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Impact of farm proximity to coal-powered electricity power plants on forage and cattle mineral status in the Transvaal Highveld region of Mpumalanga, South Africa

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Abstract

Over 75% of South Africa's electricity is generated by coal-powered plants that are primarily located near large coal deposits in the north and east of the country. The Transvaal Highveld region is characterised by commercial agricultural enterprises dispersed among coal-powered electricity plants that produce emissions, resulting in dilute acid precipitation on these landscapes. These ecosystem alterations have been implicated in both plant and livestock trace mineral imbalances. This survey evaluated the trace mineral status of forages grown and beef cattle reared on farms classified as impacted or non-impacted by emissions from coal-powered electricity plants near Middelburg, Mpumalanga. Forage samples were collected at the end and beginning of the growing season and analysed for concentrations of minerals of nutritional relevance to cattle. Soil sulphur and potassium concentrations tended to be higher on impacted than non-impacted farms, but there was no effect of location on soil pH. Farm location had no impact on forage sulphur concentrations, but forage concentrations of phosphorus, potassium, zinc, and selenium were higher on impacted than non-impacted farms. The trace mineral status of beef cattle reared in these regions was assessed by analysing liver tissue harvested from cattle at the time of slaughter. Cattle grazing forages grown in impacted areas had lower copper, selenium, and zinc concentrations than cattle reared in non-impacted areas. These data suggest that the spatial location of farms, relative to coal-powered electricity plants, may impact the mineral characteristics of forages grown at these locations and thus the mineral status of cattle consuming these forages.

Keywords: copper, selenium, sulphur

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Introduction

South Africa is the fifth-largest coal-producing country in the world, and coal-based power plants dominate the country's energy production, representing 86.1% of the country's electricity generation in 2021 (Statistics South Africa, 2021). This reliance reflects the abundance of coal deposits distributed across five provinces in 19 official coalfields. Despite the vastness of coal resources throughout the country, the majority (approximately 70%) of active coal mining occurs in the Highveld, Waterberg, and

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Witbank coalfields (Schmidt, 2008). In addition to producing coal-derived electricity, this region of South Africa is also an important area for commercial agriculture. In 2017, the Mpumalanga and Free State provinces were responsible for over 60% of the total commercial maize production of the country (23% and 44%, respectively; Department of Agriculture, Forestry and Fisheries, 2017a). Furthermore, these two provinces lead South Africa in commercial cattle farming, collectively accounting for 40% of the country's total beef production in 2017 (Department of Agriculture, Forestry and Fisheries, 2017b). This coexistence of coal-derived electricity generation and commercial food production necessitates the consideration of the potential impact of industrial pollution on the nutrient quality of plant and animal food crops produced in the area. One direct consideration is the potential impact of acid precipitation on plant and animal agriculture. Acid precipitation, often referred to as acid rain, results from both natural (Maruoka *et al.,* 2003) and industrial (Davies & Mundalamo, 2010) emissions of sulphur dioxide and nitrogen oxides. Once these compounds react with moisture in the atmosphere, a weak mixture of sulphuric and nitric acid is produced. Traveling over a wide range of distances driven by prevailing winds, this precipitation is deposited onto the landscape, causing multiple alterations in the ecosystem, such as reduced soil and water pH (U.S. Environmental Protection Agency (EPA), 2007) and increased plant sulphur concentrations (Evans, 1982).

The potential impact of acid precipitation on the trace element nutrition of humans and animals has important implications for health and well-being and deserves consideration (Gerhardsson *et al.,* 1994). The elements most likely to be impacted are copper and selenium, as they are antagonised by sulphur in grazing ruminant animals (Arthington *et al.,* 2002; Arthington & Pate, 2002; Arthington, 2008). Copper and selenium are essential trace nutrients for livestock, and are commonly found to be deficient in forages, particularly in warm-season forages grown in tropical and subtropical regions of the world (McDowell & Arthington, 2005). Notably, the influence of selenium on human health is becoming increasingly well understood (Rayman, 2000), with researchers theorising that differences in dietary selenium are a major determinant of the rate of acquired immunodeficiency syndrome-related illnesses and deaths among human immunodeficiency virus-infected individuals (Foster, 2003; Stone *et al.,* 2010). In addition to human health, the impact of trace mineral nutrition on grazing livestock is an important husbandry consideration (Arthington & Ranches, 2021). Indeed, South Africa has a long history of unique regional complexities related to the mineral nutrition of grazing ruminants (Boyazoglu, 1973), and the potential role of acid precipitation on the mineral content of forages and beef produced in the eastern Transvaal Highveld warrants investigation.

