisture content of the alfalfa is sufficiently reduced (Majak et al., 2001).

Cattle experienced 21 cases of bloat when grazing alfalfa and 30 cases when fed freshly harvested alfalfa grown under irrigation (Majak et al., 1995). The difference in

bloat incidence is attributed to the greater intake rate of the harvested forage.

Weather

Daily weather conditions affect the incidence of bloat in cattle fed fresh alfalfa (Hall et al., 1984). For example on nonirrigated pasture, bloat occurred more frequently on a day preceded by lower maximum and minimum temperatures of 1–2°C. This daily change in bloat frequency was not seen under irrigated pasture conditions, since this foliage was always quite high in water content.

In general, bloat occurred in spring, early and late summer, and fall, increasing with cool weather and frost (Hall and Majak, 1991). The fall peak may be caused by frequent heavy dew or frost. After a killing frost, which for alfalfa is −9°C (McKenzie and McLean, 1982), alfalfa has a reputation of being bloat safe. However, as long as portions of the alfalfa remain green, there is still a risk of bloat (Hall and Majak, 1991).

Animal Variability

Individuals differ in their susceptibility to pasture bloat, which is related to the rate of passage of particles in the liquid phase of the rumen contents. Frequent bloaters have a slower clearance rate than less-susceptible animals (Majak et al., 1986). Highly susceptible and less-susceptible lines of cattle were selected in New Zealand, but a simple genetic marker could not be identified to distinguish the two lines (Cockrem et al., 1983). Nevertheless, it is a good practice to cull bloat-susceptible animals from a breeding herd. A revised bulletin on frothy and feedlot bloat is available (Majak et al., 2003b).

Prevention

Oils and detergents are effective for the prevention and treatment of pasture bloat because they act as surfactants to break down the frothy condition in the rumen contents. Effective detergents include poloxalene, the active ingredient in products such as Bloat Guard® (Hall et al., 1994). However, prevention of bloat is not absolute because the product is fed free choice, and animal intake is highly variable. Water-soluble products containing pluronic detergents are available in New Zealand and Australia. For example, when Blocare® 4511 (Ancare©, NZ) was administered at a concentration of 0.06% in the drinking water, bloat was completely prevented under conditions of extreme risk, provided the treated water was the only source of drinking water (Stanford et al., 2001). A new water-soluble product called Alfasure™ is available on a prescription basis from a veterinarian. It was shown to be completely effective in the prevention of bloat (Majak et al., 2004a). Water consumption can be reduced during periods of high rainfall so dosages should be adjusted accordingly. Alfasure can also be sprayed on alfalfa or injected intraruminally to prevent bloat (Majak et al., 2005). Ionophore antibiotics can also reduce the occurrence of pasture bloat (Hall et al., 2001).

Milk Fever

The onset of lactation places such a large demand on the Ca homeostatic mechanisms of the body that most dairy cows develop some degree of hypocalcemia at calving. In some cases, plasma Ca concentrations become too low to support nerve and muscle function, resulting in parturient paresis or milk fever. Ordinarily, the cow replaces Ca lost to milk by withdrawing Ca from bone and/or by increasing the efficiency of intestinal absorption of dietary Ca; both homeostatic mechanisms are mediated by parathyroid hormone (PTH). In cows with milk fever the bone and kidney tissues have lost their sensitivity to PTH stimulation. Recent research (Goff, 2000) suggests PTH resistance is the result of diet-induced metabolic alkalosis (see below). Alkaline blood pH causes a conformational change in the PTH receptor located on the surface of bone and kidney cells that interferes with binding of the hormone. Calcium homeostatic processes are disrupted, and milk fever develops.

Blood pH and Ionic Balance

Blood pH depends on the number of cations and anions entering the blood from the diet (Stewart, 1983). The major dietary cations are K^+, Na^+, Ca^{++}, and Mg^{++}, and the major dietary anions are Cl^- and SO_4^-. The relative numbers of absorbable cations and anions in a ration, known as the dietary cation–anion difference (DCAD) can alter the pH of the blood. High-DCAD diets alkalinize the blood and cause milk fever. The major dietary cation of concern in dairy rations is excess K^+.

In simplified terms, when a K^+ enters the blood, a H^+ must leave to maintain electroneutrality (an H^+ along with an OH^- form a water molecule that has no electrical charge). As K^+ enters the blood the number of H^+ is reduced and the blood becomes more alkaline. Conversely, when Cl^- enters the blood electroneutrality is achieved by balancing the negative charges of the Cl^- with positively charged H^+. The H^+ arises from the dissociation of water molecules in the blood. In this way Cl^- absorbed into the blood acidifies it.

Manipulating Dietary Cation–Anion Difference

The K content of forages can often range from 14 to 41 g kg^{-1} DM. Plant tissue K concentrations of 21–23 g kg^{-1} DM achieve maximum yields of most grasses and legumes (Table 45.3) but can be higher with heavy fertilization. Unfortunately, in a survey by Lanyon (1980), the average alfalfa sample contained 31 g K kg^{-1} DM, a level likely to contribute to hypocalcemia in dairy cows. Nutritionists now offset the alkalinizing effects of K^+ in the ration by adding sources of Cl^- or SO_4^- ("anionic salts") to prepartum rations of dairy cows.

Table 45.3. Nutrient element concentrations found in grass and legume herbage and a guide to herbage concentrations required by sheep, cattle, and horses

Element	Grasses	Legumes	Sheep	Cattle	Horse
			(g kg^{-1})		
Ca	2–5	2–14	3–4	3–4	2.4–4.3
Cl[a]	T[e]–20	T–20	1	2	NE[f]
Mg	1–3	2–5	1.2[c]	1.9[c]	0.8–0.9
N	10–40	10–50	10–15	10–15	NE
P	2–4	3–5	2.5	3.0	1.7–2.4
K	10–30	20–37	2–6	2–6	3
Si[a]	10–40	0.5–1.5	NE	NE	NE
Na[a]	T–3	T–2	1	2	1
S	1–4	2–5	1–2	1–2	1.5
			(mg kg^{-1})		
B	3–40	30–80	NE	NE	NE
Cu	3–15	3–30	5–6[d]	7–10[d]	10
F[a]	2–20	2–20	1–2	1–2	NE
Fe[b]	50–250	50–250	30	40	40–50
Mn	20–200	20–200	25	25	40
Mo	1–5	1–10	NE	NE	NE
Zn	15–50	15–70	25–40	25–40	40
			(μg kg^{-1})		
Co	100–200	200–300	110	80	100
I[a]	40–800	40–800	500[g]	500[g]	00–600
Se[a]	10–1000	10–1000	30–700	30–700	100

Source: Herbage data are from the authors' files and Gough et al. (1979). Sheep and cattle data are adapted from Grace (1983), Grace and Clark (1991), and National Research Council (1984). Horse data are from National Research Council (1989) and Kline et al. (undated) with ranges given for mature and growing stock.

[a]Not required for plant growth.

[b]Values in excess of 100–150 mg kg^{-1} often reflect soil contamination.

[c]Must be greater than 2 g kg^{-1} for sheep and cattle diets if K and N are high.

[d]Higher Cu concentrations required if Mo and S are high in diet.

[e]Trace amounts.

[f]Not established.

[g]2 mg kg^{-1} required when grazing turnips or other brassicas.

Anionic salts used to lower the DCAD of a diet can be unpalatable. Therefore, the best strategy to reduce DCAD involves incorporation of low-K forages in the diet fed to prepartum cows. Even better is to use a low-K, high-Cl forage that can further reduce the DCAD of the ration. Chloride concentration in forages often ranges from 2.5 to 12 g kg^{-1} DM (Table 45.3), depending on agronomic practices. The K content of forage also decreases as the plants mature. However, neutral detergent fiber (NDF) and lignin also increase with maturity. It is critical to use a low-K forage in prepartum rations but not one so mature that the forage DM intake is reduced. Both low-K and high-Cl forage should be fed in the prepartum dairy ration. Mineral analysis, involving a wet ashing of the forage, should be used since near-infrared (NIRS) analysis is often unacceptable (Clark et al., 1987).

In the past, alfalfa and other legumes were left out of dry cow rations in favor of grasses because it was believed the high-Ca content of alfalfa was the cause of milk fever. However, high-dietary Ca does not cause milk fever. By restricting K application to the soil it is possible to grow alfalfa that is as low in K as many of the grass hays.

Cool-season grasses such as kentucky bluegrass, orchardgrass, and smooth bromegrass traditionally tested lower in K 20 years ago than they do today. At that time, hayfields were unlikely to receive manure applica-

tion. Due to decreased land area per cow today, hayfields that were not fertilized in the past are now used extensively as a place to deposit animal wastes. Cool-season grasses will consume soil K, and grasses can often contain 30–35 g K kg^{-1} DM. Small grain forages, such as oats, rye, and to a lesser extent, wheat, can be particularly high in K. Straw or haylages made from these crops must be used with caution in dry cow rations because of high nitrate values.

Corn is a warm-season grass, and corn silage tends to contain 10–14 g K kg^{-1} DM. Corn silage is the basis for most prepartum (close-up, dry) cow rations in the United States. Some other warm-season grasses, such as switchgrass, eastern gammagrass, and indiangrass, tend to be low in K, but their use is limited by their high NDF and low digestibility.

Parathyroid Hormone

As discussed above, the interaction between PTH and its receptor is vital to Ca homeostasis. Hypomagnesemia can also interfere with the ability of PTH to act on its target tissues. When PTH binds its receptor, it initiates activation of adenylate cyclase, resulting in production of adenosine 3′,5′-cyclic monophosphate (cyclic AMP). Adenylate cyclase requires Mg for full activity, thus hypomagnesemia can cause tissues to become nonreceptive to PTH and hypocalcemia ensues. High K and N concentrations in forage can interfere with ruminal Mg absorption. In general the best approach to avoid hypomagnesemia in dairy cows is to increase dietary Mg content to 3–4 g kg^{-1} DM in dry cow and early lactation rations by addition of inorganic Mg sources.

Grass Tetany—Hypomagnesemia

Economic Losses

Grass tetany is a Mg deficiency of ruminants usually associated with grazing of cool-season grasses during spring. This is probably the most important nutritional disease in grazing livestock. Chronic cases are not easily recognized and are documented only by a blood test. Annual death losses in the United States are estimated at $50–150 million (Mayland and Sleper, 1993). Grass tetany occurs in all classes of cattle and sheep, but is most prevalent among older females in early lactation. Magnesium must be supplied daily because it is excreted in urine and milk.

