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Review

Is it time to rethink our one-size-fits-all approach to nitrate toxicity thresholds in forages?

Mary Beth Reynolds, and Mary E. Drewnoski[1]

Department of Animal Science, University of Nebraska Lincoln, Lincoln, NE 68583-0908, USA

[1]Corresponding author: mdrewnoski2@unl.edu

Abstract

Annual forages provide a valuable grazing resource for cattle producers; however, annuals are prone to accumulating nitrate and have the potential to cause nitrate toxicity. Although these forages pose a risk of containing high nitrate concentrations, they can be a high-quality feed source. Understanding the factors that affect the potential for toxicity when using these forages is important to help nutritionists and producers make management decisions. This review describes the previous research, current guidelines for nitrate toxicity, and the potential for improvement in our current recommendations. Current extension toxicity guidelines appear to be founded primarily on drenching based studies and overestimate the nitrate toxicity potential of forages. Recommendations need to account for multiple factors that affect the threshold for toxicity. There is evidence that fresh forages have a lower risk of toxicity because of slower release of nitrate into the rumen and a slower rate of dry matter intake. Increased dietary energy and sulfur content reduce the potential for toxicity. Microbial adaptation can reduce the risk and allow use of potentially toxic forages. These factors should influence feeding recommendations. However, there is currently not enough data available to establish new guidelines that account for these main factors. Thus, there is a need for renewed research in this area. The limited number of studies grazing elevated nitrate forages seems to suggest that there is less risk in grazing situations, especially if animals graze selectively. There is a need to develop guidelines for nitrate toxicity and management recommendations when grazing. To accomplish this, there is a need for more studies to evaluate risk of toxicity in grazing situations. These grazing studies need to evaluate the effects of nitrate concentration, forage quality, and grazing management on the potential for nitrate toxicity. While the conservative guidelines that are currently in use reduce risk of nitrate toxicity, they may also cause a significant increase in feed costs for producers.

Key words: forage, grazing, nitrate toxicity

INTRODUCTION

Annual forages provide a valuable grazing resource for cattle producers; however, annuals are prone to accumulating nitrate and toxicity can be a potential challenge. Although these forages pose a risk of containing high nitrate concentrations, they can be a high-quality feed source. Understanding the factors that affect the potential for toxicity when using these forages is important to help nutritionists and producers make management decisions. This review describes the previous research used to develop guidelines for nitrate toxicity, evaluates factors that can impact the potential for toxicity, and identifies gaps in research knowledge of nitrate toxicity. Grazing situations are unique in their potential for nitrate toxicity and thus this "old topic" should be readdressed, for the specific goal of developing guidelines and management recommendations when grazing high nitrate forages. Although multiple reviews have addressed nitrate toxicity (Wright and Davison, 1964; Kemp, 1982; Crowley, 1985; Jones, 1988; Bruning-Fann and Kaneene, 1993; Hibberd et al., 1994; Klasing et al., 2005; Lee and Beauchemin, 2014; Mohini et al., 2017), none have addressed nitrate toxicity in grazing situations.

Overview of the Mechanism of Nitrate Toxicity

Before diving into the current guidelines and how various factors might affect the potential for nitrate toxicity, it is important to understand how dietary nitrate can cause toxicity in ruminants. Dietary nitrate enters the rumen where the microbial population converts nitrate to nitrite, and then ammonia (Hibberd et al., 1994). When the ruminant consumes high amounts of nitrate, the conversion of the nitrite to ammonia typically occurs at a slower rate than the reduction of nitrate to nitrite, leading to a buildup of nitrite in the rumen (Lewis, 1951a). Both nitrate and nitrite are water soluble and easily enter the bloodstream through the rumen (Wang et al., 1961). If nitrite enters the blood, it will convert ferrous hemoglobin to ferric methemoglobin, which cannot carry oxygen (Burrows et al., 1987). The time at which maximum methemoglobin is measured corresponds to the time of maximum nitrite production in the rumen, suggesting that transfer into the bloodstream is rapid (Wang et al., 1961; Kemp et al., 1977). The signs of nitrate toxicity directly result from a lack of oxygen (hypoxia). Some signs include a staggering gait, rapid breathing, collapse, abortion, and death (Bolan and Kemp, 2003). In cattle, clinical signs appear when 40% to 60% of the total hemoglobin is converted to methemoglobin, and death occurs when 70% to 90% of hemoglobin has been converted (Burrows et al., 1987; Hibberd et al., 1994). Most abortions appear to occur after methemoglobin concentrations reach near lethal levels, suggesting that the fetus is not necessarily more susceptible than the dam to toxicity (Davison et al., 1964; Crawford et al., 1966). Even when methemoglobin was

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maintained at 40% to 50% of total hemoglobin for 7 mo, there was no detrimental effects to pregnancy maintenance in heifers (Winter and Hokanson, 1964).