The objective of the current survey was to evaluate the trace mineral status of forages grown and beef cattle reared on farms impacted by the coal-fired power plants near the city of Middelburg in Mpumalanga province. Our hypothesis stated that locations impacted by industrial emissions would have higher forage sulphur concentrations and lower forage copper and selenium concentrations than forages grown at non-impacted locations. As a result, cattle consuming impacted forages would have a poorer copper and selenium status at the time of slaughter, with potentially important consequences for both animal and human health.

Materials and methods

Animal liver tissue samples were collected from privately-owned cattle processed in a commercial abattoir. Time of slaughter was based on normal beef production practices and was not influenced by the research protocol. Since the research protocol did not involve the use of live animals, it was not reviewed by an ethics committee for animal experiments.

Ten cooperating farms in the eastern Transvaal Highveld region near Middelburg, South Africa (Figure 1) were enrolled in the study, with assistance from local veterinarians. These farms were identified as being impacted (n = 5) or non-impacted (n = 5). The impacted farms were located south of Middelburg and near multiple coal-powered electricity generating plants. In contrast, the non-impacted farms were located north of Middelburg and were generally not within the path of prevailing winds that would favour the transport of emissions onto these properties (Belelie *et al.,* 2018). Cooperating sites were sampled in February (forage and soil) and November (forage only) of 2016 (Figure 1).

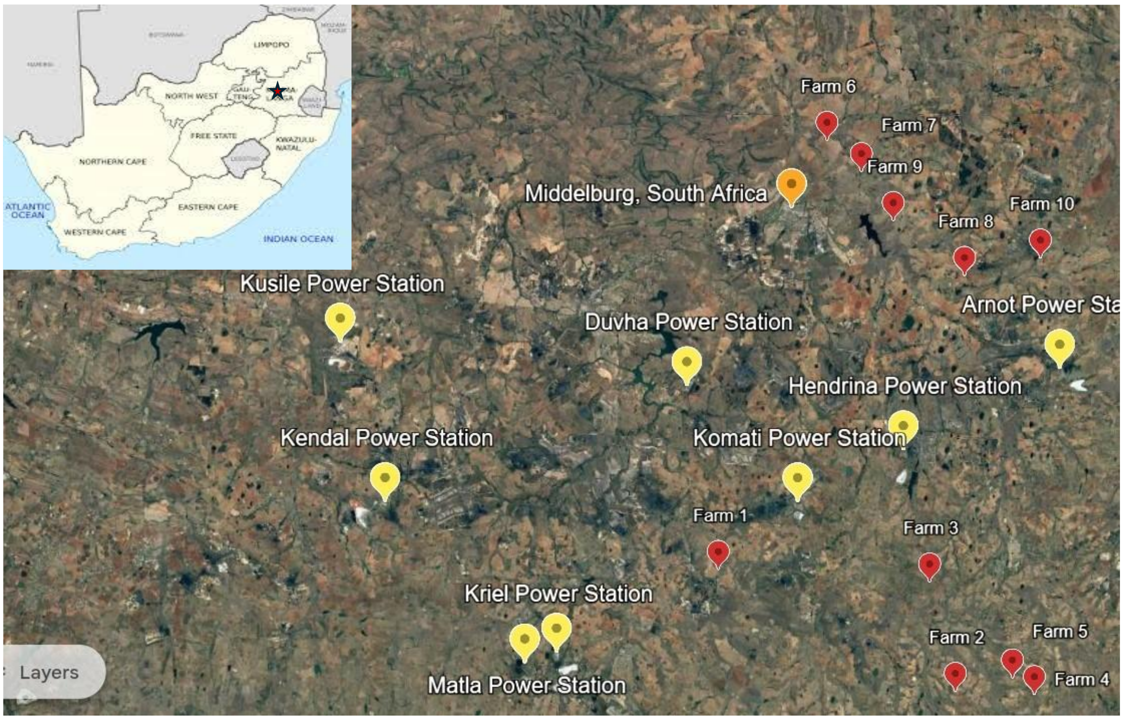

Figure 1 Location of sampling sites (red pins) relative to coal-powered electricity generation sites (yellow pins) in the eastern Transvaal Highveld in Mpumalanga province near Middelburg, South Africa. Sites 1–5 were considered impacted owing to their proximity to the coal-powered electricity generation sites. Sites 6–10 were considered non-impacted by coal-generated electricity.

