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ORIGINAL ARTICLE

Dynamics of magnesium in rangeland areas of Southeastern region of the State Rio Grande do Sul/Brazil. 2. Correlations

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Abstract – We aimed to evaluate the dynamics of magnesium (Mg) in the soil - plant – animal chain. It was conducted in two natural rangeland areas on two types of undisturbed (virgin) soils (medium/clayey texture) in the Serra do Sudeste (Rio Grande do Sul State, Brazil). In each of these areas, 12 animals (heifers) were kept under continuous extensive grazing for twelve months without mineral supplementation. Every month, samples of soil and vegetation were collected at 16 fixed points (radius: 25 m) as well as blood serum from each of the animals in each area for the determination of Mg and other minerals levels. The data were analyzed using the analysis of variance, decomposition of the annual variation of the response variables and periodic regression (harmonic analysis) for adjustment of function to express this variation. The relationship of Mg with other variables within the links of the soil-plant-animal chain is influenced by some factors such as physicochemical and biological soil reactions, floristic composition and environmental conditions. In natural non perturbed rangeland areas the organic matter is the main colloid of the soil for the availability of magnesium to plants and, consequently, to the animals.

Keywords: Beef Cattle. Blood serum. Minerals. Minerals Requirement. Natural pastures. Soil-plant-animal chain

Dinâmica sazonal do magnésio em áreas de campo natural na região Sudeste do Estado do Rio Grande do Sul/Brazil. 2. Correlações

Resumo – O objetivo deste estudo foi avaliar a dinâmica do magnésio (Mg) na cadeia solo – planta – animal. Ele foi conduzido em duas áreas de campo natural em dois tipos de solos não perturbados na Serra do Sudeste (Rio Grande do Sul, Brasil). -RS. Em cada uma dessas áreas foram mantidos 12 animais (novilhas) em regime de pastejo extensivo contínuo durante 12 meses. Foram coletadas mensalmente amostras de solo, vegetação, em 16 pontos fixos (raio: 25 m), e soro de sangue dos animais de cada área, para a determinação dos teores de Mg. Os dados foram analisados pelos procedimentos de análise de variância, decomposição da variação anual das variáveis respostas e regressão periódica (análise harmônica) para o ajustamento de função, a fim de expressar essa variação. A relação de Mg com outras variáveis dentro das ligações da cadeia solo-vegetal-animal é influenciada por alguns fatores como reações físico-químicas e biológicas do solo, composição florística e condições ambientais. Em áreas naturais não perturbadas, a matéria orgânica é o principal coloide do solo para a disponibilidade de magnésio às plantas e, consequentemente, aos animais.

Palavras–chave: Bovinos de Corte. Cadeia solo-planta-animal. Minerais. Requerimento Mineral. Pastagens naturais. Soro sanguíneo.

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Introduction

To increase the productivity of annual crops in conventional and no-tillage systems, liming and fertilization of the soils are used as tools, always considering the interactions between mineral elements. To this end, "*in väs*" experiments are carried out to determine the ideal quantity of each element. Generally, these experiments are carried out in greenhouses under ideal and controlled conditions.

These interactions among mineral elements in soils, which have an effect when a certain nutrient affects the absorption and utilization of another by the plant, producing synergistic or antagonistic effects (FAGERIA, 2014). In this sense, Rietra *et al*. (2017) indicate three types of interactions, which occurs in the soils: synergism/Liebig-synergism, antagonism, and no interaction (zero). These authors studied 94 publications, describing 117 interactions between macro and micronutrients for different crops. In 43 cases, the interactions were synergistic (synergism: 23; Liebig-synergism: 20), 17 antagonistic, and 35 cases without any interaction that occurred due to lack of significance (23) or because there was a negative response (7).

There are few studies (REIS, 2005; SANTOS *et al*., 2010) on these soil-plant chain mineral interactions in natural pastures. Therefore, it is important to acquire more profound knowledge about interactions among minerals under field conditions to establish improvement actions and, consequently, improve the productivity of grazing animals.

According to Marschner (2011), magnesium (Mg) is indispensable for the development of plants, since this element is responsible for their growth, due to his main function as the core of photosynthesis. Similarly, Mg acts by activating enzymes in the intermediate metabolism of animals by providing various biosynthetic processes, which contribute to the energy metabolism of animals (NRC, 2016).

Thus, this study aimed to evaluate the main environmental factors (rainfall and temperature), the interactions with other minerals and other soil variables that influence the dynamics of magnesium in the soil-plant-animal chain. We evaluated within each link and between the chain links in two areas of undisturbed natural grassland in the region Serra do Sudeste – RS, Brazil.