Development of Toxicity Guidelines

Research evaluating nitrate toxicity has used various nitrate sources and dosing methods. To allow for comparisons across studies and among various nitrate intake methods, the equivalent concentration of NO_3-N in mg/kg of diet dry matter (**DM**) assuming an intake of 2.5% body weight (**BW**) is provided throughout this review.

The initial work quantifying what levels of nitrate can be safely fed to ruminants was conducted by Bradley et al. (1940). To establish the minimum lethal dose, nine calves were given various levels of potassium nitrate by a stomach tube. One calf was given 75 g of KNO_3 per 45 kg of BW, three were given 50 g of KNO_3 per 45 kg of BW, one was given 30 g of KNO_3 per 45 kg of BW, and four calves 25 g of KNO_3 per 45 kg of BW. Assuming dry matter intake (**DMI**) of 2.5% of BW, these doses would equate to a feed concentration of 9,231, 6,179, 3,702, and 3,087 mg NO_3-N per kg of DM. All animals died except for two given the 25 g KNO_3 per 45 kg of BW, resulting in the lethal dose for 50% of population (LD 50) to be estimated at 25 g of KNO_3 per 45 kg of BW (3,087 mg NO_3-N/kg). Given the nitrate levels tested and the results, the authors suggested that the safe level of nitrate should be set at 1.5% KNO_3 in the diet on a DM basis, which is the equivalent of 2,100 mg NO_3-N/kg DM; However, they acknowledged that additional data were needed to establish a more accurate recommendation.

Approximately two decades later, an experiment to evaluate the effects of nitrate on reproduction was conducted using dairy heifers (Davison et al., 1964). The heifers received a sodium nitrate solution top-dressed on to hay at 440 mg $NaNO_3$/kg BW or 660 mg $NaNO_3$/kg BW. Besides ad libitum alfalfa-grass hay (*Medicago sativa* and *Phleum pretense*), the heifers were given 1.8 kg of a concentrate supplement (80% corn, 18% soybean meal, and 2% mineral per vitamin mix). If these heifers were to consume DM at 2.5% of BW, these doses would equate to 2,181 and 3,301 mg NO_3-N/kg of DM. Of the 15 heifers receiving 440 mg/kg BW treatment, there were no deaths but there was 1 abortion. For the 20 heifers receiving 660 mg $NaNO_3$, there were 2 deaths and 2 abortions. The 660 mg/kg treatment also caused 1 heifer to collapse twice, but she recovered both times and bore a live calf. The number of services per conception was greater (2.6 services) for the 660 mg/kg treatment than for the 440mg/kg (1.4 services) and the no supplemental nitrate control (1.3 services). Thus, the equivalent 3,301 mg NO_3-N/kg of DM appeared to result in negative effects, while the 2,181 mg NO_3-N/kg of DM did not.

Around this same time, Crawford et al. set out to confirm or update the lethal dose recommendations proposed by Bradley et al. (1940). The authors conducted three different studies using yearling, 2-yr-old, and mature female dairy cattle. They used several nitrate sources and delivery methods. One source was heavily fertilized oat (*Avena sativa*) hayed in the boot stage containing up to 2.3% NO_3 (5,290 mg NO_3-N/kg DM). They also drenched sodium nitrate using stomach tube. The other method of providing nitrate was hay top-dressed with calcium nitrate, potassium nitrate, or sodium nitrate salts dissolved in water and sprayed on the hay. There appeared to be no difference in the potential for toxicity between the nitrate that was naturally in the hay and that which was sprayed on the hay. However, the toxicity potential for the drenched nitrate was much greater. The authors suggested that the LD50 for nitrate toxicity was 15 g/45 kg BW (3,040 mg NO_3-N/kg DM assuming 2.5% BW DMI), if the nitrate was administered directly through a drench or stomach tube. However, if the nitrate was fed as a part of the diet, the threshold was much greater at 45 g/45 kg BW (9,119 mg NO_3-N/kg DM assuming 2.5% BW DMI). Thus, when animals received nitrate via a drench, the LD50 estimated by Crawford et al. (1966) was similar to Bradley et al. (1940). However, the LD50 for animals fed nitrate as a part of the diet was three times higher. The higher tolerance of nitrate when in the diet was attributed to a slower rate of nitrate entering the rumen. This was one of the first studies to suggest a rate of availability and not just nitrate concentration alone plays a major role in the potential for toxicity.