Soil surface samples to a maximum depth of 15 cm were randomly collected within actively grazed pastures from each farm (n = 5; collected in February only). These samples were dried and composited into a single sample for each farm prior to being analysed for total phosphorus, potassium, sulphur, zinc, copper, iron, manganese (U.S. EPA, 2014a: method 6010D), and selenium (U.S. EPA, 2014b: method 6020B) concentrations using inductively coupled plasma mass spectrometry (ICP-MS) at a commercial laboratory (Midwest Laboratories, Omaha, NE, USA). In addition to the mineral content, the soil pH (U.S. EPA, 2014c: method 9045) and total Kjeldahl nitrogen (U.S. EPA, 2014d: method PAI-DKO1) were determined.

Forage samples were randomly collected within actively grazed pastures at the end (February) and beginning (November) of the growing season. Pastures predominantly consisted of *Eragrostis plana* mixed with less prevalent species such as *Cynodon dactylon, Heteropogon* spp., and *Melinis repens.* Individual samples (n = 5 and n = 4 samples per farm in February and November, respectively) were collected by hand-clipping and were then dried at 60 °C for 72 hours, ground to pass through a 1 mm screen using a Wiley mill (Udy Corporation, Fort Collins, CO), and analysed for mineral content by a commercial laboratory using ICP-MS procedures (Dairy One Forage Laboratory, Ithaca, NY, USA).

The trace mineral status of beef cattle reared in the region was assessed using liver tissue samples harvested from 36 cull cows (18/location) at the time of slaughter. Because injectable trace mineral treatments are common in this region, cooperation with a local veterinarian was sought to ensure that the cull animals had previously resided on or near the study's enrolled farms and that these animals had not received injectable trace mineral treatments in the previous six months. Liver samples (approximately 75 g) were dried at 60 °C for 72 hours and sent to a commercial laboratory (Animal Health Diagnostic Laboratory, Michigan State University, Lansing, MI) for mineral analysis using ICP-MS procedures as described by Braselton *et al.* (1997).

Data were analysed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC, USA, version 9.2), with Satterthwaite approximation to determine the denominator degrees of freedom for the test of fixed effects. The model statement for the analysis of forage and soil data contained the fixed effect of location and replicate (farm) as the random variable. The model statement for the analysis of liver mineral data contained the fixed effect of location. For forage and soil mineral analyses, the individual farm was the experimental unit. For liver mineral analyses, the location was the experimental unit. Results are reported as least square means and were separated using PDIFF. Significance was set at $P \leq 0.05$ and tendencies were examined if $P > 0.05$ and ≤ 0.10.

Results and discussion

The total soil sulphur concentration tended (P = 0.07) to be higher in samples from impacted than non-impacted farms (Table 1). This may have been due to the deposition of sulphur as dilute sulphuric acid resulting from sulphur dioxide emissions from neighbouring coal-powered electricity plants (i.e. acid precipitation). However, the soil pH did not differ (P = 0.96) between the impacted and non-impacted farms (5.40 versus 5.42; standard error of the mean (SEM) = 0.303) and was characteristic of soil pH levels previously reported for this region (Courtman *et al.,* 2012). Despite the tendency for the soil sulphur concentrations to differ, forage sulphur concentrations did not differ (P = 0.36) between the locations (Table 2) and were adequate to meet the nutritional requirements of beef cattle (National Academies of Sciences, Engineering, and Medicine (NASEM), 2016).

Soils from both locations were classified as Acrisols, with phenotypic classes favouring rhodic Acrisols north of Middelburg (non-impacted) and paraplinthic Acrisols south of Middelburg (impacted). Plinthic Acrisols are iron-rich, and this was observed in the soil test results, with soil samples from non-impacted farms containing over 4.5× the total iron concentration of soil samples from impacted farms (Table 1). Differences in the soil iron concentrations between locations were reflected in the total forage iron concentrations, with forages from non-impacted farms containing 94% more iron than forages from impacted farms. In addition to the soil and forage iron differences, soil from impacted farms contained more (P = 0.021) organic nitrogen than soil from non-impacted farms (2436 versus 1047 mg/kg; SEM = 343.9), corresponding to higher (P <0.001) forage phosphorus and potassium concentrations (Table 2).