Blood Cation Concentrations

Plasma Mg levels are normally 18–32 mg Mg L^{-1}. Blood plasma or serum less than 18 mg Mg L^{-1} and urine values less than 20 mg Mg L^{-1} (Puls, 1994) are indicators of hypomagnesemia, and concern is expressed when any of these values fall below 15 mg Mg L^{-1} (Mayland, 1988; Vogel et al., 1993). The dramatic signs of tetany are clearly evidenced at levels below 10 mg L^{-1}. Physical symptoms of Mg tetany proceed from a reduced appetite, dull appearance, and staggering gait to signs of increased nervousness, frequent urination and defecation, muscular tremors, and excitability followed by collapse, paddling of feet, coma, and death (Martens and Schweigel, 2000). These visible symptoms may precede death by less than 4–6 hr.

Grass tetany is a complex disorder. First, Mg requirements are greater for lactating than for nonlactating animals and are greater for older than for younger animals. Second, bovine breeds differ in susceptibility to grass tetany with Brahman and Brahman crossbreeds being most tolerant and European breeds being least tolerant (Greene et al., 1989). Third, many factors influence Mg concentration and availability in the herbage. The principal factor is a high level of soil K that negatively affects soil Mg uptake by plants and availability of herbage Mg to animals (Cherney et al., 2002). Also, low levels of readily available energy, Ca and P or high levels of organic acids, higher fatty acids, and N in the ingested herbage reduce the absorption of or retention of Mg by the animal. Concentrations greater than 2.0 g Mg kg^{-1} DM or a milliequivalent ratio of less than 2.2 for K $(Ca + Mg)^{-1}$ are considered safe (Grunes and Welch, 1989). This ratio (Fig. 45.5) is the best single forage indicator of grass tetany risk.

Prevention

Agronomic practices to reduce risk of tetany include splitting applications of N and K fertilizers, liming acid soils with dolomitic rather than calcitic limestone, or spraying Mg on herbage (Robinson et al., 1989). One might also use cultivars or species having high Mg and Ca and low K concentrations (Sleper et al., 1989; Moseley and Baker, 1991; and Mayland and Sleper, 1993). Animal husbandry practices include assigning less-susceptible breeds (Braman types) and classes (nonlactating) of livestock to tetany-prone pastures (Greene et al., 1989). Magnesium can be supplemented through additions to herbage, drinking water, stock salt, molasses licks, or other energy sources (Robinson et al., 1989).

Laminitism—Lameness

Foot problems in cattle and horses are attributed to several causes, one of which is nutritional. Overloads of readily fermentable carbohydrates ingested by animals grazing lush pasture grasses or consuming grains can produce acidosis and ultimately lead to laminitis or sore feet (Nocek, 2001). The etiology of laminitis is not fully understood but it seems to accompany advanced stages of acidosis and is a complex and costly disorder (Longland and Cairns, 2000).

Laminitis in horses is described as a noninfectious inflammation or failure of the attachment between the distal phalanx and the inner hoof wall (Pollitt, 2005). It is

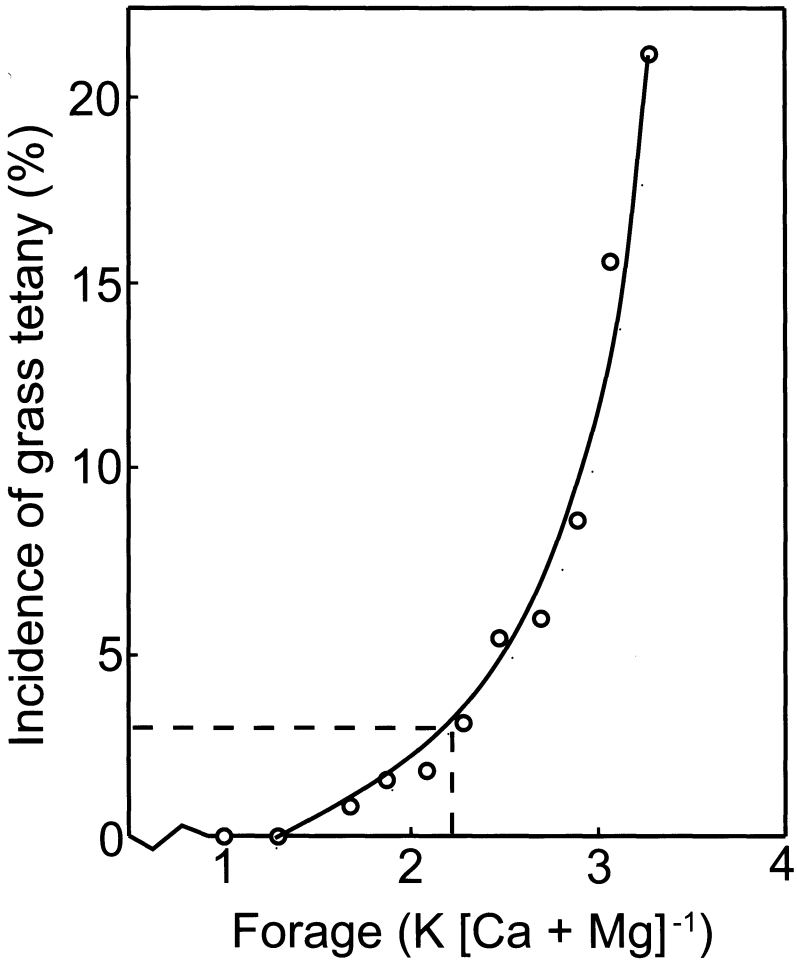

FIG. 45.5. Relationship between the forage K/(Ca + Mg), calculated on an equivalent basis and the relative incidence of grass tetany in The Netherlands. (Adapted from Kemp and 'tHart, 1957.)

often associated with excessive ingestion of high starch grain but is also commonly associated with grass founder, which is caused by ingestion of rapidly digestible plants by horses and ponies (Longland and Cairns, 2000). The problem has been attributed to the ingestion of fructans in the form of the inulin-like sugar, raffinose. This sugar can cause laminitis by interfering with insulin function.

Laminitis in cows is associated with a shortage of roughage in the ration. It often starts with a disturbance of digestion and accumulation of excess amounts of readily fermentable carbohydrates, which predispose a cow to laminitis. This is followed by an excessive accumulation of lactic acid, imbalances of microflora, and decreases in ruminal pH (Westwood et al., 2003; Whitaker et al., 2004). Laminitis also occurs in cows on pasture and is the most costly disease condition affecting dairy herds in New Zealand and Australia. Forages associated with this condition are characterized as low in fiber, high in water content, and having a rapid rate of fiber digestion.

Nitrate Poisoning

Description

Nitrate (NO_3^-) accumulates in plant tissue because of luxuriant uptake of soil N when plant metabolism of N is slow or even stopped. This condition is promoted by cool temperature, cloudy weather, drought, or other physiological stress that slows growth. Plant NO_3^- itself is not normally toxic, but it is usually reduced to nitrite (NO_2^-) in the rumen. If the NO_2^- is not reduced further, the accumulated NO_2^- can cause several conditions detrimental to animal health (Bush et al., 1979). These

Table 45.4. Livestock responses to nitrate-N in forage and drinking water

Nitrates	Comments
Forage[a] (mg N kg^{-1})	
< 1000	Safe to feed under most conditions.
1000–1500	Safe to feed to nonpregnant animals. Limit use for pregnant animals to 50% of total DM intake.
1500–2000	Safely fed if limited to 50% of total DM intake.
2000–3500	Forage should be limited to 35%–40% of the total DM intake. Do not feed to pregnant animals.
3500–4000	Forage should be limited to 25% of the total DM intake. Do not feed to pregnant animals.
> 4000	Forage is potentially toxic. DO NOT FEED.
Water[b] (mg N L^{-1})	
< 20	Generally considered safe.
20–40	Caution: Consider additive effect of NO_3-N in feed.
40–200	Greater caution especially if feed contains > 1000 mg NO_3-N
> 200	Acute toxicity and some death losses in swine and ruminants.

[a]Forage information from Holland and Kezar, 1990.
[b]Water information from Cash et al., 2002.

include methemoglobinemia, abortion, and vasodilation leading to cardiovascular collapse (Singer, 1972).

Intensive applications of N fertilizer to silage crops often result in appreciable amounts of NO_3^- in the herbage. During ensiling, the NO_3^- is completely or partially degraded (Spoelstra, 1985). End products are ammonia and nitrous oxide, with nitrite and nitric oxide occurring as intermediates. Suspicious crops should be checked for NO_3^- and NO_2^- before feeding.

Toxicity

Silofiller disease is an illness of farm workers caused by inhalation of nitric and nitrous oxides from fermenting forages containing high N concentrations (Wright and Davison, 1964). These gases are heavier than air and accumulate just above the silage in upright silos. Good air ventilation will reduce the health hazard of these noxious gases.

The most common effect of NO_3^- poisoning is the formation of methemoglobin that occurs when NO_2^- oxidizes the ferrous iron of blood hemoglobin to ferric iron (Deeb and Sloan, 1975). This produces a chocolate brown methemoglobin that cannot release O_2 to body tissue. As the toxicity intensifies, the brownish-colored blood casts a brownish discoloration to the nonpigmented areas of skin and the mucous membranes of the nose, mouth, and vulva. Clinical signs progress with staggering, rapid pulse, frequent urination, and labored breathing, followed by collapse, coma, and death. Sublethal toxicity may be evidenced by abortion of pregnant females. Animals suffering from excess NO_3^- intake may be given drenches of methylene blue, which can turn methemoglobin back into normal hemoglobin. Affected animals should be given an alternative source of forage.

Causes

The rate and degree of NO_3^- reduction in the rumen depend on the microflora present and the amount of energy available for continued reduction of NO_3^- to NO_2^- to NH_3^+ and then amino nitrogen forms. This interaction of available energy and NO_3^- reduction results in mixed responses (Table 45.4). Sheep, receiving a low-energy diet, have been poisoned by as little as 500 mg N kg^{-1} DM as NO_3^-, whereas with high-energy diets, 8000 mg N kg^{-1} DM as NO_3^- had no effect (Singer, 1972). Other data show that 2000 mg N kg^{-1} DM as NO_3^- in forage was the threshold limit for cattle (Bush et al., 1979), whereas no problem occurred with feeding forage containing 4600 mg N kg^{-1} DM as NO_3^- (Davison et al., 1964). A level of 4600 mg N kg^{-1} DM as NO_3^- was recommended as a safe level.