Material and Methods

The study was carried out in partnership with the Brazilian Agricultural Research Corporation (Embrapa Temperate Agriculture), in the city of Piratini, RS, located in the Southeastern Mountain Range. We used two rural areas representing the typical production system of the region, in the 2nd and 4th sub-district of the city (Area 1: 31°22'14" S and 53°11'08" W, 401.10 meters a.s.l.; Area 2: 31°15'44" S and 52°59'43" W, 321.0 meters a.s.l.). The criteria for choosing the areas and animals for the study were: undisturbed (virgin) natural grasslands and the availability of 12 heifers (yearlings, ± 200 kg PV, Ibagé crosses) without any mineral supplementation for one year (Ethics Committee on Animal Experimentation: UFPEL code 5068-2017).

We identified the soils of the two areas according to the Brazilian Soil Classification (STRECK *et al*., 2008). The Area 1 soil (12.6 ha) is Argisol greyish-brown Tb Eutrophic umbric (Soil Taxonomy: Mollic Hapludalf). Area 2 (10.6 ha) is Argisol greyish-brown Aluminic umbric (Soil Taxonomy: Typic Kanhaplohumult).

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Table 1. Monthly averages of meteorological variables of the municipality of Piratini - RS during the experimental period.

Month	Temperature (ºC)[1]				Area 1[2]		Area 2[3]	
	max.	min.	aver.	abs. min.	total prec. (mm)	rainy days (nº)	total prec. (mm)	rainy days (nº)
May	22.03	2.68	12.35	-5.0	9.7	2	0.0	0
Jun.	20.70	2.43	11.57	-8.0	96.6	6	81.0	7
Jul.	n.a.	n.a.	n.a.	n.a.	5.7	2	14.0	3
Aug.	21.03	6.06	13.60	-2.0	171.2	9	141.0	8
Sep.	19.03	8.17	13.60	-3.0	80.1	8	75.0	8
Oct.	24.52	12.90	18.71	5.0	171.0	10	171.0	10
Nov.	26.69	12.13	19.41	6.0	79.0	5	79.0	5
Dez.	29.03	16.42	22.73	9.0	67.0	6	67.0	6
Jan.	31.90	17.55	24.73	11.0	61.4	6	67.0	6
Feb.	27.50	16.50	22.00	11.0	304.5	6	301.0	10
Mar.	28.10	13.23	20.66	4.0	31.0	1	29.0	3
Apr.	26.30	10.23	18.27	3.0	35.5	4	61.0	5
May	22.45	9.21	16.14	-3.0	166.1	3	139.0	3
Jun.	15.50	5.73	10.62	-3.0	143.7	9	205.0	9

n.a.: not available; max.: maximum; min.: minimum; aver.: average; abs. min.: absolute minimum; prec.: precipitation.[1]Temperature common to the two areas; [2]Source: Piratini Meteorological Station, located at the Municipal Agricultural School Alaor Tarouco, Latitude: 31º25'49"S; Longitude: 53º06'26"W; Altitude: 401.1 meters a.s.l; [3]Source: Farm São Thomas. Latitude: 31°15'44" S; Longitude: 52°59'43" W; Altitude: 321.0 meters a.s.l.

The vegetation of the two areas consisted of species typical from the natural grasslands of the region. A flora survey determined that both areas present amounts of the main groups of species of the natural vegetation, with a predominance of warm-season grasses (79 %), predominantly ‘*Paspalum* spp’. and ‘*Axonopus* spp.”, throughout the year (REIS *et al*, 2008).

In each area, we chose 16 fixed spots and placed numbered stakes on them. These spots were strategically allocated, according to the topography, distributed in four levels: high area, half high slope, half low slope, and low area. The monthly sampling of soil and vegetation was carried out surrounding each fixed spot (20 - 25 subsamples) within a radius of 25 m, totaling 16 units, i.e., four units per topographic level.

The soil was sampled in a 20 cm depth profile using a stainless auger to avoid contamination. We did not consider plants despised by animals or consumed in small quantities (broadleaf plants), representing the grazing selectivity. We determined the Mg levels and other minerals in soil and vegetation according Tedesco *et al*. (1995). Organic matter, pH, and clay were also determined in soils. We evaluated soil parameters according to CQFRS/SC (2004) since this approach is more appropriate to the region's soil types. We also determined the Mg and other minerals content monthly in the blood serum (samples: 10 mL whole blood; through puncture of the jugular vein) of grazing animals in both areas according Fick *et al*. (1980).

The climatic data of the municipality of Piratini-RS during the period of execution of the data collection are presented in Table 1.