Table 1 Mineral concentrations (mg/kg, reported on a dry matter basis) of soils* from farms either impacted or non-impacted by nearby coal-powered electricity plants

Mineral	Impacted	Non-impacted	SEM	*P*-value
Nitrogen	2436	1047	343.9	0.021
Phosphorus	461	365	122.1	0.60
Potassium	838	505	113.4	0.072
Sulphur	308	182	42.4	0.068
Iron	10 434	48 084	11 410	0.048
Zinc	38.3	31.8	13.11	0.74
Copper	8.8	21.4	5.02	0.12
Manganese	191	491	198.1	0.32
Selenium	1.32	1.09	0.190	0.42

SEM: standard error of the mean. *Soil surface samples to a maximum depth of 15 cm were collected from each farm (n = 5 per farm, collected in February 2016) and dried and composited into a single sample prior to analysis.

In many regions of the world, forage concentrations of nutritionally relevant minerals are limited, potentially impacting the performance and health of grazing livestock (McDowell & Arthington, 2005). The soil pH values measured for the farms sampled in this study (average pH = 5.41) represent acidic conditions. These conditions typically reduce the availability of several key macronutrients, especially phosphorus, because of iron and aluminium fixation, while increasing the solubility and relative availability of certain micronutrients, such as iron and manganese (Barrow & Hartemink, 2023). Of the macrominerals measured in the current study, forage calcium concentrations did not differ by location, but were only marginally adequate to support the nutritional requirements of a typical pregnant, lactating beef cow (NASEM, 2016; assuming 540 kg body weight and 7 kg of daily milk production). In contrast, forage phosphorus concentrations differed (P <0.001) between the locations. Assuming a similar beef cow example, forages grown on the farms located in the impacted region would be marginally adequate, and farms located in the non-impacted region inadequate, in terms of phosphorus requirements. These results reflect those of Ayanda *et al.* (2016), who evaluated the forage mineral concentrations of several forage species grown in the Eastern Cape Province of South Africa. In their study, *E. plana*, the predominant forage species in the current study, contained average calcium and phosphorus concentrations of 2.2 and 0.7 g/kg, respectively. Similar to the current study, the phosphorus concentration of the forage was low and inadequate to meet the nutritional requirements of a lactating beef cow. Inadequate forage phosphorus concentrations are generally the most common mineral deficiency impacting the growth and reproduction of grazing livestock throughout the world (McDowell & Valle, 2000). In the current study, forage potassium concentrations were adequate for all classes of beef cattle at both locations. However, the forage magnesium concentration was inadequate for all classes of beef cattle at both locations. Boyazoglu (1973) reported extensive forage magnesium deficiencies over many regions of the country in a large South African survey (approximately 5000 samples) conducted in the 1930s. Similarly, Mokolopi (2019) reported inadequate forage magnesium concentrations throughout the year in the North West Province of South Africa. These findings, combined with the current study's results, suggest that hypomagnesemia may be impacting grazing cattle in many regions of the country.

Table 2 Mineral concentrations of forages* from farms either impacted or non-impacted by nearby coal-powered electricity plants

Mineral	Impacted	Non-impacted	SEM	*P*-value
Reported in g/kg dry matter:				
Calcium	2.7	2.8	0.11	0.48
Phosphorus	1.8	1.2	0.08	<0.001
Magnesium	0.9	0.9	0.06	0.66
Potassium	14.5	10.0	0.49	<0.001
Sodium	0.08	0.08	0.030	0.97
Sulphur	2.9	2.6	0.19	0.38
Reported in mg/kg dry matter:				
Iron	173	336	19.3	<0.001
Zinc	40	24	5.7	0.045
Copper	5.8	5.3	0.33	0.36
Manganese	77	74	7.2	0.82
Cobalt	0.23	0.21	0.010	0.08
Molybdenum	0.35	0.25	0.060	0.25
Selenium	0.036	0.030	0.0024	0.05

SEM: standard error of the mean. *Forage samples consisting of predominantly *E. plana* were collected at the end (February) and beginning (November) of the growing season. Five farms were sampled in each region (impacted and non-impacted)

Of the microminerals of nutritional relevance to beef cattle, forage zinc concentrations were higher ($P < 0.05$) in samples collected from impacted farms than in those collected from non-impacted farms (Table 2). Forage zinc concentrations were adequate on impacted farms and inadequate to meet beef cattle requirements on non-impacted farms (NASEM, 2016). Forage cobalt and selenium concentrations also tended to be higher ($P < 0.10$) on impacted than non-impacted farms (Table 2). Forage cobalt was adequate and forage selenium inadequate to meet the nutritional requirements of beef cattle at both locations (NASEM, 2016).

