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ORIGINAL PAPER

EFFECT OF BASIC CATION SATURATION RATIOS IN SOIL ON YIELD OF ANNUAL RYEGRASS *(LOLIUM MULTIFLORUM* L.)*

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Abstract

A pot experiment was carried out in a greenhouse to investigate the influence of the percentage of Ca, Mg, K and H occupying the soil's cation exchange capacity (CEC) on the yield of annual ryegrass. The experiment comprised 13 fertilization treatments with various basic cation saturation ratios in soil. The experimental design consisted of three parts. In part A, the soil's saturation level of Ca was increased (from 41% to 71%), in part B, the saturation level of Mg was elevated relative to the remaining cations (from 5% to 33%), and in part C, the saturation level of K was raised (from 2% to 11%). The results of this study indicate that high yields of annual ryegrass with balanced mineral composition can be achieved when 50-60% of the exchange complex is occupied by Ca, 8-12% by Mg and 4-5% by K. A rise in K saturation above 5% increased ryegrass yield, but it also led to deterioration in the quality of green forage due to excessive accumulation of K and lower concentrations of Mg and Ca in grass. A significant decrease in the yield of annual ryegrass was noted when the soil's base saturation level of K dropped below 4%. The increase in the soil's saturation level of Mg from 5% to 12% contributed to an increase in the weight of annual ryegrass plants. Despite the absence of significant differences in yield between treatments, the increase in Mg saturation from 5% to 12% was fully justified because it improved the quality of green forage. The soil's saturation levels of all major cations is an important indicator of soil productivity.

Keywords: exchangeable cation percentage, magnesium, potassium, ryegrass, yield.

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INTRODUCTION

There are two approaches to establishing optimal fertilizer doses based on the results of soil analysis. In the first and more popular approach, known as the sufficiency level of available nutrients (SLAN), sufficient amounts of each soil nutrient are identified in soil. In the second approach, referred to as the basic cation saturation ratio (BCSR), the optimal percent base saturation of the CEC with major cations are determined to guarantee high yields and high quality of crop plants (McLean, Carbonell 1972, Liebhardt 1981, Olson et al. 1982, McLean et al. 1983).

In line with the BCSR concept, optimal base saturation levels in soil that ensure high yields and high quality crops should approximate 65-85% Ca, 10-15% Mg and 5% K (McLean, Carbonell 1972, Zalewska 2008). Extensive research into the usefulness of the BCSR concept revealed, however, that there is no "ideal" per cent saturation range of Ca^{2+}, Mg^{2+}, K^{+} and H^{+} for all plant species and all soil types. The concept of an optimal basic cation saturation ratio (BCSR) is debatable because plant yield and the percentage of the CEC occupied by cations were not always highly correlated in experiments. A significant decrease in plant weight was often unobserved in soils whose saturation percentages of CEC diverged from the "ideal" level (Eckert, McLean 1981, Liebhardt 1981, McLean et al. 1983, Kopittke, Menzies 2007). It should be noted, however, that K, Mg and Ca concentrations in plants, in particular in vegetative parts, were always significantly correlated with BCSR values (McLean et al. 1983, Zalewska 2005*a*,*b*, 2008, Zalewska et al. 2017).

Most researchers are in agreement that the Mg : K ratio in soil should be maintained at minimum 2 : 1 to achieve high yields of crops with balanced mineral composition (McLean, Carbonell 1972, Zalewska, 2003, 2008). When the Mg : K ratio decreases below 2, the first consequence is the deterioration in fodder quality due to excessive accumulation of K and decreased Mg concentration (Zalewska 2005*a*, 2008, Zalewska et al. 2017). A drop in yield is noted only at much greater disproportions between those elements in soil. In a study by Zalewska (2008), an increase in the soil's base saturation level of K above 5% frequently contributed to an increase in yield, but also deteriorated the mineral composition of plants due to excessive accumulation of K and lower content of Mg and Ca, particularly in crops grown for green fodder.

Amézketa (1999) observed that basic cation saturation ratios also influence soil structure, in particular surface crusting, compaction and hydraulic conductivity. The high exchangeable Ca content (65%) of a "balanced soil" is beneficial in maintaining and improving soil structure and aggregate stability. A lower Ca saturation level and higher Mg saturation level relative to the BCSR concept can lead to a deterioration in soil structure because aggregates more saturated with Ca are less susceptible to dispersion (Rengasamy 1983, Zhang, Norton 2002).

Some authors disprove the usefulness of the BCSR concept (St. John 2005, Kopittke, Menzies 2007). Ologunde and Sorensen (1982) and Eckert (1987) reported that in soils with an optimal supply of Ca, Mg and K, the basic cation ratios in soil (Ca : Mg, Ca : K and K : Mg) generally did not influence plant yield. Numerous studies revealed that in soils with balanced pH, the Ca : Mg ratio had a limited influence on the yield and mineral composition of plants (Fox, Piekielek 1984, Kelling et al. 1996, Schönbeck 2000, Zalewska 2005*b*). In a study by McLean and Carbonell (1972), a Ca : Mg ratio of 2.2 : 1 - 14.3 : 1 did not exert a significant effect on plant yield, and Liebhardt (1981) found that a wide range of values of the Ca : Mg ratio met the nutritional requirements of maize and soybeans.