The study comprised two factors, area and month, with two and twelve levels, respectively. We analyzed the data using the SAS program (2020). Analysis of variance, trigonometric periodic regression analysis (harmonic analysis), with significance tests at $\alpha = 0.05$ level, and function adjustment to express the variation of magnesium content in soil, plant, and blood serum of animals. This adjustment considered the function with the highest order harmonic component, not higher than that expressed by the trimester trend:

$$Zi = a_0 + a_1x_{1i} + b_1y_{1i} + a_2x_{2i} + b_2y_{2i} + a_3x_{3i} + b_3y_{3i} + a_4x_{4i} + b_4y_{4i} + e_i,$$

where: $x_{1i}=\sin(\pi i/6)$, $y_{1i}=\cos(\pi i/6)$, $x_{2i}=\sin(\pi i/3)$, $y_{2i}=\cos(\pi i/3)$, $x_{3i}=\sin(\pi i/2)$, $y_{3i}=\cos(\pi i/2)$, $x_{4i}=\sin(2\pi i/3)$, $y_{4i}=\cos(2\pi i/3)$, i=1-july, 2-august, 3-september...,12-june.

Results and Discussion

The correlations between the main climatic elements and magnesium (Mg) levels in the soil-plant-animal chain links are presented in Table 2. For the evaluation, we considered the rainfall and temperature data of the month prior (previous month) to collection and those obtained in the month (current month) of collection. There was no correlation between rainfall in the previous and current months of sampling with Mg levels in the chain links for Areas 1 and 2. This lack of correlation is because the amounts of total rainfall and the number of rainy days (see Table 1) varied considerably between months in each area and between areas during the year. Then, the distribution of rainy days during a month and between months differed, both in each area and between areas, affecting correlations with Mg. Although there is no direct correlation of rainfall, it should be considered that the Mg potentially leachable (CONTE *et al.*, 2017) and soil can lose up to 80 kg/ha depending on soil texture (OLIVEIRA *et al.*, 2002). In the case of sandy loam soils, as in the present study, there was probably some effect of rainfall as a result of leaching and percolation of Mg to deeper horizons of the soil.

The correlation between the temperature and Mg content in the chain links of the soil was positive. It behaved differently in both areas. There was no effect on the soil in the previous and current months for Area 1, whereas the effect was significant in the previous and current months for Area 2.

The correlation between temperature and Mg also behaved differently in the vegetation of each area. It was significant both in the previous and current months for Area 1, and there was a significant correlation only with the current month for Area 2. This result is because the increase in temperature influences the availability of minerals in the soil solution. The warmer the soil, the greater the amount of nutrients available for absorption by plants since the temperature influences the rate of release by organic matter. The absorption of minerals by plants increases with the temperature, as it facilitates the absorption of minerals from the soil solution by the roots, and translocation and utilization of nutrients, especially during vegetation growth (MUZZILLI, 2002).

Table 2. Correlations of magnesium levels in soil, plant and animal with temperature and precipitation in the previous and current month in area 1 (A1) and area 2 (A2).

		Precipitation previous month		Precipitation current month		Temperature previous month		Temperature current month	
		r	P	r	P	r	P	r	P
A 1	soil	- 0.08	0.799 ns	0.32	0.305 ns	0.51	0.092 ns	0.08	0.804 ns
	plant	- 0.03	0.921 ns	- 0.22	0.497 ns	0.63	0.027 *	0.67	0.017 *
	animal	0.22	0.491 ns	0.30	0.357 ns	0.72	0.009**	0.25	0.431 ns
A 2	soil	- 0.16	0.624 ns	0.17	0.602 ns	0.78	0.003**	0.64	0.024 *
	plant	0.08	0.799 ns	- 0.20	0.537 ns	0.42	0.170 ns	0.65	0.023 *
	animal	0.23	0.473 ns	0.23	0.465 ns	0.75	0.005**	0.30	0.347 ns

r: Pearson correlation coefficient; P: Prob.>|r|; ns: not significant (P>0,05); *: significant 0,01<P<0,05; **: highly significant (P<0,01).

The same correlation with animals was also positive. It was highly significant for both areas only in the previous month. This correlation is due to the milder and warmer temperatures that lead to high vegetation growth, Mg availability for plants, and excellent absorption of Mg by animals.

The correlation between the Mg and other variables within each chain link behaved differently for each area and between them (Table 3). Annual averages of soil Mg levels were 1.81 cmolc/dm³ for Area 1 (1.55 – 2.18 cmolc/dm³) and 1.90 cmolc/dm³ for Area 2 (1.55-2.20 cmolc/dm³). These contents are considered high for the entire year CQFRS/SC (2004).