The forage mineral analyses conducted in this study reflect both the minerals assimilated into the plant tissue and the minerals associated with particulates present on the surface of the plant. This particulate matter (dust), derived from industrial emissions, settles on forages and contributes minerals to the grazing landscape that are not necessarily part of the plant tissue (Zeeshan *et al.,* 2024). Contributions would be expected to vary significantly after rainfall events, as rain could wash away particulate matter that had accumulated on the forages. Gummow *et al.* (2006) designed a detailed, systematic study to create an exposure model to assess vanadium intake in South Africa using cattle as sentinels. In that study, the investigators noted that forage intake was the predominant source of vanadium exposure, and that this was greatest in the dry season because of the build-up of dust on the forages. Acid precipitation may reduce the soil pH, resulting in less forage selenium uptake (Mushak, 1985). However, the soil pH did not differ between the two locations sampled in this study, suggesting that any potential differences in forage selenium concentrations may be due to mineral contributions from particulate sediment derived from industrial emissions associated with these regions. Maize grain grown in the same region as the current study has also been reported to be low in selenium (Courtman, 2012). Despite having largely adequate soil selenium concentrations in this region, the low soil pH limits plant selenium accumulation, and this is likely exacerbated by acid precipitation caused by localised industrial emissions (Courtman, 2012). Forage copper and manganese concentrations did not differ ($P > 0.35$) between locations (Table 2). Forage manganese concentrations were adequate and forage copper concentrations inadequate to meet the nutritional requirements of beef cattle at both locations (NASEM, 2016).

Liver zinc concentrations tended to be higher ($P = 0.09$) in the cattle grazing forages in the non-impacted region, compared to those from the impacted region (Table 3). These differences were surprising as forage concentrations of zinc tended ($P = 0.05$) to be higher on the impacted farms. Liver zinc concentrations were considered marginal for cattle from both regions (Puls, 1988). Zinc is an essential trace element for many physiological functions, particularly those related to rapid cell division, because it is required by enzymes essential for DNA and RNA synthesis. These tendencies, although interesting, should be viewed with caution, as liver tissue is not considered a reliable indicator of zinc status in cattle (Puls, 1988).

Table 3 Liver mineral concentrations* (mg/kg, on a dry matter basis) of cattle from farms either impacted or non-impacted by nearby coal-powered electricity plants

Mineral	Impacted	Non-impacted	SEM	*P*-value
Copper	58	233	29.7	<0.001
Zinc	162	267	42.3	0.09
Manganese	11.5	11.6	1.24	0.93
Iron	281	368	38.6	0.12
Molybdenum	3.23	4.19	0.342	0.06
Cobalt	0.31	0.36	0.024	0.20
Selenium	0.70	1.35	0.090	<0.001

SEM: standard error of the mean. *The trace mineral status of beef cattle raised in this region was assessed using liver tissue harvested from 36 cull cows (18/location) at the time of slaughter.

Selenium and copper are two important trace mineral nutrients that are commonly found to be deficient in forages throughout the world (McDowell & Arthington, 2005). Liver copper and selenium concentrations were higher ($P < 0.001$) in the cattle grazing forages in the non-impacted region (Table 3). These differences were surprising, as forage concentrations of selenium tended ($P = 0.05$) to be higher on the impacted farms and forage copper concentrations did not differ between the locations ($P = 0.36$). Liver selenium concentrations were adequate in the cattle from the non-impacted region, but marginally deficient in the cattle from the impacted region, despite the impacted farms tending to have higher forage selenium levels. Puls (1988) classified cattle as selenium deficient when their liver concentrations were below 0.61 mg/kg dry matter. This is similar to the selenium deficiency threshold specified by the Michigan State University Diagnostic Center for Population and Animal Health (0.70 mg/kg dry matter; Michigan State University, 2024). Liver copper concentrations were indicative of deficiency in the cattle derived from the impacted region and adequate for the cattle derived from the non-impacted region (Table 3). Puls (1988) classified cattle as copper deficient when they had liver copper concentrations of <90 mg/kg dry matter, assuming an average liver tissue dry matter content of 28% (Herdt & Hoff, 2011).