Factors that Affect Toxicity Potential

Factors that impact toxicity have been divided into four categories: 1) nitrate levels in the diet, 2) nitrate consumption rate, 3) nitrate and nitrite reduction rates, and 4) ruminal passage rate (Lee et al., 2015). There is evidence that moisture content of the forage, length of exposure to nitrates (microbial population present in the rumen), rate of nitrate intake, energy content of the diet, and the sulfur content of the diet all affect the potential for toxicity. Thus these factors should influence feeding recommendations.

Moisture Content of the Forage

Fresh forages may have a greater toxicity threshold than dry forages. When hay was submerged in distilled water, 80% of the nitrate in hay was released after 20 min. Freshly chopped turnips and grass only resulted in a maximum of 30% of the nitrate released in water after 20 min (Geurink et al., 1979). This slower release may indicate a slower availability of nitrates to the rumen microbes and decrease the likelihood that nitrite will build up in the rumen fluid.

Compiled data from 40 studies illustrate differences in methemoglobin concentrations when feeding a dried or pre-wilted forage compared with a fresh forage (Kemp, 1982). In these studies, Friesian cows (dry and lactating) were fed hay or pre-wilted silage that was consumed within 1 h, and compared with fresh turnips or grass consumed within 2 h. The resulting methemoglobin levels were lower for the fresh forage compared with hay or pre-wilted forage. At the greatest intakes (1.1% of BW), 50% methemoglobin occurred when cows consumed fresh forage with ~8,400 mg NO_3-N/kg DM vs. ~4,500 mg NO_3-N/kg DM for hay per pre-wilted silage. They attributed this to both a slower rate of intake and differences in the rate of nitrate release in the rumen. Given that there was a difference in time allotted for intake, the rate of intake, and the moisture content of the forage cannot be separated. However, when evaluating the hay or pre-wilted silage consumed at 0.55% of BW within an hour, 50% methemoglobin occurred when the forage contained ~6,600 mg NO_3-N/kg DM. In contrast, 50% methemoglobin occurred at ~8,400 mg NO_3-N/kg DM for the fresh forage consumed at 1.1% BW within 2 h. These data would suggest that fresh forages may pose a lower risk of toxicity at the same nitrate concentration than hay, even if rate of intake is similar.

Microbial "Adaptation"

It is important to note that the capacity of the microbial population in the rumen to reduce nitrite to ammonia will change with exposure to nitrate. In fact, sheep (55 kg) have been acclimated to a 2.5 g KNO_3/kg BW (23,000 mg NO_3-N/kg DM) diet by increasing the basal diet with 0.5 g KNO_3/kg BW every 2 wk (Alaboudi and Jones, 1985). This is 5–10 times the typical toxicity thresholds suggested in the extension literature. When using rumen fluid from adapted or non-adapted sheep, they saw the rumen fluid from adapted sheep reduced nitrate at a rate three times that of the rumen fluid from non-adapted sheep. While the reduction rate of nitrite in the rumen fluid of adapted sheep was five times faster than non-adapted (Alaboudi and Jones, 1985).

Energy Content of the Diet

The upper threshold for nitrate toxicity in ruminants may be affected by the amount of ruminal available energy in the diet. In vitro experiments using rumen fluid from sheep on a "poor-quality" hay retained nitrite in the rumen fluid for a longer time than the rumen fluid from sheep on a "high-quality" hay (Sapiro et al., 1949). Regardless of diet quality, they observed an accelerated rate of nitrite disappearance when glucose was added to the rumen fluid, suggesting that providing more energy to the rumen microbes can decrease the potential for nitrite accumulation and thus nitrate toxicity.

In a follow-up study, they tested the effects of a potassium nitrate drench with and without glucose on methemoglobin concentrations when sheep were fed a "poor-" or "high-" quality diet. When given no additional glucose, and 20 g of KNO_3 per 45 kg of BW on the poor-quality diet, more methemoglobin production occurred than when a 50 g KNO_3 per 45 kg of BW was given to sheep on the high-quality diet. For both diets, additional glucose appeared to protect the animals and decreased methemoglobin production.