The clay texture classified as Class IV (CQFRS/SC, 2004) in the soils of both areas showed a significant negative correlation with Mg only for Area 2. This result was not expected, because although the clay activity (AR) was 6.2 %, base saturation (% BS) 14.7 %, and cation exchange capacity (CEC) 17.3 % higher in Area 2 (AR = 95.5 $cmol_c\ kg^{-1}$; % BS = 64.36; CEC = 63.6 $cmol_c\ kg^{-1}$) than Area 1 (AR = 89,9 $cmol_c\ kg^{-1}$; % BS = 56.12; CEC = 54.2 $cmol_c\ kg^{-1}$), the saturation per Mg was 3.4 % higher in Area 1 (Mg % = 14.03) than Area 2 (Mg % = 13.57). It is probably due to the high levels of other exchangeable cations in Area 2, whose saturations were higher (Ca % = 46.70; K % = 3.46) than Area 1 (Ca % = 38.76; K % = 2.70). Thus, the negative correlation Mg × Clay in Area 2 is probably also because of other interfering factors, such as pH, organic matter (MO), climatic conditions, and interactions with other soil nutrients.

There was no correlation of Mg × pH for Area 1 (4.82), considered very low. For Area 2, the correlation was significantly positive, and the pH value (5.02) is considered low. The correlation occurred because in acidic soils with pH > 5, there is a change in the quantity and composition of microorganisms. This change causes greater adsorption of Mg by soil colloids, especially organic matter (OM). The exchangeable acidity increases the clearance of charges occupied by other cations and promotes the adsorption of divalent cations such as Mg (FASSBENDER; BORNEMISZA, 1994; MARSCHNER, 2011; MUZZILLI, 2002). OM levels in Area 1 (4.19%) and Area 2 (4.45%) are considered average (CQFRS/SC, 2004). The correlation with Mg was highly significant and positive for both areas. This is due to the fact that almost all OM is formed by negative charges (LOPES; GUILHERME, 2004) and, thus, promotes greater adsorption of exchangeable bases, including Mg.

Table 3. Correlations of magnesium contents within the links of the soil-plant-animal chain with the other variables in the soil and plant (observation by collection point) and in the blood serum of grazing animals (observation by animal), eliminating the effects of months and collection points.

	Area 1						Area 2					
	soil-soil		plant-plant		serum-serum		soil-soil		plant-plant		serum-serum	
	r	P	r	P	r	P	r	P	r	P	r	P
Clay	-	-	-	-	-	-	- 0.324	0.0245*	-	-	-	-
pH	-	-	-	-	-	-	0.318	0.0277*	-	-	-	-
OM	0.802	< 0.0001**	-	-	-	-	0.499	0.0003**	-	-	-	-
Al	-	-	-	-	-	-	- 0.385	0.0068**	-	-	-	-
B	-	-	-	-	-	-	-	-	-	-	-	-
N	0.751	< 0.0001**	-	-	-	-	-	-	-	-	-	-
P	-	-	-	-	-	-	-	-	-	-	0.453	< 0.0001**
K	0.427	0.0025**	-	-	0.373	< 0.0001**	0.297	0.0401*	0.317	0.0282*	0.242	0.0034**
Ca	0.926	< 0.0001**	0.539	< 0.0001**	0.453	< 0.0001**	0.821	< 0.0001**	-	-	0.709	< 0.0001**
S	-	-	-	-	-	-	0.288	0.0475*	-	-	-	-
Zn	0.477	0.0006**	-	-	-	-	-	-	-	-	0.208	0.0124*
Cu	0.299	0.0390*	0.321	0.0262*	0.205	0.0136*	-	-	-	-	- 0.292	0.0004**
Mn	0.294	0.0424*	-	-	-	-	-	-	-	-	-	-
Na	-	-	-	-	0.250	0.0025**	-	-	-	-	0.351	< 0.0001**
Fe	-	-	-	-	0.264	0.0014**	-	-	-	-	-	-

r: Pearson correlation coefficient; P: Prob.>|r|; ^{ns}: not significant (P > 0.05); *: significant 0.01 < P < 0.05; **: highly significant (P < 0.01).