Suspect forages should be tested for NO_3^- levels. Be aware that these test levels may be reported as nitrate (NO_3^-) or as nitrate nitrogen (N) on an elemental N basis. Thus a value of 4400 NO_3^- ppm (nitrate) is equivalent to a value of 1000 ppm NO_3^--N (nitrate nitrogen). (Metric units are used here, whereas lab results may be shown in parts per million, or ppm). The milligrams per kilogram (mg kg^{-1}) units are equivalent to parts per million.

Although risky, feeding additional forage low in NO_3^- will dilute the NO_3^- intake. Energy supplements will help in the complete reduction of inorganic N.

No methemoglobin, therefore no nitrate toxicosis, was produced in horses when feeding oat hay containing 3650 mg NO_3^- N kg^{-1} DM (Les Burwash, Alberta Horse Improvement Program, personal communication, 23 April 2004). Some Pacific Rim hay brokers are calling for hay to contain less than 1000 ppm NO_3^- N to allow a safety margin when mixed with local hays containing high NO_3^-. There is a diurnal cycling of nitrates in plants, with higher concentrations in the morning and lower in the afternoon (Fisher et al., 2002). Thus afternoon cutting will reduce nitrate concentrations in the hay and retain more sugar than if cut in the morning.

Forage Management

Sudangrass, sorghums, corn, and small grains are often indicted in NO_3^- poisoning. These crops are often heavily fertilized with N and when subject to drought, frost, or other stress may accumulate large concentrations of NO_3^-. Perennial grasses generally are less of a problem because they usually receive lower levels of N fertilizer and have greater tolerance of drought and frost. Legumes fix their own N into reduced forms and generally do not contribute to NO_3^- poisoning. However, alfalfa grown under low or high temperature or water stress may contain in excess of 1000 mg N kg^{-1} DM as nitrate.

Diurnal cycling of NO_3^- has recently been noted from anecdotal information in which a forage rape (brassica hybrid) pasture receiving large amounts of manure was toxic to grazing swine in the morning but not toxic in the afternoon (Herb Simon, Glenn Allen, Alaska, personal communication, November 5, 2003). Similar trends have been noted by Fisher et al. (2002). The NO_3^- supply contributes to the formation of N products in the presence of soluble sugars produced by photosynthesis. Concentrations of these sugars are minimal in the morning, allowing the accumulation of NO_3^- in the forage. The reverse is true in the afternoon.

Mineral Elements: Deficiency, Toxicity, and Interaction

Copper, Molybdenum, Sulfur and Interactions

Copper (Cu) deficiency significantly affects ruminant livestock production in large areas of North America (Gooneratne et al., 1989) and elsewhere (Grace, 1983), often in areas where soils are naturally high in molybdenum (Mo) and sulfur (S) (Kubota and Allaway, 1972). In ruminant nutrition, the two-way and three-way interactions between these three elements are unique in their complex effects on animal health.

Sheep consuming a complete diet, low in S and Mo and with modest Cu (12–20 mg kg^{-1} DM), can succumb to Cu toxicity. Sheep grazing another pasture of similar Cu concentration, but high in Mo and S, will produce Cu-deficient lambs showing clinical signs of swayback disease (Suttle, 1991). Copper-deficient cattle and sheep appear unthrifty and exhibit poor growth and reproduction. Copper deficiency reduces the level of melanin pigments in hair and wool so that normally dark-colored fibers will be white or gray (Grace, 1983; Grace and Clark, 1991). Low dietary Cu levels may limit effectiveness of the immune system in animals.

Forage plants growing on soil or peat high in Mo will produce a scouring disease known as molybdenosis. In the presence of S, high intake of Mo can induce a Cu deficiency due to formation of insoluble Cu-Mo-S complexes in the digestive tract that reduce the absorption of Cu. Several pathways exist by which two-way and three-way interactions of Cu, Mo, and S mediate their effect on ruminants (Suttle, 1991). Most clinical signs attributed to the three-way interaction are the same as those produced by simple Cu deficiency and probably arise from impaired Cu metabolism. The tolerable risk threshold of Cu:Mo depends on Mo concentration—declining from 5:1 to 2:1 as pasture Mo concentrations increase from 2–10 mg Mo kg^{-1} DM. Risk assessment has been only partially successful, because the interactions are not yet fully understood (Suttle, 1991). Clinical signs in cattle grazing high Mo were recently summarized (Majak et al., 2004b).

Cattle are more sensitive than sheep to molybdenosis; however, sheep are more susceptible to Cu toxicity (Suttle, 1991). Sheep should not be allowed to graze pastures that recently received poultry or swine manure, especially if Cu salts are fed to poultry or swine to control worms or used in foot baths to control foot problems in dairy cattle. The practice of using $CuSO_4$ or $ZnSO_4$ in foot baths in dairies is also leading to increased Cu and Zn in waste products and recipient pasture and forage lands.

Copper-depleted animals appear to respond equally well to dietary Cu supplements, oral Cu boluses or pellets, and Cu injections. Copper fertilization of Cu-deficient pastures should be done carefully because the range between plant sufficiency and plant toxicity is quite small.

Selenium Deficiency and Toxicity

Herbage–Se concentrations are marginal to severely deficient for herbivores in many areas of the world. These areas include the Pacific Northwest and the eastern one-third of the United States (Kubota and Allaway, 1972; Mayland et al., 1989). Herbage Se concentrations of 0.03 mg Se kg^{-1} are generally adequate. However, 0.1 mg Se kg^{-1} may be necessary when high S in the herbage reduces Se availability to the animal. Climate conditions and management practices that favor high forage yield may dilute Se concentrations to critical levels in herbage.

Selenium deficiency causes white muscle disease in lambs, calves, and colts. The young may be born dead or

die suddenly within a few days of birth because Se intake by the gestating dam was inadequate. A delayed form of white muscle disease occurs in young animals, whereas a third form is identified as ill-thrift in animals of all ages. Injectable Se, often with vitamin E, or oral supplementation (selenized salt or Se boluses) may meet animal requirements. Selenium fertilization of soils is legal only in New Zealand and Finland.

In many semiarid areas of the world, grasses and forbs contain adequate (0.03–0.1 mg Se kg^{-1} DM) to toxic (>5 mg Se kg^{-1} DM) levels of Se for grazing animal requirements. These areas include desert, prairie, and plains regions (Cretaceous geology) of North America where Se toxicity is observed in grazing animals. Some plants growing in these areas will accumulate 100–1000 mg Se kg^{-1} DM. Animals eating these generally unpalatable plants will likely die. Grasses, small grains, and some legumes growing on the Se-rich Cretaceous geological materials may contain 5–20 mg Se kg^{-1} DM. Some animals eating this herbage may die, but most are likely to develop chronic sclerosis called *alkali disease*, in which there is hair loss and hoof tissues become brittle. In these instances, some animals may develop a tolerance for as much as 25 mg Se kg^{-1} DM.

A second chronic disorder in ruminants called *blind staggers* also occurs in these areas. This disorder, while historically attributed to Se, is likely caused by excess S (Mayland, unpublished data). High sulfate levels in the drinking water and ingested herbage have led to the occurrence of blind staggers (Beke and Hironaka, 1991). Changing to high-quality, low-sulfate water and forage reduces the risk.

Under conditions of marginally available soil Se, increased S reduces the uptake of Se by plants and the bioavailability of dietary Se to animals. However, when high concentrations of Se are present in soils, the addition of S has little effect in reducing Se uptake by plants and subsequent toxicity to animals. Replacing high-Se forage with low-Se forage is the most effective way of countering Se toxicity.

Cobalt, Iodine, Zinc

Cobalt (Co) deficiencies in herbivores have been identified in the southeastern United States, Atlantic seaboard states, and along the Wasatch Front in Utah (Kubota and Allaway, 1972). Cobalt is a metal cofactor in vitamin B_{12}, which is required in processes of energy metabolism in ruminants. The signs of Co deficiency include a transient unthriftiness and anemia leading to severely reduced feed or forage intake and eventual death. Two other conditions attributed to Co deficiency are ovine (sheep) white liver disease and phalaris staggers (Graham, 1991).

Pasture herbage levels of at least 0.11 and 0.08 mg Co kg^{-1} DM will provide adequate Co for sheep and cattle, respectively, but the mechanism by which oral Co supplementation prevents staggers is not understood. Cobalt injections or oral supplements can be given to animals. Pastures may also be fertilized with cobalt sulfate. Manganese and Fe in feed are antagonists to Co absorption (Grace, 1983).

Plants do not require iodine (I), and herbage in the northern half of the United States is generally deficient for animal requirements. These deficiencies are noted by the occurrence of goiter in animals (Kubota and Allaway, 1972). The use of iodized salt has easily met I needs of animals on pasture.

Zinc (Zn) concentration in pasture plants ranges from 10–70 mg kg^{-1} DM but is most often in the 10–30 mg kg^{-1} DM range. Cattle grazing forage having 15–20 mg Zn kg^{-1} DM gained weight faster when supplemented with additional Zn (Mayland et al., 1980). Blood Zn levels were higher in supplemented than in control animals, but the difference was too small to be a useful diagnostic tool. More information is needed on Zn requirements and diagnostic tests.

Fluorosis and Silicosis

Plants do not require fluorine (F), but herbage generally contains 1–2 mg kg^{-1} DM, which is adequate for bone and tooth development in animals. At higher levels, the development of fluorosis is influenced by the age, species, dietary form, and length of exposure. Fetuses and young animals are most susceptible to excess F. Dietary concentrations in excess of 5 mg F kg^{-1} DM result in mottling of tooth enamel or even structural weaknesses; otherwise, long-term intakes of 30 mg F kg^{-1} d^{-1} may be tolerated by ruminants before bone abnormalities appear (Underwood, 1977). In areas of endemic fluorosis, plants may be contaminated by naturally fluoridated dust from rock phosphate or other smelters. During manufacture of superphosphate and di-calcium phosphate, 25%–50% of the original F is lost. Excess F may also be absorbed by plants that are sprinkler irrigated with thermal groundwater. Rock phosphate supplement and naturally fluoridated drinking water are the primary dietary sources of excess F.