In the same South African province as the current study, selenium deficiency was diagnosed in beef calves suffering from stillbirth and perinatal mortality and weakness, with further survey results revealing selenium deficiencies in neighbouring farms in the same district (Davis & Myburgh, 2016). Although these differences in the cattle liver copper and selenium concentrations do not reflect differences in the forage copper and selenium concentrations, other factors may be contributing. Sulphur is an antagonist of both copper and selenium in ruminants, and diets with dietary sulphur concentrations exceeding 0.25% can have detrimental impacts on these elements (Arthington *et al.,* 2002; Arthington & Pate, 2002; Arthington, 2008). The soil sulphur content tended to be greater on the impacted farms, and cattle at these locations may have thus consumed larger quantities of sulphur through the natural consumption of soil during the grazing process, which may be as much as 100 g of soil/100 kg of body weight (Jurjanz *et al.,* 2017). Using the example described earlier, a 540 kg beef cow could consume nearly 0.50 kg of soil daily. However, this would only add approximately 165 mg of sulphur per day to the total dry matter intake from grazing forages in the impacted region, a minimal contribution.

The liver concentration is considered a good indicator of the selenium and copper status of cattle and is commonly used to diagnose deficiency (Underwood & Suttle, 2001). Therefore, these findings provide strong evidence that cattle derived from regions impacted by emissions from coal-powered electricity plants may benefit from supplemental selenium and copper. Work by Van Ryssen (2001) summarised current knowledge related to the selenium status of herbivores throughout South Africa and created a map illustrating regional differences. Although the area of the current study was recognised as marginally deficient to adequate, the localised impacts of industrial emissions from power plants were recognised as potentially causing impacts on the selenium status of grazing animals. Beyond the potential impacts on animal health and productivity, these findings may also have implications for the nutritional quality of the meat products produced by animals in these areas and consumed by humans (Foster, 2003).

Nutritional interventions, such as mineral supplementation protocols, can be implemented to help address deficiencies in grazing cattle. However, industrial emissions, such as those impacting the farms in the current study, complicate the mineral nutrition of cattle. A better understanding of regional forage mineral characteristics and the impacts of mineral antagonists will help refine and improve supplementation strategies. Further research is warranted to better elucidate potential mineral antagonists resulting from industrial emissions near grazing lands.

Conclusions

The important interaction between acid precipitation and mineral nutrition in humans and animals is gaining attention. Reduced soil pH, combined with increased sulphur contributions to the environment, decreases the ability of plants to accumulate copper and selenium in their tissues, thus reducing the selenium concentration in the food products grown on soils impacted by acid precipitation (Mushak, 1985). Furthermore, increased plant sulphur concentrations create mineral × mineral antagonisms in ruminants (Ivancic & Weiss, 2001; Arthington *et al.,* 2002; Arthington, 2008). These antagonisms impede selenium and copper absorption in food animals and result in reduced selenium and copper concentrations in the meat and milk products derived from these animals. In addition to the reduced nutritional quality of these animal-sourced foods, selenium and copper deficiencies can cause reduced animal performance and health, such as poor fertility, reduced growth, and impaired immunity (Underwood & Suttle, 1999). These events can further contribute negatively to the economic well-being of the individuals rearing them.

Grazing beef cattle consume essential minerals via the combined contribution of forage and water intake. In most situations, these sources supply inadequate amounts of several minerals, thus the need for supplementation. Supplements should be formulated based on local forage deficiencies, the presence of mineral antagonists, and mineral ratios. Industrial emissions, such as those associated with coal-powered electricity plants, may complicate these considerations by contributing essential, non-essential, and antagonistic minerals to the grazing landscape. The current study provides evidence that grazing cattle in the Transvaal Highveld region of Mpumalanga have disparate mineral-status outcomes depending on the locations of the farms where they are reared. In contrast to our original hypothesis, forages grown on farms directly impacted by industrial emissions contained greater concentrations of zinc and selenium, but, supporting our hypothesis, cattle reared in these areas had lower liver tissue concentrations of selenium and copper, and tended to have lower liver tissue concentrations of zinc, compared to cattle reared on non-impacted farms. These results are contradictory and imply that factors other than the forage mineral content are impacting the trace mineral status of cattle reared on farms impacted by industrial emissions. Additional investigation is warranted to improve our understanding of these impacts and develop management strategies to improve the mineral status of livestock reared in these areas.

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Authors‘ contributions

J.D. Arthington provided initial project conceptualisation, data analysis, and initial manuscript preparation. J.G. Myburgh contributed editorially to the submitted manuscript. J.G. Myburgh and M. Ferreira coordinated site selection and producer cooperation, including the coordination of tissue collection at the commercial abattoir following animal slaughter.

Conflict of interest declaration

The authors declare that they have no conflicts of interest related to the publication of this study.

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