Aluminum (Al) contents were considered low (CQFRS/SC, 2004) for both Area 1 (0.54 cmol$_c$/dm^3) and Area 2 (0.28 cmol$_c$/dm^3). Although the Al content was two times higher in Area 1, there was no correlation with Mg. We found a negative and highly significant correlation for Area 2. This is due to the effective CEC in this area, that was 16.3 % higher in Area 2 (ECEC= 9.29 cmol$_c$ kg^{-1}) than Area 1 (ECEC = 7.78 cmol$_c$ kg^{-1}). So, there was higher adsorption of Al to soil colloids. Boron (B) levels were considered high (CQFRS/SC, 2004) for Area 1 (0.77 mg/dm^3) and Area 2 (0.92 mg/dm^3); there was no correlation of Mg × B for these areas. Nitrogen (N) showed a positive and highly significant correlation with Mg for Area 1 (0.22 %), also linked of Al to soil colloids. Boron (B) levels were considered high (CQFRS/SC, 2004) for Area 1 (0.77 mg/dm^3) and Area 2 (0.92 mg/dm^3); there was no correlation of Mg × B for these areas. Nitrogen (N) showed a positive and highly significant correlation with Mg for Area 1 (0.22 %), also linked to N correlation with OM and plant growth. There was no correlation for Area 2 (0.25 %).

There was no correlation Mg × phosphorus (P) for Area 1 and Area 2, probably because P levels were considered very low and low (CQFRS/SC, 2004) for Area 1 (4.76 mg/dm^3) and Area 2 (7.21 mg/dm^3),

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respectively.

The exchangeable bases of potassium (K) and calcium (Ca) were considered high for both areas (CQFRS/SC, 2004), and the correlations with Mg were positive. The Mg × K correlation for Area 1 (135.92 mg/dm^3) was highly significant. The K (188.98 mg/dm^3), which presented 28.1% higher, was only significant for Area 2. The Mg × Ca correlation was highly significant and positive for Area 1 (5.00 cmol$_c$/dm^3) and Area 2 (6,54 cmol$_c$/dm^3). Probably, this occurred because the ratios K/Mg (Area 1 = 5.86:1; Area 2 = 4.21:1) and Ca/Mg (Area 1 = 2.54:1; Area 2 = 3.10:1) were considered well balanced for both areas, and the ratio of (Ca + Mg)/K exchangeable for Area 1 (19.5) and Area 2 (17.4) were close to the optimal range between 20 - 30 (OLIVEIRA; CARMELLO; MASCARENHAS, 2001).

Sulfur (S) levels in the soil were considered high for both areas (CQFRS/SC, 2004). There was no Mg × S correlation for Area 1 (19.92 mg/dm^3). But there was a positive and significant correlation for Area 2 (17.38 mg / dm^3), although the S contents in Area 1 were 12.8% higher.

The cation contents of zinc (Zn) and copper (Cu) were considered high and manganese (Mn) very high for both areas (CQFRS/SC, 2004). For Area 1, the correlation of Mg × Zn (5.63 mg/dm^3) was positive and highly significant, Mg × Cu (1.95 mg/dm^3) and Mg × Mn (118.04 mg/dm^3) were positive and significant. There was no correlation between these micronutrients and Mg for Area 2 (Zn: 8.67 mg/dm^3; Cu: 0.57 mg/dm^3; Mn: 102.46 mg/dm^3), being Zn and Cu contents considered high and Mn contents very high in this area.

We did not find any correlation between Mg and sodium (Na) or iron (Fe) for both areas. Probably because the concentration of Na was very low and Fe was high (CQFRS/SC, 2004), both for Area 1 (Na: 18.58 mg/dm^3; Fe: 4,06 g/dm^3) and Area 2 (Na: 20.00 mg/dm^3; Fe: 3,05 g/dm^3), fact that may have masked these relationships.

The average Mg content for Area 1 vegetation was 2.3 g/kg DM, ranging from 1.8 g in the cold season to 2.6 g in the hot season. We observed a similar effect for Area 2. This area also had an average content of 2.3 g /kg DM, ranging from 2.0 g in the cold season to 2.7 g in the hot season. The annual average levels of Mg in vegetation for both areas are in the range of 1.8 – 3.6 g kg/DM observed in grasses and legumes (SUTTLE, 2010).

In vegetation, Mg and most of the studied variables did not show any correlation. As shown in Table 3 there was no correlation between Mg and K in vegetation of Area 1 (9,2 g/kg DM). But for Area 2 (11.1 g/kg DM), there was a positive and significant correlation. In this area, the K levels in the soil were 17.1% higher than Area 1. So, there was greater availability of this element for absorption by plants.

Conversely, there was a positive and highly significant correlation of Mg × Ca (4.6 g/kg DM) for Area 1. In Area 2 (5.0 g/kg DM), we did not observe any correlation between these elements, although Ca levels in the soil of this area were 8.0% higher. Thus, the correlation between Mg and K or Ca levels in plants is independent of their content in the soil. Depending on the selective absorption by the roots and other interactions in the soil. The average levels of K and Ca in the vegetation of the two areas are within the forage sufficiency range (CQFRS/SC, 2004; SUTTLE, 2010).