Grasses contain more silicon (Si) than do legumes and account for the large amount of Si ingested by grazing animals. Silicon may be needed in trace amounts by animals. While not required by herbage plants, it is known to increase disease and insect resistance in many horticultural plants. Silicon adversely affects forage quality and may affect animal performance and selectivity of plants. Silicon serves as a varnish on the cell walls, complexes microelements that reduce their availability to rumen flora, and inhibits the activity of cellulases and other digestive enzymes (Shewmaker et al., 1989). The net effect of forage Si is to reduce DM digestibility by three percentage units for each 10 g kg^{-1} DM Si present (Van Soest and Jones, 1968).

Silicon is also responsible for urolithiasis (urinary calculi or range water belly) in steers. Incidences of water belly are associated with reduced water intake and urine volume and only weakly related to herbage Si. Steers are more sensitive because castration often reduces internal diameter of the ureter. Management strategies in high-Si areas include stocking only heifers and providing adequate drinking water. If feasible, the Ca:P ratio in the diet should be reduced and urine acidified by supplementing animals with ammonium chloride NH_4Cl (Stewart et al., 1991).

Soil Ingestion

Most grazing animals consume soil present as mud or dust contamination on herbage. Nevertheless, animals may actively eat soil for unknown reasons. Ingested soil may serve as a source of minerals. In addition, soil may contain residual chemicals applied to pasture or derived from atmospheric fallout. Some soil particles are harder than tooth enamel and will cause excessive abrasion and premature loss of teeth. Ingested soil, as a possible contaminant, must also be considered in experimental pasture studies (Mayland et al., 1977).

Natural Toxicants in Forages

Plants are protected against herbivores by such physical defenses as leaf hairs, spines, thorns, highly lignified tissue (e.g., wood), and growth habitat (e.g., prostrate form) and by chemical defenses such as a wide array of often complex chemicals that are toxic or poisonous. These chemicals may be synthesized by the plant itself or produced by symbiotic or mutualistic fungi growing with the plant. These are usually secondary compounds (e.g., alkaloids) that do not function directly in cellular metabolism, but apparently are synthesized to serve as the plant's defensive arsenal.

Chemicals synthesized by fungi, known as *mycotoxins,* may be produced by fungi living on or in forage plants. Mycotoxins are responsible for many disorders of grazing animals. For example, an endophytic fungi, *Neotyphodium coenophialum* (Morgan-Jones & Gams) Glenn, Bacon, & Halin (formerly *Acremonium coenophialum* Morgan-Jones & W. Gams), of tall fescue produces ergot alkaloids that cause fescue foot, summer fescue toxicosis, and reproductive disorders, while an endophyte in perennial ryegrass produces lolitrems that cause ryegrass staggers (see Chap. 33). In the United States, total livestock-related losses attributed to the tall fescue endophyte are estimated between $500 million and $1 billion a year (Ball et al., 1993). The economic impact of an array of poisonous plants on livestock production in the western United States is estimated at hundreds of millions of dollars annually (James et al., 1988).

Toxins of plant origin can be classified into several major categories, including alkaloids, glycosides, proteins and amino acids, and phenolics (tannins). Alkaloids are bitter substances containing N in a heterocyclic ring structure. There are hundreds of different alkaloids, which are classified according to the chemical structure of the N-containing ring(s). For example, the pyrrolizidine alkaloids in *Senecio* species have a pyrrolizidine nucleus of 2 five-membered rings, whereas ergot alkaloids have an indole ring structure. Lupines (*Lupinus* L.) contain quinolizidine alkaloids, which are based on 2 six-membered rings. Glycosides are composed of a carbohydrate (sugar) portion linked to a noncarbohydrate group (aglycone) by an ether bond. Examples are cyanogenic glycosides, glucosinolates, saponins, and coumarin glycosides. Their toxicity is associated with the aglycone, such as cyanide in cyanogenic glycosides. Glycosides are hydrolyzed by enzymatic action, releasing the aglycone, often when tissues are damaged by wilting, freezing, mastication, or trampling. A good example of this is the production of toxic cyanide when forage sorghums such as sudangrass are frosted. The breakdown of cell structure releases the glycoside from storage vacuoles, allowing it to be hydrolyzed by enzymes in the cytosol, releasing free cyanide.

Many toxic amino acids occur in plants. One of the best known is mimosine, a toxic amino acid in the tropical forage legume, leucaena (Mimosaceae). Others include lathyrogenic amino acids in *Lathyrus* L., indospicine in hairy indigo, and the brassica anemia factor, which is caused by S-methylcysteine sulfoxide, a metabolic product of forage brassicas.

Phenolic compounds, including condensed and hydrolyzable tannins, are substances containing aromatic rings with one or more hydroxyl groups. The hydroxyl groups are chemically reactive and can react with functional groups of proteins to form indigestible complexes. The tannin–protein complexes are astringent and reduce feed intake (Min et al., 2003). All plants contain phenolic compounds. In some cases, their type or concentration may cause negative animal responses. These include reduced feed intake and protein digestibility of birdsfoot trefoil and sericea lespedeza. Oak (*Quercus* spp.) poisoning is caused by tannins in oak browse. Many tree legumes used in tropical agroforestry can contain sufficient levels of tannins to impair animal performance.

Toxins and Animal Disorders Associated with Forage Legumes

Phytoestrogens occur in grass and forage legumes such as *Phalaris* spp., alfalfa, red clover, and subterranean clover. Phytoestrogens reduce sheep fertility and cause various abnormalities of genitalia. Plant breeders have developed low-estrogen cultivars of subterranean clover, greatly reducing animal losses.

Toxins associated with specific forage legume species will be briefly described. Further detail is provided by Cheeke (1988).

Red Clover

When infected with the black patch fungus (*Rhizoctonia leguminicola* Gough & E.S. Elliot), red clover hay may contain the indolizidine alkaloid, slaframine. Slaframine is a cholinergic agent that causes excessive salivation (clover slobbers), eye discharge, bloat, frequent urination, and watery diarrhea. These effects are due to stimulation of the autonomic nervous system. The fungal infection and potential to cause toxicity develop most rapidly in periods of high humidity. Prompt removal of the toxic forage from livestock generally alleviates all signs of intoxication.

White Clover

This legume may contain cyanogenic glycosides that may confer some resistance to slugs and other pests. Cyanogens in white clover are below toxic levels for livestock, but they may reduce DM intake during midsummer.

Alsike Clover

Poisoning from alsike clover has been reported in Canada and the northern United States, especially with horses. Though not proven, circumstantial evidence strongly suggests the poisoning is caused by clover (Nation, 1991). Toxicity signs include photosensitization, neurological effects such as depression and stupor, and liver damage. In some cases, the liver is extremely enlarged, whereas in others it is shrunken and fibrotic.

Sweetclover

Sweetclover causes significant animal health problems in North America. It contains coumarin glycosides, which are converted by mold growth to dicoumarol. Dicoumarol is an inhibitor of vitamin K metabolism in animals, thus causing an induced vitamin K deficiency. Sweetclover poisoning causes a pronounced susceptibility to prolonged bleeding and hemorrhaging, due to the essential role of vitamin K in blood clotting. Wet, humid weather that favors mold growth during curing of sweetclover hay increases the likelihood of poisoning. Cattle are the main livestock affected.

Moldy sweetclover hay should not be fed to animals or should be used with caution. Ammoniation of stacked hay with anhydrous ammonia reduces dicoumarol levels. Animals with signs of sweetclover poisoning are treated with injections of vitamin K. Low-coumarin cultivars of sweetclover have been developed and should be used in areas where sweetclover poisoning is a problem. Coumarin has a vanilla-like odor, and is responsible for the characteristic smell of sweetclover.

Other Forages

Additional forage legumes contain various toxins. As mentioned above, birdsfoot trefoil and lespedeza contain tannins. Crownvetch contains glycosides of 3-nitropropionic acid, which are metabolized in ruminants to yield NO_2^-. Concentrations are rarely sufficient to cause poisoning, but the glycosides contribute to reduced intake of crownvetch. Cicer milkvetch, a minor forage legume in the northern United States, has caused photosensitization in cattle and sheep (Marten et al., 1987; 1990).

Common Vetch

The seeds of common and hairy vetch contain toxic lathyrogenic amino acids, which cause damage to the nervous system, with signs such as convulsions and paralysis. This occurs primarily in nonruminants that consume seeds as a contaminant of grain. Poisoning of ruminants consuming hairy vetch forage has been reported in the United States (Kerr and Edwards, 1982) and South Africa (Kellerman et al., 1988). Signs include severe dermatitis, skin edema, conjunctivitis, corneal ulcers, and diarrhea. About 50% of affected animals die. The toxic agent in hairy vetch has not been identified.

Lathyrus spp.

Many plants in this genus contain toxic amino acids that cause neurological problems and skeletal defects known as lathyrism. Flatpea, a forage crop for degraded soils such as reclaimed strip-mined areas, is nearly free of toxicity (Foster, 1990), but Foster noted that "the question of flatpea toxicity must be answered conclusively before this plant can be recommended for use by livestock producers." For example, sheep fed flatpea hay showed typical signs of neurolathyrism (Rasmussen et al., 1993).

Lupinus spp.

Plants in the genus *Lupinus* contain a variety of alkaloids of the quinolizidine class. The sweet lupines such as *L. albus* and *L. angustifolius* contain low levels of various alkaloids (e.g., cytisine, sparteine, lupinine, lupanine). These alkaloids cause feed refusal and neurological effects. Sheep are frequently poisoned by wild lupines on rangelands, because they avidly consume the seedpods. On rangelands in western North America, there are many species of wild lupines that are toxic to livestock. Some species (e.g., silky lupine, tail cup lupine, spurred lupine) contain anagyrine, an alkaloid that is teratogenic in cattle. It causes crooked calf disease if consumed by pregnant cows during days 40–70 of gestation. Severe skeletal deformations in the fetuses may occur. This alkaloid does not occur in genetically improved *Lupinus* spp. In Australia, sweet lupines (low alkaloid) are extensively grown as a grain crop; sheep are grazed on the lupine stubble after harvest. Often the stems of lupines are infected with *Phomopsis leptostromiformis* (Köhn) Bubak, a fungus that produces toxic phomopsins. These mycotoxins cause liver damage, including fatty liver and necrosis, eventually leading to liver failure and death. This condition is referred to as lupinosis.