The objective of this study has been to determine the basic cation saturation ratio in soil which contributes to the optimal yield and favourable mineral composition of annual ryegrass plants.

MATERIALS AND METHODS

A pot experiment was performed in a greenhouse at the University of Warmia and Mazury in Olsztyn, Poland (2007). Thirteen fertilization treatments with various basic cation saturation ratios in soil were analyzed. The experiment consisted of three parts. In part A, soil's saturation level of Ca was increased (from 41% to 71%), in part B, the saturation level of Mg was elevated relative to the remaining cations (from 5% to 33%), and in part C, the saturation level of K was raised (from 2% to 11%).

Pots were filled with 6.0 kg of air-dry soil with the textural composition of loamy sand, which contained 81.3% of sand (particle size: 2.0-0.05 mm), 16.9% of silt (particle size: 0.05-0.002 mm) and 1.7% of clay (particle size: <0.002 mm) according to the USDA textural soil classification. The remaining physical and chemical properties of soil used in the experiment are presented in Table 1. The experimental plant was annual ryegrass (*Lolium multiflorum* L. cv. Kroto), harvested four times at the early heading stage.

In order to obtain different levels of Ca, Mg and K saturation in experimental treatments (with four replications per treatment), adequate amounts of the above cations were applied to the soil prior to sowing (Table 2). Cal-

Table 1

Physico-chemical properties of soil used in the experiment

CEC (mmol$_c$ kg^{-1} soil)	Exchangeable cations (mg kg^{-1} soil)			Cation saturation of CEC (%)				Hh (mmol H$^+$ kg^{-1} soil)	pH$_{KCl}$	C$_{org}$ (g kg^{-1} soil)
	Ca	Mg	K	Ca	Mg	K	H			
114.4	550	52	86	24.0	3.7	1.9	70.5	80.6	4.2	26.2

Table 2

Soil cation ratios, cation saturation of CEC and other chemical properties of soil after incubation with fertilizer

Cation ratios in soil ($mmol_c$)				Cation saturation of CEC (%)				BS** (%)	Hh (mmol $H^+ kg^{-1}$ soil)	pH_{KCl}	Exchangeable cations (mg kg^{-1} soil)			Dose (mg kg^{-1} soil)		
Ca	Mg	K	H	Ca	Mg	K	H				Ca	Mg	K	Ca	Mg	K
Part A																
19.7	1.0	0.49	6.7	70.7	3.6	1.8	24.0	76.1	34.1	5.8	2026	62	98	1476	11	12
15.2	1.0	0.51	5.7	68.0	4.5	2.3	25.2	74.8	35.6	5.7	1954	79	129	1439	28	43
10.7	1.0	0.52	4.3	64.9	6.1	3.2	25.9	74.2	35.8	5.6	1820	111	176	1270	59	90
7.0*	**1.0**	**0.50**	**3.4**	**58.8**	**8.4**	**4.2**	**28.6**	**71.4**	**39.8**	**5.5**	**1637**	**153**	**246**	**1087**	**102**	**160**
2.8	1.0	0.52	2.5	41.3	14.7	7.6	36.3	63.6	49.0	5.2	1124	272	438	574	221	352
Part B																
6.6	0.5	0.50	3.1	61.4	4.8	4.6	29.2	70.8	40.2	5.5	1733	81	260	1184	29	174
7.0	**1.0**	**0.50**	**3.4**	**58.8**	**8.4**	**4.2**	**28.6**	**71.4**	**39.8**	**5.5**	**1637**	**153**	**246**	**1087**	**102**	**160**
6.4	1.4	0.50	3.4	54.6	12.3	4.3	28.7	71.2	38.2	5.5	1553	217	231	1003	166	145
6.4	2.6	0.50	3.8	48.1	19.6	3.7	28.6	71.4	39.0	5.5	1343	375	203	793	324	117
6.4	5.7	0.50	4.7	37.1	32.7	2.9	27.3	72.7	36.0	5.6	1020	618	152	470	567	67
Part C																
6.6	1.0	0.26	3.2	59.8	9.0	2.3	28.9	71.1	38.4	5.6	1683	157	125	1133	105	39
7.0	**1.0**	**0.50**	**3.4**	**58.8**	**8.4**	**4.2**	**28.6**	**71.4**	**39.8**	**5.5**	**1637**	**153**	**246**	**1087**	**102**	**160**
6.8	1.0	0.75	3.5	56.6	8.3	6.2	29.0	71.1	40.2	5.5	1593	148	360	1043	97	274
6.7	1.0	0.95	3.5	54.9	8.2	7.8	29.1	70.9	40.8	5.5	1553	145	465	1003	93	379
6.4	1.0	1.41	4.1	49.8	7.7	10.9	31.6	68.4	44.4	5.3	1475	137	665	925	86	579