There was no Mg × Zn correlation in vegetation for Area 1 (33.62 mg/kg DM) and Area 2 (37.29 mg/kg

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DM). Cu (10.87 mg/kg DM) was positive and significantly related to Mg for Area 1. For Area 2 (11.20 mg/kg DM), there was no interaction between these elements. This lack of correlation is probably due to the 3.42 times higher soil levels for Area 1 than Area 2. Although the Cu content in the soil was higher in Area 1, the absorption by the plant roots was higher in Area 2. The results of these two cations suggest a selectivity of mineral absorption by plants, mainly because of the floristic composition of each area, reactions in the soil of each area, and environmental conditions.

The average levels of Mg in the blood serum of the grazing animals were 3.05 mg/100 mL for Area 1 and 3.06 mg/100 mL for Area 2. These values are considered within the normality range since levels between 1.8 –4.0 mg/100 mL are normal in cattle (GONZÀLES; SILVA, 2019; KANEKO *et al.*, 2008). We observed a linear increase in Mg levels from the beginning (Area 1 = 2.37 mg/100 mL; Area 2 = 2.36 mg/100 mL) until the end of the experiment (Area 1 = 3.81 mg/100 mL; Area 2 = 3.64 mg/100 mL). The increase is because the absorption efficiency is higher in growing animals than adults are. As the animal grows, the digestion of fibrous feed improves, making more of this element available for absorption by the animal (KIRCHGESSNER *et al*., 2014; SUTTLE, 2010; VELÁSQUEZ-PEREIRA *et al*., 1997).

The correlation Mg × P (6.5 mg/100 mL) was positive and highly significant for Area 2. There was no correlation of Mg × P for Area 1 (7.6 mg/100 mL), even though the P levels were 14.5% higher in the blood serum of animals in this area. However, the synergism between these elements is a fact, since Mg is an enzymatic activator of almost all phosphorylated enzymes and a P-carrier in the absorption by plants (FAGERIA, 2001; SILVA; TREVIZAM, 2015) and animals (GONZÀLES; SILVA, 2019; KANEKO *et al.*, 2008). P values in blood serum of animals are considered within the normality range (GONZÀLES; SILVA, 2019; KANEKO *et al.*, 2008).

We found a highly significant and positive correlation of Mg × K in the blood serum of animals for Area 1 (5.27 meq/L) and Area 2 (5.20 meq/L). This result is related to the ruminal absorption of Mg since the enzyme Na-K-ATPase is necessary for the active absorption of Mg. Similarly, Ca, which is also actively absorbed in the rumen (GONZÁLES; SILVA, 2019; RÉMOND; MESCHY; BOIVIN, 1996) was high significant and positively related to Mg for Area 1 (14.4 mg/100 mL) and Area 2 (14.2 mg/100 mL).

There was no Mg × Zn correlation for Area 1 (78.5 µg/100 mL). This correlation was positive and significant for Area 2 (73.0 µg/100 mL) since Mg favors the Zn absorption (GONZÁLES; SILVA, 2019). Cu (51,3 µg/100 mL) was positive and significantly related to Mg for Area 1. However, for Area 2 (41.6 µg/100 mL), the correlation was negative and highly significant because contents below 50.0 µg/100 mL indicate deficiency (GONZÁLES; SILVA, 2019). The reason for these correlations is that the cations together with Mg are part of or are cofactors that activate enzymes. The higher or lesser presence of these ions in the digestive tract may affect their absorption by the animal, influencing the relationship with magnesium positively or negatively in blood serum. There was no correlation of Mg × Mn for any area. Probably because the levels of this element in vegetation are considered very high in both areas Area 1 = 384.8 mg/kg DM; Area 2 = 253.1 mg/kg DM (SUTTLE, 2010).

The Mg × Na correlation was positive and highly significant for Area 1 (127.15 meq/L) and Area 2 (126.5 meq/L), fact that is due to the active absorption mode of Mg in the rumen, which is modulated by the

Na/K-ATPase system (GONZÁLES; SILVA, 2019; RÉMOND; MESCHY; BOIVIN, 1996).

The Mg × Fe correlation was positive and highly significant (72.5 µg/100 mL) for Area 1. Although Fe levels in vegetation were 23.8 % higher for Area 2, there was no correlation between Mg and Fe in blood serum of the animals (64.7 µg/100 mL) in this area. This may have occurred because in some plants the roots limit the translocation of some metals to the aerial part of the plants (SILVA; VITTI; TREVIZAM, 2007).