Leucaena

Leucaena contains a toxic amino acid, mimosine. In the rumen, mimosine is converted to various metabolites, including 3,4-dihydroxypyridine (DHP). Both mimosine and DHP are toxic to ruminants, causing dermatitis, hair loss, and poor growth (mimosine), and goitrogenic (thyroid-inhibitory) effects. Australian researchers (Jones and Megarrity, 1986) learned that Hawaiian ruminants, adapted to a leucaena diet, had mimosine-degrading rumen bacteria that eliminated the toxicity. These bacteria have now been introduced into cattle in Australia, allowing leucaena to be used as a productive source of high-protein forage (Quirk et al., 1988). Hammond et al. (1989) in Florida also reported detoxification of mimosine by use of natural or introduced rumen microbes.

Other Tropical Legumes

Many legume plants in this group contain toxic factors, probably to act as a grazing deterrent or for pest resistance. Many *Indigofera* spp. contain the toxic amino acid indospicine (Aylward et al., 1987). The jackbean contains canavanine, an amino acid analog of arginine (Cheeke, 1998). Generally, the grazing diet contains other species that dilute the effects of the toxins.

Toxins and Animal Disorders Associated with Grasses

In contrast with other herbaceous plants, grasses are generally not well-defended chemically. Most grasses have coevolved with grazing animals and by growth habit survive frequent defoliation. Hence, there are few intrinsic toxins in common forage grasses. More frequent are mycotoxins produced by fungi living in or on grasses. Fungi living within plant tissues or tissue spaces and showing no external signs are called *endophytes*. Many livestock syndromes are attributed to endophyte toxins. Examples of toxins intrinsically present in grasses without an associated fungus are the alkaloids of *Phalaris* spp., cyanogens in forage sorghums (e.g., sudangrass), and oxalates in many tropical grasses. These have been reviewed by Cheeke (2005).

Phalaris Poisoning

A neural disorder (phalaris staggers) and a sudden death syndrome can occur in cattle and sheep grazing or consuming hay of *Phalaris* spp. (Nicholson et al., 1989; East and Higgins, 1988; Simpson et al., 1969; Lean et al., 1989). Phalaris staggers is characterized by convulsions and other neurological signs due to brain damage, culminating in death (Bourke et al., 1988). The syndrome is caused by tryptamine alkaloids believed to inhibit serotonin receptors in specific brain and spinal cord nuclei (Bourke et al., 1990). These tryptamine alkaloids are also responsible for the low palatability of the grass and poor performance of animals on reed canarygrass pastures (Marten et al., 1976). As many as four different chemicals, including a cardio-respiratory toxin, thiaminase, and amine cosubstrate, cyanogenic compounds, and NO_3^- compounds, have been implicated (Bourke and Carrigan, 1992). Cultivars of reed canarygrass, bred for low alkaloid concentrations, give improved animal productivity (Marten et al., 1981; Wittenberg et al., 1992).

Hydrocyanic Acid Poisoning

Forage sorghums such as sudangrass contain cyanogenic glycosides from which free cyanide can be released by enzymatic action. Damage to the plant from wilting, trampling, frost, drought stress, and so on, results in the breakdown of the cellular structure, exposing the glycosides to the hydrolyzing enzymes and formation of free cyanide. Cyanide inhibits the enzyme cytochrome oxidase that is needed for oxidative respiration in the animal. The risks of high concentrations of glycosides or cyanide in the plant are increased with N fertilization, immaturity, and frost damage (Wheeler et al., 1990).

Signs of poisoning include labored breathing, excitement, gasping, convulsions, paralysis, and death. The likelihood of acute cyanide poisoning may be greater when feeding sorghum hay than when grazing fresh plants because of the more rapid DM intake. Ground and pelleted sorghum hay may be especially toxic because of the rapid rate of intake and cyanide release (Wheeler and Mulcahy, 1989). Ensiling markedly reduces the cyanide risk.

Oxalate Poisoning

Many tropical grasses contain high levels of oxalate, which when ingested by ruminants, complexes dietary Ca and forms insoluble Ca oxalate. This leads to disturbances in Ca and P metabolism involving excessive mobilization of bone mineral. The demineralized bones become fibrotic and misshapen, causing lameness and "bighead" in horses. Ruminants are less affected, but prolonged grazing by cattle and sheep of some tropical grass species can result in severe hypocalcemia, that is, Ca deposits in the kidneys and kidney failure. Tropical grasses that have high oxalate levels include *Setaria* spp., *Brachiaria* spp., buffelgrass, 'Pangola' digitgrass, and kikuyugrass. Providing mineral supplements high in Ca to grazing animals overcomes the adverse effect of oxalates in grasses.

Facial Eczema

Facial eczema of grazing ruminants is a classic example of secondary or hepatogenous photosensitization due to liver damage. Facial eczema is a major problem of sheep and cattle on perennial ryegrass pastures in New Zealand and has been reported sporadically in other countries. The fungus *Pithomyces chartarum* (Berk. & M.A. Curtis) M.B. Ellis grows on the dead litter in ryegrass pastures and produces large numbers of spores. The spores contain

a hepatotoxin, sporidesmin, which is only slowly broken down in the liver. Spores consumed during grazing lead to sporidesmin-induced liver damage. The damaged liver is unable to metabolize phylloerythrin, a metabolite of chlorophyll breakdown, which then accumulates in the blood. Phylloerythrin is a photodynamic agent that reacts with sunlight, causing severe dermatitis of the face, udder, and other exposed areas. There are species differences in susceptibility to sporidesmin: for example, goats are much more resistant to facial eczema than sheep, probably because of a faster rate of sporidesmin detoxification in the liver (Smith and Embling, 1991).

Mycotoxicosis

Seedheads of many grasses are susceptible to infection with *Claviceps purpurea* (FR:FR.) Tul and other *Claviceps* spp. that form ergot alkaloids. In the United States, dallisgrass poisoning is the major *Claviceps*-caused ergotism. Ergot alkaloids cause vasoconstriction and reduced blood supply to the extremities, resulting in sloughing of ear tips, tail, and hooves. There are also neurological effects, including hyperexcitability, incoordination, and convulsions. Ergotism can be avoided by preventing seed set in grasses.

Fescue Toxicosis

Tall fescue cultivars (older cultivars and most turf types) are likely infected with the endophytic fungus *Neotyphodium coenophialum*. This fungus produces an ergot alkaloid called ergovaline that conveys tolerance to grazing and other stresses but is responsible for reduced animal performance (Porter and Thompson, 1992) and three types of livestock disorders when forage or seed is consumed. These disorders include fescue foot, summer fescue toxicosis, and fat necrosis. These occur because of the inhibition of prolactin secretion by the pituitary gland. New forage cultivars are being developed that contain an endophytic fungus that provides acceptable tolerance to grazing and high temperature to tall fescue, but is not toxic to livestock (Nihsen et al., 2004; Chap. 28).

Ryegrass Staggers

Besides facial eczema (described above), two other major syndromes are perennial ryegrass staggers and annual ryegrass toxicity. Perennial ryegrass staggers is caused by compounds called tremorgens. Affected animals exhibit various degrees of incoordination and other neurological signs (head shaking, stumbling and collapse, severe muscle spasms), particularly when disturbed or forced to run. Even in severe cases, there are no pathological signs in nervous tissue, and upon a change of feed, affected animals usually spontaneously recover. The growth rate of the animal is also reduced (Fletcher and Barrell, 1984). In Australia and New Zealand, ryegrass staggers occurs in sheep, cattle, horses, and deer. It has been reported in sheep and cattle in California (Galey et al., 1991). It also occurs in sheep grazing winter forage and stubble residue of endophyte-enhanced turf-type ryegrasses in Oregon.

The main causative agents of ryegrass staggers are a group of potent tremorgens called *lolitrems*, the most important of which is lolitrem B (Gallagher et al., 1984). Lolitrem B is a potent inhibitor of neurotransmitters in the brain. The lolitrems are produced by an endophytic fungus, *Neotyphodium* (formerly *Acremonium*) *lolii*, which is often present in perennial ryegrass. Turf cultivars of both tall fescue and perennial ryegrass are often deliberately infected with endophytes, because the endophyte increases plant vigor and stress tolerance, in part by producing ergot alkaloids (*N. coenophialum*) and tremorgens (*N. lolii*) that would be deleterious to livestock.

In Australia and South Africa, annual ryegrass toxicity is a significant disorder of livestock. It has an interesting etiology, involving annual ryegrass, a nematode, and bacteria. Although the neurological signs are superficially similar, annual ryegrass toxicity and ryegrass staggers are totally different disorders. In contrast to the temporary incoordination seen with ryegrass staggers, permanent brain damage occurs with annual ryegrass toxicity. The neurological damage is evidenced by convulsions of increasing severity that terminate in death.

Annual ryegrass toxicity is caused by corynetoxins, which are chemically similar in structure to the tunicamycin antibiotics. Corynetoxins are produced by a *Clavibacter* spp. (formerly designated *Corynebacterium* spp.). This bacterium parasitizes a nematode (*Anguina agrostis*) that infects annual ryegrass. Ryegrass is toxic only when infected with the bacteria-containing nematode *A. agrostis*.

The parasitized nematodes infect the seedling shortly after germination, and the larvae are passively carried up the plant as the plant stem elongates. They invade the florets, producing a nematode gall instead of seed. When consumed by animals, corynetoxins from the bacteria inhibit an enzyme involved in glycoprotein synthesis, leading to defective formation of various blood components of the reticulo-endothelial system. This impairs cardiovascular function and vascular integrity, causing inadequate blood supply to the brain.

Corynetoxins have been identified in other grasses besides annual ryegrass, including *Polypogon* and *Agrostis* spp. (Finnie, 1991; Bourke et al., 1992). Annual ryegrass toxicity can be avoided by not allowing animals to graze mature ryegrass containing seed heads or by clipping pastures to prevent seedhead development. In Australia, these measures are often impractical because of the extensive land areas involved.