Similarly, supplementing corn can decrease methemoglobin concentrations (Burrows et al., 1987). Three-year-old cows on a prairie hay diet (*Andropogon scoparius* and *Panicum virgatum*) were supplemented with 0, 1.6, or 3.2 kg of dry rolled corn for 10 d, before administering a sodium nitrate drench at 0.3 g $NaNO_3$/kg BW (equivalent of 1,967 NO_3-N/kg DM) through a rumen cannula. Both ruminal nitrate and methemoglobin linearly decreased with increasing corn supplementation. There was a quadratic decrease in the mean of the maximum methemoglobin concentration with increasing corn supplementation. The supplementation of the first 1.6 kg of corn resulted in a greater rate of decline than adding the additional 1.6 kg in the 3.2 kg treatment. However, 3.2 kg of corn resulted in the lowest methemoglobin concentration in the blood.

The protective effect of more dietary energy may be because of an acceleration in using ammonia for microbial growth (Bruning-Fann and Kaneene, 1993; Hibberd et al., 1994) or it may be due to the effect on ruminal pH. The optimal pH for nitrate reduction is 6.5, whereas the optimal pH for nitrite reduction is 5.6 (Lewis, 1951b). Later pH observations by Tillman et al. (1965) agreed with the lower pH favoring nitrite reduction, and also observed increased nitrite absorption into the bloodstream when pH was higher. Animals consuming more digestible forages may be at less risk than those consuming less digestible forages. However, there has not been enough research to adjust guidelines based on the energy content of the diet. Again, there is a need for future studies as many of the annual forages containing elevated nitrates would also be highly digestible, and thus potentially lower risk that currently suggested.

Sulfur Content

Sulfur-reducing bacteria and nitrate-reducing bacteria compete for hydrogen (Leng, 2008). The impact of sulfur on nitrate reduction in the rumen has been demonstrated through L-cysteine supplementation to sheep treated with a high dose of nitrate (0.45% NO_3-N; 4,500 mg NO_3-N/kg DM) through a stomach tube (Takahashi et al., 1998). Cysteine supplementation, which added 0.24% S to the diet, prevented the buildup of nitrite in the rumen, preventing methemoglobin formation in the blood (Takahashi et al., 1998).

Brassicas (*Brassica* spp.), such as turnips (*Brassica rapa*) and radishes (*Raphanus sativus*), have become popular in late summer annual forage mixes (Drewnoski et al., 2015). However, they have a propensity to accumulate nitrates. Samples of brassicas submitted by producers to a commercial forage-testing laboratory suggest that brassica often contain high nitrate concentrations, with 16% of samples containing between 2,100 and 5,000 mg NO_3-N/kg of DM and 31% of samples containing over 5,000 mg NO_3-N/kg of DM (Lenz et al., 2019). Given these concentrations and the current recommendations for the threshold for nitrate toxicity, 47% of the brassicas tested would be potentially toxic. Brassicas also often contain high concentrations of sulfur. In New Zealand, a study observed kale (*Brassica oleracea* L. *cv*. Kestrelto) have 0.85% sulfur, rape (B. *napus* L. *cv.* Titan) 0.61% sulfur, swedes (*B. napus* L. *cv*. Dominion) 0.56% sulfur, and turnips (B. campestris L. cv. Appin) 0.69% sulfur on a DM basis (Sun et al., 2012). In Nebraska, radish tops and roots (*R. sativus* L.) sampled from November to January averaged 0.95% and 1.03% sulfur on a DM basis, respectively. Turnip (*B. rapa* ssp. rapa L.) tops and roots sampled in the same fields as the radishes averaged 0.82% and 0.69% sulfur (Lenz et al., 2019). This high sulfur content of brassicas may reduce the potential for nitrate toxicity. Brassicas are highly digestible (85% to 87% IVOMD) and even the leaf and stem of vegetative brassicas would be a high energy feed (Lenz et al., 2019). The high energy and high sulfur may cause grazing of high nitrate brassicas to be lower risk than what the nitrate content would suggest. Again, there is a need for more research to provide guidance to producers.