In general, when evaluating the correlations within each link of the soil-plant-animal chain, it is observed that the correlation of Mg with the other variables varied differently in both areas. Thus, regardless of the levels of the variables, higher or lower, there were or not correlations with Mg in each area. In addition, the same variable was negatively or positively correlated with Mg in each area. Thus, it is inferable that in undisturbed natural pasture areas interactions with Mg depend also on other factors such as: soil physical-chemical and biological reactions, floristic composition and environmental conditions.

The relationships between the links in the chain soil- plant-animal are presented in Table 4. There was no correlation between soil-plant links except for the pH effect for Area 2, which was higher than Area 1 and presented a more favorable environment for absorption by plants (see Table 3). This is probably due to two main factors. The first is quantitative; almost all the exchangeable cations and anions showed high levels for the soils of both areas. The second is that, since the minerals in sufficient quantities were available for absorption by the species of the natural grassland, the plants performed a selective and balanced absorption. In this sense, Fageria (2001) indicates that, generally, an excess of one cation in the nutrient medium reduces the net uptake of others cations, whereas the sum of cations in the plant tissue often remains nearly constant.
Most of the variables were not related to Mg between the plant-blood serum links.

The Mg × S correlation was negative and significant for Area 1. Much of the S from the feed's sulfates and breakdown of sulfur amino acids by sulfate-reducing bacteria are absorbed in the rumen like Mg. But this absorption occurs by simple diffusion and not by the Na/K-ATPase system. Absorption refers to the non-dissociated form (H_2S) that is fat-soluble and passively absorbed with volatile fatty acids (RÉMOND; MESCHY; BOIVIN, 1996). Therefore, the absorption mechanisms are different, and there is no competition of these elements for absorption by animals. It is also important to note that the S levels in the vegetation for Area 1 (0.14 g/kg DM) and Area 2 (0.13 g/ kg DM) were very similar. Thus, the mechanism of this antagonistic relationship must be connected to reactions with micronutrients in the rumen (Na, Mo, Cu, Cd) and the effectiveness of the S utilization by the rumen's microorganisms on the formation of sulfur amino acids in animals and to higher or lower availability of them in the rest of the digestive tract. Furthermore, it should also be considered that sulfate (*in* vitro) is a potent inhibitor of Mg uptake across the rumen epithelium, due possibly to a rise in lumenal pH (SUTTLE, 2010). There was no correlation of Mg × S for Area 2.

The Mg × B correlation was positive and highly significant for both areas. B is essential for plant growth. It is also essential for the absorption of Mg by plants because as they grow, there is some increase in the absorption of minerals available in the soil solution and, consequently, greater availability for animals. The main site for Mg absorption (up to 80 %) in ruminants is the rumen (GONZÁLES; SILVA, 2019; RÉMOND; MESCHY; BOIVIN, 1996), and a more limited absorption occurs on a decreasing scale in the other segments of the digestive tract up to the colon (ALCALDE *et al*., 1999). Although B has no known function in the ruminant organism, in non-ruminants, its presence in the digestive tract increases the absorption of Mg and other minerals (Ca, K) in the intestine (EREN; UYANIK; KÜÇÜKERSAN, 2004). Thus, the presence of B in the intestine of ruminants probably also influences the absorption of Mg.

Table 4. Correlations of magnesium contents between links of the soil - plant – animal chain with the other variables: soil - plant (observation by collection point), plant - blood serum and soil - blood serum (observation by animal), eliminating the effects of month and collection points or animal.

	Area 1						Area 2					
	soil-plant		plant-serum		soil-serum		soil-plant		plant-serum		soil-serum	
	r	P	r	P	r	P	r	P	r	P	r	P
Clay	-	-	-	-	-		-	-	-	-	-	-
pH	-	-	-	-	-		0.3008	0.0377^{*}	-	-	-	-
OM	-	-	-	-	0.8884	0.0001^{**}	-	-	-	-	0.9253	$< 0.0001^{**}$
Al	-	-	-	-	-		-	-	-	-	-	-
B	-	-	-	-	0.7582	0.0043^{**}	-	-	-	-	0.7958	0.0020^{**}
N	-	-	-	-	0.7581	0.0043^{**}	-	-	-	-	-	-
P	-	-	-	-	-		-	-	-	-	-	-
K	-	-	-	-	-		-	-	-	-	-	-
Ca	-	-	-	-	-		-	-	-	-	-	-
Mg	-	-	-	-	0.8374	0.0007^{**}	-	-	-	-	0.6870	0.0136^{*}
S	-	-	- 0.5975	0.0402^{*}	-		-	-	-	-	-	-
Zn	-	-	-	-	-		-	-	-	-	-	-
Cu	-	-	-	-	-		-	-	-	-	0.6904	0.0129^{*}
Mn	-	-	-	-	0.7687	0.0035^{**}	-	-	-	-	-	-
Na	-	-	-	-	- 0.8811	0.0002^{**}	-	-	-	-	- 0.8392	0.0006^{**}
Fe	-	-	-	-	0.5877	0.0445^{*}	-	-	-	-	-	-

r: Pearson correlation coefficient; P: Prob.>|r|; ^{ns}: not significant (P > 0.05); *: significant 0.01 < P < 0.05; **: highly significant (P < 0.01).