Other Grass Toxins

Kikuyugrass is a common tropical forage that is occasionally toxic to livestock (Peet et al., 1990). Clinical signs in-

clude depression, drooling, muscle twitching, convulsions, and sham drinking (Newsholme et al., 1983). Rumen motility is lost, and severe damage occurs to the mucosa of the rumen and omasum. In many but not all cases, kikuyugrass poisoning occurs when the pasture is invaded by armyworm (*Spodoptera exempta*). The causative agent has not been identified, and it is not conclusively known if the armyworm has a role in the toxicity.

Photosensitization of grazing animals often occurs with *Panicum* and *Brachiaria* spp. (Bridges et al., 1987; Cornick et al., 1988; Graydon et al., 1991). The condition is usually accompanied by accumulation of salt crystals in and around the bile ducts in the liver. Miles et al. (1991) have shown that the crystals are formed from metabolites of saponins, which are common constituents of *Panicum* spp. The crystals impair biliary excretion, leading to elevated phylloerythrin levels in the blood, causing secondary (hepatic) photosensitization as previously described.

Toxins in Other Forages

Most common forages are legumes or grasses. Other forages include buckwheat, spineless cactus, saltbush, and forage brassicas such as kale, rape, cabbage, and turnips. *Brassica* spp. contain glucosinolates (goitrogens) and the "brassica anemia" factor. Glucosinolates are primarily of concern in brassicas grown for seed, such as rapeseed and mustard. Forage brassicas contain a toxic amino acid, S-methylcysteine sulfoxide (SMCSO), the brassica anemia factor. Ruminants often develop severe hemolytic anemia on kale or rape pastures, and growth is markedly reduced. The SMCSO is metabolized in the rumen to dimethyl disulfide, an oxidant that destroys the red blood cell membrane. This leads to anemia, hemoglobinuria (red urine), liver and kidney damage, and frequent mortality. Because the SMCSO content of brassicas increases with plant maturity, it is not advisable to graze mature brassica or use these crops for late winter pasture in temperate areas. Avoiding the use of S and high N in fertilizer reduces SMCSO levels and toxicity. Brassica anemia is reviewed by Cheeke (1998) and Smith (1980).

Buckwheat is a fast-growing broad-leaved annual sometimes grown as a temporary pasture. Buckwheat seed and forage contain a photosensitizing agent, fagopyrin. This compound is absorbed into the blood; at the surface of the skin it reacts with sunlight, causing photodermatitis (photosensitization). Light-skinned animals are particularly susceptible.

Other Health Problems

Acute bovine pulmonary emphysema may occur when cattle are moved from sparse dry pasture to lush grass, legume, or brassica pasture. The abrupt change in pasture type results in a disturbance in the rumen microbes, resulting in excessive conversion of the amino acid tryptophan to a metabolite, 3-methyl indole (3-MI). The 3-MI is absorbed and is toxic to the lung tissue, causing pulmonary edema and emphysema (Carlson and Breeze, 1984). The condition, also called summer pneumonia, may be fatal. Provision of supplementary feed before moving cattle on to lush meadows is helpful in preventing the disorder.

Blister beetles (*Epicauta* spp.) contain cantharidin, a toxin that causes irritation of the lining in the digestive tract, and at high enough doses is lethal to horses (Helman and Edwards, 1997). Alfalfa (especially that grown east of 100th meridian in the United States and Canada) is often associated with blister beetle infestation. The toxicity to horses depends on insect species and sex, the horse's size and condition, and the number of insects ingested with the hay. Intake of 1 mg cantharidin per kilogram body weight is considered the lethal threshold. Concentrations of cantharidin are highest in male beetles in the 'vittata' group, or the "stripped" beetle group. Ingestion of 75 stripped male beetles could be fatal for a 375-kg horse.

Animal Metabolism of Plant Toxins

Plants and animals have coevolved. As plants developed the enzymatic means to synthesize defensive chemicals, animals evolved detoxification mechanisms to overcome the plant defenses. The most fundamental of these are the drug-metabolizing enzyme systems of the liver, such as the cytochrome P450 system. This enzyme system (also called the mixed function oxidase system) oxidizes hydrophobic, nonpolar substances such as plant toxins by introducing a hydroxyl (−OH) group to change the chemical. The hydroxyl group increases the water solubility of the compound, mainly by providing a site to react (conjugate) with other water-soluble compounds such as amino acids (e.g., glycine), peptides (glutathione), and sugars (e.g., glucuronic acid). These conjugated compounds are much less toxic and can be excreted in the urine or bile of animals consuming *Panicum* spp. Differences in susceptibility among livestock species to plant toxins are due mostly to differences in liver metabolism. In contrast, some toxins are bioactivated, or made more toxic, because of liver metabolism (e.g., aflatoxin, slaframine). The relative rates at which the active metabolites are formed and detoxified determine the extent of cellular damage.

Browsing animals such as sheep and goats are generally more resistant to plant toxins because they have been exposed to greater concentrations of plant toxins during their evolution than have grazing animals such as horses and cattle. Sheep and goats find plants containing toxins more palatable than do cattle and horses (Cheeke, 2005). Sometimes, as with pyrrolizidine alkaloids in *Senecio* spp., the resistance of sheep and goats is due to a lower rate of bioactivation of the compounds to the toxic metabolites in the liver (Cheeke, 1988).

Browsing animals are also better able than grazers to resist adverse effects of dietary tannins and phenolic compounds, which are common constituents of shrubs, trees, and other browse plants. For example, deer, which are browsers, have salivary tannin-binding proteins, absent in sheep and cattle, which counteract the astringent effects of tannins (Austin et al., 1989). Mehansho et al. (1987) reviewed the roles of salivary tannin-binding proteins as animal defenses against plant toxins. Resistance to tannin astringency results in tannin-containing plants being more palatable to browsers than to grazers, which lack the tannin-binding proteins.

In ruminants, metabolism of toxins by rumen microbes is an important factor in altering sensitivity to plant toxins. In some cases, for example, cyanogenic glycosides and the brassica anemia factor, the toxicity is increased by rumen microbial fermentation. Sometimes, for example, mimosine or oxalate toxicity, the compounds are detoxified by microbial metabolism. The toxic amino acid mimosine has been of particular interest in this regard. As discussed earlier, the successful use of leucaena as a high-protein forage was not possible in Australia and many other areas until ruminants were dosed with mimosine-degrading bacteria. The effective bacteria are transferred orally as uninoculated animals graze plants covered with slobbers from animals having the effective organism.

References

Austin, P.J., L.A. Suchar, C.T. Robbins, and A.E. Hagerman. 1989. Tannin-binding proteins in saliva of sheep and cattle. J. Chem. Ecol. 15:1335–47.

Aylward, J.H., R.D. Court, K.P. Haydock, R.W. Strickland, and M.P. Hegarty. 1987. *Indigofera* species with agronomic potential in the tropics: Rat toxicity studies. Aust. J. Agric. Res. 38:177–86.

Ball, D.M., J.F. Pedersen, and G.D. Lacefield. 1993. The tall-fescue endophyte. American Scientist 81: 370–9.

Beke, G.J., and R. Hironaka. 1991. Toxicity to beef cattle of sulfur in saline well water: A case study. Sci. Total Environ. 101:281–90.

Berg, B.P., W. Majak, T.A. McAllister, J.W. Hall, D. McCartney, B.E. Coulman, B.P. Goplen, S.N. Acharya, R.M. Tait, and K.-J. Cheng. 2000. Bloat in cattle grazing alfalfa cultivars selected for a low initial rate of digestion: A review. Can. J. Plant Sci. 80: 493–502.

Bourke, C.A., and M.J. Carrigan. 1992. Mechanisms underlying *Phalaris aquatica* "sudden death" syndrome in sheep. Aust. Vet. J. 69:165–7.

Bourke, C.A., M.J. Carrigan, and R.J. Dixon. 1988. Experimental evidence that tryptamine alkaloids do not cause *Phalaris aquatica* sudden death syndrome in sheep. Aust. Vet. J. 65:218–20.

Bourke, C.A., M.J. Carrigan, and R.J. Dixon. 1990. The pathogenesis of the nervous syndrome of *Phalaris aquatica* toxicity in sheep. Aust. Vet. J. 67:356–8.

Bourke, C.A., M.J. Carrigan, and S.C.J. Love. 1992. Flood plain staggers, a tunicaminyluracil toxicosis of cattle in northern New South Wales. Aust. Vet. J. 69:228–9.

Bridges, C.H., B.J. Camp, C.W. Livingston, and E.M. Bailey. 1987. Kleingrass *(Panicum coloratum)* poisoning in sheep. Vet. Pathol. 24:525–31.

Bush, L., J. Boling, and S. Yates. 1979. Animal disorders. pp. 247–92. In R.C. Buckner and L.P. Bush (eds.), Tall fescue. Am. Soc. Agron., Madison, WI.

Carlson, J.R., and R.G. Breeze. 1984. Ruminal metabolism of plant toxins with emphasis on indolic compounds. J. Anim. Sci. 58:1040–9.

Cash, D., D.R. Funston, M. King, and D. Wichman. 2002. Nitrate toxicity of Montana forages. Montana State University Extension Service, MontGuide, MT 200205 AG.

Chamblee, D.S., and M. Collins. 1988. Relationship with other species in a mixture. pp. 439–66. In AA Hanson (ed.), Alfalfa and alfalfa improvement. Am. Soc. Agron., Madison, WI.

Cheeke, P.R. 1988. Toxicity and metabolism of pyrrolizidine alkaloids. J. Anim. Sci. 66:2343–50.

Cheeke, P.R. 1998. Natural toxicants in feeds, forages, and poisonous plants. Prentice Hall, Upper Saddle River, NJ.

Cheeke, P.R. 2005. Applied animal nutrition: Feeds and feeding. Prentice Hall, Upper Saddle River, NJ.

Cherney, J.H., E.A. Mikhailova, and D.J.R. Cherney. 2002. Tetany potential of orchardgrass and tall fescue as influenced by fertilization with dairy manure or commercial fertilizer. J. Plant Nutri. 25:1501–25.

Clark, D.H., H.F. Mayland, and R.C. Lamb. 1987. Mineral analysis of forages with infrared reflectance spectroscopy. Agron. J. 79:485–490.

Cockrem, F.R.M., J.T. McIntosh, and R. McLaren. 1983. Selection for and against susceptibility to bloat in dairy cows: A review. Proc. N Z Soc. Anim. Prod. 43:101–6.