Grazing Situations

Given the above discussion, are grazing situations less risky than feeding hay at the same concentration of nitrate in the forage? Few have conducted experiments evaluating nitrate toxicity in grazed forages. However, the scat data would suggest that risk of toxicity may be lower. Steers grazing ryegrass that had potentially toxic concentrations of nitrate did not appear to have any issues (Hodgson and Spedding, 1966). At turn out on the pasture contained ~2,500 mg NO_3-N/kg DM. Later in the grazing period, the forage contained ~3,500 mg NO_3-N/kg DM, yet no toxicity signs were observed and methemoglobin concentrations were reported to be negligible. Similarly, lactating ewes rotationally grazing on potentially toxic perennial ryegrass (*Lolium perenne*) pastures had no issues (Dickson and Macpherson, 1976). The nitrate content of the pastures ranged from 300 to 6,700 mg NO_3-N/kg DM. In both years, there were no health issues and the maximum methemoglobin reached on the most heavily fertilized pasture was 0.2 g per 100 mL blood (13% to 25% methemoglobin, assuming 8 and 16 g/dL hemoglobin in sheep). Gradual adaptation of the microbial population in the sheep's rumen likely occurred as the pastures increased in nitrate concentrations over the grazing period, allowing the sheep to graze with no adverse consequences.

Embryo growth and survivability in dairy heifers on heavily fertilized spring pasture (*L. perenne*) was also unaffected by elevated concentrations of nitrate (Laven et al., 2002). The fertilized pastures had nitrate concentrations ranging from 1,932 to 3,200 mg NO_3-N/kg DM and the control forage contained 1,132 mg NO_3-N/kg DM. The heifers (20–57 d pregnant) were adapted to the high nitrate pastures over a 1-wk period that included grazing the pasture during the day and feeding a mixed ration in the evening. After the 1-wk adaptation, the heifers grazed the pastures with a supplement for 6 wk. The study was a 2 × 2 factorial with forage nitrate concentration and amount of concentrate supplemented (3 or 8 kg/d) as the two factors. Embryo growth and survival were not affected by diet (Laven et al., 2002).

After receiving many questions about high nitrate concentrations in late summer planted annual forages, we recently conducted a retrospective analysis of annual forage samples from fall grazing trials conducted with growing calves (Table 1). The sample handling and analysis was described by Lenz et al. (2019). Weaned calves grazing these forages had no observable signs of nitrate toxicity and gained well, even though the nitrate concentrations in most of the trials were high, with the majority being above 2,100 mg NO_3-N/kg DM. The oat (*A. sativa*) were sampled at ground level and the brassicas (*B. rapa* and *R. sativus*) were pulled up to allow analysis of the root and the leaf. Thus, the nitrate concentrations represent the worst-case scenario. The calves were given access to the whole field (60–90 days' worth of forage) at the start of grazing and remained in the same area for the whole grazing period. This management may have reduced risk of toxicity as it initially allows for selectivity by the animals.

Animal selectivity can have a large impact on the composition of the diet consumed. Typically, leaves contain less nitrate than stems (Wright and Davison, 1964). If intensive grazing management is not being used, animals can be selective and typically consume the leaves before the stems. Depending on grazing management, the microbial population in the rumen may have time to adapt to higher nitrate concentrations before consuming the stem and lower portions of the plant. In pastures that contain multiple species, selectivity may also have a large impact on nitrate content of the consumed diet. Rate of DM consumption may be reduced in grazing compared with hay feeding situations, further decreasing the potential for nitrate toxicity. The limited number of studies grazing of elevated nitrate forages does not allow any firm conclusions to be made about nitrate toxicity risk when grazing. However, given the nitrate concentrations of the forages in these studies and the lack of negative consequences, grazing situations may pose less risk. Overall, these data highlight the need for more studies to evaluate risk of nitrate toxicity in grazing situations. It is clearly important to consider not only the nitrate content of the forage but also grazing management in future studies.

Current Nitrate Toxicity Guidelines

A simple search on Google using the terms "Nitrate Toxicity" or "Nitrate Poisoning" and "Livestock" produces a plethora of information from extension programs across the United States. The guidelines from the first 13 states represented in the search results are shown in Table 2. It is apparent that many of the guidelines are based on the initial drenching study from Bradley et al. (1940) and then apply a margin of safety. Out of the 13 extension guidelines, only 4 suggest that concentrations above 1,500 mg NO_3-N/kg DM would be safe. Seven out of the 13 differentiate pregnant and nonpregnant animals, lowering the threshold for pregnant animals. While most comment on factors that can decrease risk, such as adaptation, rate of intake, and grain supplementation, none actually provide differential guidelines for thresholds. Few discuss grazing situations and only two suggest that grazing situations might have a lesser risk than the same nitrate concentrations when feeding harvested forages.