Although the N levels in the soil for Area 1 were lower than Area 2 (+ 12 %), the Mg × N correlation in blood serum for Area 1 was positive and highly significant. We did not observe this correlation for Area 2. There was no correlation of Mg in the animals' blood serum with P and K in the soil for any area.

As expected, Mg levels in soil positively related to blood serum for both areas. However, the correlation was highly significant for Area 1, whereas for Area 2, it was only significant at P < 0.05 level. This was probably because Mg content for Area 2 was 4.7 % higher in soil than Area 1, masking the relation.

There was no Cu × Mg correlation between soil-blood serum links for Area 1. For Area 2, it was positive and significant. Perhaps, this occurred because Cu levels in the soil of Area 1 were 3.4 times higher than Area 2, masking the relationships between these elements. The opposite effect occurred in the Mg × Mn correlation. It was positive and highly significant for Area 1, which was 13.2 % higher in the soil of this area. There was no correlation for Area 2.

The Mg × Na correlation was negative and highly significant for both areas. This is because Mg is actively absorbed in the rumen, and for this, the Na/ K-ATPase is required. This enzyme requires a balanced

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(5:1) Na:K ratio (GONZÁLES; SILVA, 2019; RÉMOND; MESCHY; BOIVIN, 1996). Na has high bioavailability for plants and animals as the Na levels were very low in the soils of both areas, the absorption by plants and consequently by animals corresponded to the low levels in the soil.

The Mg × Fe correlation was positive and significant for Area 1. There was no correlation for Area 2. This is probably because the Fe levels in the soil of Area 2 were 24.9 % lower than at Area 1. On the other hand, the Fe levels in the vegetation of Area 2 (893.3 mg/kg DM) were 23.8% higher than Area 1 (681.0 mg/kg DM), probably due to the difference in the floristic composition of both areas. We also should consider that the bioavailability of Fe varies a lot (10-40 %) in forages (SUTTLE, 2010), and the absorption by growing animals is between 15 and 20 % (GONZÁLES; SILVA, 2019), which is the animal category of the present study.

Similarly, to the relationship between Mg and the other variables studied within each link of the soil-plant-animal chain, we observed that among the links in the chain, regardless of the levels, higher or lower, correlations occurred or not with Mg in each area.

The results obtained in the present study revealed negative interactions (antagonism) between Mg with clay and Al in the soil for Area 2, Mg × Cu in the blood serum of animals for Area 2 (Table 3) within each link of the soil-plant-animal chain, Mg × S between the plant-animal links for Area 1, and Mg × Na between the soil-animal links for both areas (Table 4). All other relationships were positive (synergism). This is probably because most of the cations presented high levels in the soils of both areas, except for Al and Na. About the anions, only P contents were considered low within chain links since B and S were considered high (CQFRS/SC, 2004). These results are in accordance with the observations of Rietra *et al.* (2017), which report the existence of synergistic correlation between most divalent cations.

Based on the results obtained within and between the links of the soil-plant-animal chain, it is possible to visualize the behavior of the minerals to develop improvement actions, such as soil correction and introduction of species, which allow the improvement of the productivity of grazing animals.

Therefore, we infer that there is no correlation between rainfall and Mg in the soil-plant-animal chain. There was a positive correlation between temperature and Mg in the chain. The relationship of Mg with other variables within the links of the soil-plant-animal chain is influenced by some factors such as physicochemical and biological soil reactions, floristic composition and environmental conditions. In natural undisturbed rangeland areas, the organic matter is the main colloid of the soil, for the availability of magnesium to plants and, consequently, to the animals. There was no correlation between the soil-plant links of the chain. There was a highly significant relationship between soil-animal links of the chain.

Conflict of interest

The authors declare that the research was conducted in the absence of any potential conflicts of interest.

Ethical statements

The authors confirm that the ethical guidelines adopted by the journal were followed by this work, and all authors agree with the submission, content and transfer of the publication rights of the article to the journal.

They also declare that the work has not been previously published nor is it being considered for publication in another journal.

The authors assume full responsibility for the originality of the article and may incur on them, any charges arising from claims, by third parties, in relation to the authorship of the article.

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