Cornick, J.L., G.K. Carter, and C.H. Bridges. 1988. Kleingrass: Associated hepatotoxicosis in horses. J. Am. Vet. Med. Assn. 193:932–5.

Davison, K.L., W. Hansel, L. Krook, K. McEntee, and M.J. Wright. 1964. Nitrate toxicity in dairy heifers. I. Effects on reproduction, growth, lactation and vitamin A nutrition. J. Dairy Sci. 47:1065–73.

Deeb, B.S., and K.W. Sloan. 1975. Nitrates, nitrites, and health. Illinois Agri. Expt. Sta. Bull. 750.

East, N.E., and R.J. Higgins. 1988. Canary grass (*Phalaris* sp.) toxicosis in sheep in California. J. Am. Vet. Med. Assn. 192:667–9.

Fay, J.P., K-J. Cheng, M.R. Hanna, R.E. Howarth, and J.W. Costerton. 1980. In vitro digestion of bloat-safe

and bloat-causing legumes by rumen microorganisms: Gas and foam production. J. Dairy Sci. 63:1273–81.

Finnie, J.W. 1991. Corynetoxin poisoning in sheep in the southeast of South Australia associated with annual beard grass (*Polypogon monspeliensis*). Aust. Vet. J. 68:370.

Fisher, D.W., H.F. Mayland, and J.C. Burns. 2002. Variation in ruminant preference for alfalfa hays cut at sunup and sundown. Crop Sci. 42:231–237.

Fletcher, L.R., and G.K. Barrell. 1984. Reduced liveweight gains and serum prolactin levels in hoggets grazing ryegrasses containing *Lolium* endophyte. N Z Vet. J. 32:139–40.

Foster, J.G. 1990. Flatpea (*Lathyrus sylvestris*): A new forage species? A comprehensive review. Adv. Agron. 43:241–313.

Galey, F.D., M.L. Tracy, A.L. Craigmill, B.C. Barr, G. Markegard, R. Peterson, and M. O'Connor. 1991. Staggers induced by consumption of perennial ryegrass in cattle and sheep from northern California. J. Am. Vet. Med. Assn. 199:466–70.

Gallagher, R.T., A.D. Hawkes, P.S. Steyn, and R. Vleggaar. 1984. Tremorgenic neurotoxins from perennial ryegrass causing ryegrass staggers disorder of livestock: Structure elucidation of lolitrem B. J. Chem. Soc. Chem. Commun. 614–16.

Goff, J.P. 2000. Pathophysiology of Ca and phosphorus disorders. Vet. Clin. North Am. Food Anim. Pract. 16:319–37.

Gooneratne, S.R., W.T. Buckley, and D.A. Christensen. 1989. Review of copper deficiency and metabolism in ruminants. Can. J. Anim. Sci. 69:819–45.

Gough, L.P., H.T. Shacklette, and A.A. Case. 1979. Element concentrations toxic to plants, animals, and man. Geol. Survey Bull. 1466. US Govt. Printing Office, Washington, DC.

Grace, N.D. 1983. The mineral requirements of grazing ruminants. N Z Soc. Anim. Prod., Occasional Publ. No. 9. Palmerston North, NZ.

Grace, N.D., and R.G. Clark. 1991. Trace element requirements, diagnosis and prevention of deficiencies in sheep and cattle. pp. 321–46. Physiological aspects of digestion and metabolism in ruminants: Proc. 7th Int. Symp. Ruminant Physiol., Academic Press, Inc.

Graham, T.W. 1991. Trace element deficiencies in cattle. Vet. Clin. North Am. Food Animal Pract. 7:153–215.

Graydon, R.J., H. Hamid, P. Zahari, and C. Gardiner. 1991. Photosensitization and crystal-associated cholangiohepatopathy in sheep grazing *Brachiaria decumbens*. Aust. Vet. J. 68:234–6.

Greene, L.W., J.F. Baker, and P.F. Hardt. 1989. Use of animal breeds and breeding to overcome the incidence of grass tetany: A review. J. Anim. Sci. 67:3463–69.

Grunes, D.L., and R.M. Welch. 1989. Plant contents of magnesium, calcium, and potassium in relation to ruminant nutrition. J. Anim. Sci. 67:3486–94.

Hall, J.W., and W. Majak. 1991. Relationship of weather and plant factors to alfalfa bloat in autumn. Can. J. Anim. Sci. 71:861–6.

Hall, J.W., and W. Majak. 1995. Effect of time of grazing or cutting and feeding on the incidence of alfalfa bloat in cattle. Can. J. Anim. Sci. 75:271–3.

Hall, J.W., W. Majak, R.J. Williams, and R.E. Howarth. 1984. Effect of daily weather conditions on bloat in cattle fed fresh alfalfa. Can. J. Anim. Sci. 64:943–50.

Hall, J.W., I. Walker, and W. Majak. 1994. Evaluation of two supplements for the prevention of alfalfa bloat. Can. Vet. J. 35: 702–4.

Hall, J.W., W. Majak, T.A. McAllister, and J.K. Merrill. 2001. Efficacy of Rumensin controlled release capsule (CRC) for the control of alfalfa bloat in cattle. Can. J. Anim. Sci. 81:281–3.

Hammond, A.C., M.J. Allison, M.J. Williams, G.M. Prine, and D.B. Bates. 1989. Prevention of leucaena toxicosis of cattle in Florida by ruminal inoculation with 3-hydroxy-4-(1H)-pyridone-degrading bacteria. Am. J. Vet. Res. 50:2176–80.

Helman, R.G., and W.C. Edwards. 1997. Clinical features of blister beetle poisoning in equids: 70 cases (1983–1996). J. Am. Vet. Med. Assoc. 211:1018–1021.

Hemingway, R.G. 1999. The effect of changing patterns of fertilizer applications on the major mineral composition of herbage in relation to the requirements of cattle: A 50-year review. Animal Science: British Soc. Anim. Sci. 69:1–18.

Holland, C., and W. Kezar 1990. Pioneer Forage Manual. A nutritional guide. Pioneer Hi-Bred International Inc. Des Moines, IA.

James, L.F., M.H. Ralphs, and D.B. Nielsen. 1988. The ecology and economic impact of poisonous plants on livestock production. Westview Press. Boulder, CO.

Jones, R.J., and R.G. Megarrity. 1986. Successful transfer of DHP-degrading bacteria from Hawaiian goats to Australian ruminants to overcome the toxicity of leucaena. Aust. Vet. J. 63:259–62.

Kemp, A. and M.L. 'tHart. 1957. Grass tetany in grazing milking cows. Neth. J. Agric. Sci. 5:4–17.

Kellerman, T.S., J.A.W. Coetzer, and T.W. Naude. 1988. Plant poisonings and mycotoxicoses of livestock in southern Africa. Oxford University Press, Cape Town.

Kerr, L.A., and W.C. Edwards. 1982. Hairy vetch poisoning in cattle. Vet. Med. Small Anim. Clin. 77:257–61.

Kubota, J., and W.H. Allaway. 1972. Geographic distribution of trace element problems. pp. 525–54. In J.J. Mortvedt, P.M. Giordano, and W.L. Lindsay (eds.), Micronutrients in agriculture. Am. Soc. Agron., Madison, WI.

Lanyon, L.E. 1980. Pennsylvania alfalfa growers program alfalfa mineral relationships. Proc Annual Conf. Penn. Forage and Grasslands Council. Nov. 24–25, pp. 46–52.

Lean, I.J., M. Anderson, M.G. Kerfoot, and G.C. Marten. 1989. Tryptamine alkaloid toxicosis in feedlot sheep. J. Am. Vet. Med. Assn. 195:768–71.

Longland, A.G. and A.J. Cairns, 2000. Laminitis: Fructans and their implications in the etiology of laminitis. URL. http://members.aol.com/wdds1/horsetalk/dh-sci1lam.htm (verified July 6, 2006).

Majak, W., R.E. Howarth, A.C. Fesser, B.P. Goplen, and M.W. Pedersen. 1980. Relationships between ruminant bloat and the composition of alfalfa herbage. II. Saponins. Can. J. Anim. Sci. 60: 699–708.

Majak, W., R.E. Howarth, K-J. Cheng, and J.W. Hall. 1983. Rumen conditions that predispose cattle to pasture bloat. J. Dairy Sci. 66:1683–8.

Majak, W., J.W. Hall, L.M. Rode, and C.M. Kalnin. 1986. Rumen clearance rates in relation to the occurrence of alfalfa bloat in cattle. 1. Passage of water-soluble markers. J. Dairy Sci. 69:1560–7.

Majak, W., R.M. Jordan, and E.A. Ristau. 1990. Performance and adverse response of sheep during grazing of four legumes. Crop Sci. 30:860–6.

Majak, W., J.W. Hall, and W.P. McCaughey. 1995. Pasture management strategies for reducing the risk of legume bloat in cattle. J. Anim. Sci. 73:1493–8.

Majak, W., J.W. Hall, and T.A. McAllister. 2001. Practical measures for reducing risk of alfalfa bloat in cattle. J. Range Manage. 54:490–3.

Majak, W., G.J. Garland, and T.J. Lysyk. 2003a. The effect of herbage mixtures of alfalfa and orchardgrass on the incidence of bloat in cattle. Can. J. Anim. Sci. 83:827–9.

Majak, W., T.A. McAllister, D. McCarney, K. Stanford, and K-J. Cheng. 2003b. Bloat in cattle. Alberta Agric, Food, and Rural Develop. Edmonton, AB. Canada. T6H 5T6.

Majak, W., G.J. Garland, T.J. Lysyk, and M.E. Olson. 2004a. Efficacy of water-soluble feed supplements for the prevention of bloat in cattle. Can. J. Anim. Sci. 84:155–7.

Majak, W., D. Steinke, J. McGillivray, and T. Lysyk. 2004b. Clinical signs in cattle grazing high molybdenum forage. J. Range Manage. 57:269–274.

Majak, W., T.J. Lysyk, G.J. Garland, and M.E. Olson. 2005. Efficacy of Alfasure™ for the prevention and treatment of alfalfa bloat in cattle. Can. J. Anim. Sci. 85:111–113.

Marten, G.C., R.M. Jordan, and A.W. Hovin. 1976. Biological significance of reed canarygrass alkaloids and associated palatability to grazing sheep and cattle. Agron. J. 68:909-14.