So why are these apparent deficiencies in the guidelines so common? Perhaps it is because of a lack of definitive data that would allow for truly research-based recommendations. One publication noted that "a number of recommendations and guidelines still found today are based largely on early field observations and limited research data obtained in the late 1950s and 1960s and have not been updated to more recent research and field experiences" (Adams et al., 2016). While there has been some research and certainly a lot of observations in this area since the 1960s, replicated, large-scale research has not been conducted. Given the complexity of the topic, extension programs appear to have been cautious. Reading these extension publications, there are some that acknowledge the complexity of the issue and even that the recommendations provided are conservative. However, the result could be recommendations that do not accurately reflect the risk of the various situations encountered.

Table 1. Nitrate-nitrogen concentrations of late-summer planted annual forages[1] grazed by growing calves in the late fall and early winter and the resulting average daily gain[2]

Forage type	NO_3-N, mg/kg DM	Year	ADG, kg/d	
Oat, turnip, radish mix	6,146	2014	1.00	Cox-O'Neill et al. (2017)
Oat, turnip, radish mix	4,655	2015	0.59	Cox-O'Neill et al. (2017)
Oat, turnip, radish mix	2,158	2015	0.73	Speer et al. (2021)
Oat (hill)	912	2015	0.50	Brinton et al. (2019)
Oat (valley)	4,414	2015	0.68	Brinton et al. (2019)
Oat (hill)	3,921	2016	1.05	Brinton et al. (2019)
Oat (valley)	8,026	2016	1.14	Brinton et al. (2019)

[1] Oat sampled to ground level. Brassicas sampled by harvesting the entire plant and separating the top from the root.

[2] No calves showed signs of any adverse effects due to nitrate consumption. Calves were allowed access to 60–90 days' worth of forage at the onset of grazing and thus were allowed to selectively graze.

Table 2. Dietary nitrate thresholds suggested by various state extension programs in the United States

State	Author, year	Upper limit suggested as safe[1], mg NO_3-N/kg of DM		Factors discussed that affect toxicity potential			
		Non-pregnant	Pregnant	Grain feeding	Rate of intake	Adaptation	Grazing less risk
Alabama	Mullenix, 2016	2,500	1,500	X	X		
Arkansas[2]	Gadberry and Jennings, 2016	1,400	700	X	X	X	
Colorado	Whittier, 2014	1,150[3]			X	X	X
Georgia	Hancock, 2013	1,500	1,000	X		X	
Iowa	Ensley and Barnhart, 2012	1,500[3]		X	X	X	
Kansas	Roozeboom et al., 2011	1,380	690	X	X	X	
Kentucky	Arnold and Gaskill, 2014	2,262	1,130	X	X	X	
Montana[2]	Glunk et al., 2015	1,130	565	X	X	X	
North Dakota	Stoltenow and Lardy, 2015	1,500[3]			X	X	
Oklahoma	Strickland et al., 2017	1,150[4]		X	X		
Pennsylvania	Adams et al.,2016	1,000[3]		X	X	X	X
Texas	Provin and Pitt, 2003	2,300[3]					
Wisconsin[2]	Undersander et al., 1999	2,000	1,000	X	X	X	

[1] If range provided, then upper concentration was used in this table. If dilution was recommended then concentration was calculated based on dilution recommendation.
[2] Authors acknowledge that recommendations are conservative.
[3] Risk for pregnant vs. non-pregnant not differentiated.
[4] Suggest upper concentration is risky for pregnant animals but does not provide a threshold of safety for pregnant animals.

CONCLUSIONS

When made based solely on laboratory analysis, there is an overestimation of nitrate toxicity risk in certain situations. An evaluation of the whole picture is needed for reasonable assessment of the nitrate toxicity threshold. The factors that need to be considered include: forage type (moisture content and quality), feeding method and rate of intake (harvested vs. grazed), energy content of any other feeds being fed, length of time of exposure to nitrates (microbial population present in the rumen) and, if grazing, the grazing management. However, there is not enough data available to establish guidelines which account for these main factors. Thus, there needs to be more research.

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Conflict of interest statement

The authors declare no conflict of interest.

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