Marten, G.C., R.M. Jordan, and A.W. Hovin. 1981. Improved lamb performance associated with breeding for alkaloid reduction in reed canarygrass. Crop Sci. 21:295-8.

Marten, G.C., F.R. Ehle, and E.A. Ristau. 1987. Performance and photosensitization of cattle related to forage quality of four legumes. Crop Sci. 27:138–45.

Marten, G.C., R.M. Jordan, and E.A. Ristau. 1990. Performance and adverse response of sheep during grazing of four legumes. Crop Sci. 30:860-6.

Martens, H., and M. Schweigel. 2000. Pathophysiology of grass tetany and other hypomagnesemias. Implications for clinical management. Vet. Clin. North Am. Food Anim. Pract. 16:339–68.

Mathison, G.W., R. Soofi-Siawash, P.T. Klita, E.K. Okine, and G. Sedgwick. 1999. Degradability of alfalfa saponins in the digestive tract of sheep and their rate of accumulation in rumen fluid. Can. J. Anim. Sci. 79:315–319.

Mayland, H.F. 1988. Grass tetany. pp. 511–23, 530–531. In D.C. Church (ed.), The ruminant animal: Its physiology and nutrition. Prentice-Hall. Englewood Cliffs, NJ.

Mayland, H.F., and D.A. Sleper. 1993. Developing a tall fescue for reduced grass tetany risk. Proc. 1993 Int. Grassl. Congr., Palmerston, NZ.

Mayland, H.F., G.E. Shewmaker, and R.C. Bull. 1977. Soil ingestion by cattle grazing crested wheatgrass. J. Range Manage. 30:264–5.

Mayland, H.F., R.C. Rosenau, and A.R. Florence. 1980. Grazing cow and calf responses to zinc supplementation. J. Anim. Sci. 51:966–74.

Mayland, H.F., L.F. James, K.E. Panter, and J.L. Sonderegger. 1989. Selenium in seleniferous environments. pp. 15–50. In L.W. Jacobs (ed.), Selenium in agriculture and the environment. Special Publ no. 23. Soil Sci. Soc. Am., Madison, WI.

McKenzie, J.S., and G.E. McLean. 1982. The importance of leaf frost resistance to the winter survival of seedling stands of alfalfa. Can. J. Plant Sci. 62:399–405.

McMahon, L.R., W. Majak, T.A. McAllister, J.W. Hall, G.A. Jones, J.D. Popp, and K-J. Cheng. 1999. Effect of sainfoin on in vitro digestion of fresh alfalfa and bloat in steers. Can. J. Anim. Sci. 79:203–12.

Mehansho, H., L.G. Butler, and D.M. Carlson. 1987. Dietary tannins and salivary proline-rich proteins: Interactions, induction, and defense mechanisms. Ann. Rev. Nutr. 7:423 –40.

Miles, C.O., S.C. Munday, P.T. Holland, B.L. Smith, P.P. Embling, and A.L. Wilkins. 1991. Identification of a sapogenin glucuronide in the bile of sheep affected by *Panicum dichotomiflorum* toxicosis. N Z Vet. J. 39:150–152.

Min, B.R., T.N. Barry, G.T. Attwood, and W.C. McNabb. 2003. The effect of condensed tannins on the nutrition and health of ruminants fed fresh temperate forages: A review. Anim. Feed Sci. Tech. 106:3–19.

Moseley, G., and D.H. Baker. 1991. The efficacy of a high magnesium grass cultivar in controlling hypomagnesemia in grazing animals. Grass Forage Sci. 46:375–80.

Nation, P.N. 1991. Hepatic disease in Alberta horses: A retrospective study of "alsike clover poisoning" (1973–1988). Can. Vet. J. 32:602–7.

National Research Council. 1984. Nutrient requirements of beef cattle, 6th ed. National Academy Press, Washington, DC.

National Research Council. 1989. Nutrient requirements of horses, 5th ed. National Academy Press, Washington, DC.

Newsholme, S.J., T.S. Kellerman, G.C.A. Van Der Westhuizen, and J.T. Soley. 1983. Intoxication of cattle on kikuyu grass following army worm (*Spodoptera exempta*) invasion. Onderstepoort J. Vet. Res. 50:157–67.

Nicholson, S., B.M. Olcott, E.A. Usenik, H.W. Casey, C.C. Brown, L.E. Urbatsch, S.E. Turnquist, and S.C. Moore. 1989. Delayed phalaris grass toxicosis in sheep and cattle. J. Am. Vet. Med. Assn. 195:345–6.

Nihsen, M.E., E.L., Piper, C.P. West, R.J. Crawford, T.M. Denard, Z.B. Johnson, C.A. Roberts, D.A. Spiers, and C.F. Rosenkrans. 2004. Growth rate and physiology of steers grazing tall fescue inoculated with novel endophytes. J. Anim. Sci. 82:878–883.

Nocek, J.E. 2001. The link between nutrition, acidosis, laminitis and environment. http://members.aol.com/wdds1/horsetalk/lamin-9.htm.

Peet, R.L., J. Dickson, and M. Hare. 1990. Kikuyu poisoning in goats and sheep. Aust. Vet. J. 67:229–30.

Pollitt, C.C. 2005. Laminitis research at the Australian Equine Laminitis Research Unit. Parts 1 and 2. http://www.uq.edu.au/%7Eapcpolli/downloads/chrispollit_Laminitisresearch_AELRU_part1.pdf (verified July 6, 2006).

Porter, J.K., and F.N. Thompson, Jr. 1992. Effects of fescue toxicosis on reproduction in livestock. J. Anim. Sci. 70:1594–603.

Puls, R. 1994. Mineral levels in animal health: Diagnostic data. 2nd ed. Sherpa International Publisher. Clearbrook, BC. Canada.

Quirk, M.F., J.J. Bushell, R.J. Jones, R.G. Megarrity, and K.L. Butler. 1988. Live-weight gains on leucaena and native grass pastures after dosing cattle with rumen bacteria capable of degrading DHP, a ruminal metabolite from leucaena. J. Agric. Sci. 111:165–70.

Rasmussen, M.A., M.J. Allison, and J.G. Foster. 1993. Flatpea intoxication in sheep and indications of ruminal adaptation. Vet. Human Toxicol. 35:123–7.

Robinson, D.L., L.C. Kappel, and J.A. Boling. 1989. Management practices to overcome the incidence of grass tetany. J. Anim. Sci. 67:3470–84.

Shewmaker, G.E., H.F. Mayland, R.C. Rosenau, and K.H. Asay. 1989. Silicon in C-3 grasses: Effects on forage quality and sheep preference. J. Range Manage. 42:122–127.

Simpson, B.H., R.D. Jolly, and S.H.M. Thomas. 1969. *Phalaris arundinacea* as a cause of deaths and in coordination in sheep. N Z Vet. J. 17:240–4.

Singer, R.H. 1972. The nitrate poisoning complex. Proc. US Anim. Health Assn. 310–322.

Sleper, D.A., K.P. Vogel, K.H. Asay, and H.F. Mayland. 1989. Using plant breeding and genetics to overcome the incidence of grass tetany. J. Anim. Sci. 67: 3456–62.

Smith, B.L., and P.P Embling. 1991. Facial eczema in goats: The toxicity of sporidesmin in goats and its pathology. N Z Vet. J. 39:18–22.

Smith, R.H. 1980. Kale poisoning: The brassica anemia factor. Vet. Rec. 107:12–15.

Spoelstra, S.F. 1985. Nitrate in silage. Grass Forage Sci. 40:1–11.

Stanford, K., Y. Wang, B.P. Berg, W. Majak, D.H. McCartney, V. Baron, and T.A. McAllister. 2001. Effects of alcohol ethoxylate and pluronic detergents on the development of pasture bloat in cattle and sheep. J. Dairy Sci. 74:167–176.

Stewart, P.A. 1983. Modern quantitative acid-base chemistry. Can. J. Physiol. Pharmacol. 61:1444–61.

Stewart, S.R, R.J. Emerick, and R.H. Pritchard. 1991. Effects of dietary ammonium chloride and variations in Ca to phosphorus ratio on silica urolithiasis in sheep. J. Anim. Sci. 69:2225–9.

Suttle, N.F. 1991. The interactions between copper, molybdenum, and sulfphur in ruminant nutrition. Ann. Rev. Nutr. 11:121–40.

Thompson, D.J., B.M. Brooke, G.J. Garland, J.W. Hall, and W. Majak. 2000. Effect of stage of growth of alfalfa on the incidence of bloat in cattle. Can. J. Anim. Sci. 80:725–727.

Underwood, E.J. 1977. Trace elements in human and animal nutrition. 4th ed. Academic Press, New York.

Van Soest, P.J., and L.H.P. Jones. 1968. Effect of silica in forages upon digestibility. J. Dairy Sci. 51:1–5.

Vogel, K.P., B.C. Gabrielsen, J.K. Ward, B.E. Anderson, H.F. Mayland, and R.A. Masters. 1993. Forage quality, mineral constituents, and performance of beef yearling grazing two crested wheatgrasses. Agron. J. 85:584–90.

Westwood, C.T., E. Bramlayand, and I.J. Lean. 2003. Review of the relationship between nutrition and lameness in pasture-fed dairy cattle. N Z Vet. J. 51:208–218.

Wheeler, J.L., and C. Mulcahy. 1989. Consequences for animal production of cyanogenesis in sorghum forage and hay: A review. Tropical Grasslands 23: 193–202.

Wheeler, J.L., C. Mulcahy, J.J Walcott, and G.G. Rapp. 1990. Factors affecting the hydrogen cyanide potential of forage sorghum. Aust. J. Agric. Res. 41:1093–100.

Whitaker, D.A., A.I. Macrae, and E. Burrough. 2004. Disposal and disease rates in British dairy herds between April 1998 and March 2002. Vet. Record 155:43–44, 45–47.

Wittenberg, K.M., G.W. Duynisveld, and H.R. Tosi. 1992. Comparison of alkaloid content and nutritive value for tryptamine- and carboline-free cultivars of reed canarygrass (*Phalaris arundinacea* L.). Can. J. Anim. Sci. 72:903–9.

Wright, M.J., and K.L. Davison. 1964. Nitrate accumulation in crops and nitrate poisoning in animals. Adv. Agron. 16:197–247.