* This treatment belongs to parts A, B and C

** BS – base saturation

cium and magnesium were applied as oxides and potassium as KCl and K_2SO_4 in two equal parts. In addition, 0.51 g of N and 0.57 g of P pot^{-1} (in the form of $(NH_4)_2HPO_4$) were applied before sowing in equal doses in all the treatments. During the growing season, ammonium nitrate was added in the amount of 0.5 g N pot^{-1} per regrowth. After three weeks of soil incubation with fertilizers, annual ryegrass seeds were sown. After germination, 20 plants were left per pot. Soil moisture was maintained at 70% of maximum water-holding capacity during the experiment.

Simultaneously, another experiment was carried out, in which soil samples containing Ca, Mg and K in the amounts identical to those used in the experiment with ryegrass (expressed per kg of soil) were incubated for 3 weeks. The analysis of soil samples after incubation provided the basis for determining the initial cation saturation of soil. Table 2 presents the doses of Ca, Mg and K used in the experiment, the concentrations of exchangeable cations determined after soil incubation with fertilizers, and the per cent saturation of the CEC with Ca, Mg and K in each fertilization treatment.

Soil samples were air-dried, passed through a 2-mm sieve and analyzed for exchangeable K, Ca and Mg after extraction with 1M NH_4OAc at pH = 7.00 (Van Reeuwijk 2002). The content of K and Ca was determined by flame emission spectrometry, and the Mg content was determined by atomic absorption spectrometry. The grain-size composition of soil was determined by laser diffraction with the use of a Mastersizer 2000 particle size analyzer. The organic C content was determined by the Tiurin's method, soil hydrolytic acidity (Hh) – by the Kappen's method, and soil pH in 1 M KCl (1 : 2.5 soil : solution ratio) – by the potentiometric method. The CEC (cation exchange capacity) was estimated by summation of exchangeable bases (Ca, Mg, K) and soil hydrolytic acidity (Hh):

The 'effective CEC' was calculated as:

$$\text{CEC} = \text{Exch. (Ca + Mg + K + Hh) [cmol}_c\text{ kg}^{-1}\text{ air-dry soil].}$$

The exchangeable cation percentage was calculated as:

$$\text{exchangeable cation percentage} = \frac{\text{exchangeable cation}}{\text{CEC}} \cdot 100\%.$$

The cation ratios in soils were calculated on the mmoles of charge basis ($mmol_c$) (Van Reeuwijk 2002).

The results were processed by one-way ANOVA for completely randomized orthogonal designs. Differences between means (significance level of 1%) were estimated by the Tukey's HSD test. The relationships between selected parameters were determined by correlation and regression analyses. Statistical analyses were performed using Statistica v. 7.0 program.

RESULTS AND DISCUSSION

The influence of the basic cation saturation ratios on the yield of annual ryegrass was presented based on the total weight of four cuts because the observed change trends in yield were similar for every cut (Table 3). The percentage of the CEC occupied by K was the major determinant of plant yield. An increase in the saturation level of K from 2.3% to 10.9% contributed to a continued increase in the weight of annual ryegrass plants (fertilization treatments – part C). The above was confirmed by the results of correlation and regression analyses, which revealed that the soil's base saturation level of K had a significant, positive effect on the yield of annual ryegrass (Figure 1*a*). The determination coefficient for the noted relationship was very high at $R^2 = 0.89$. Potassium saturation of 6-8%, accompanied by Mg at 8% and Ca at approximately 55%, seems to be sufficient to achieve the

Table 3

Effect of soil's cation saturation on the yield of annual ryegrass

Cation saturation of CEC (%)				Yield (g DM pot^{-1})				
Ca	Mg	K	H	I cut	II cut	III cut	IV cut	∑ cut
Part A								
70.7	3.6	1.8	24.0	22.3	18.9	24.7	15.0	80.9
68.0	4.5	2.3	25.2	24.6	20.6	26.3	15.7	87.2
64.9	6.1	3.2	25.9	25.5	21.1	26.3	15.9	88.8
58.8*	**8.4**	**4.2**	**28.6**	**26.6**	**23.0**	**28.0**	**17.2**	**94.8**
41.3	14.7	7.6	36.3	28.9	22.6	28.8	17.5	97.8
Part B								
61.4	4.8	4.6	29.2	27.3	21.8	28.1	16.5	93.6
58.8	**8.4**	**4.2**	**28.6**	**26.6**	**23.0**	**28.0**	**17.2**	**94.8**
54.6	12.3	4.3	28.7	28.3	22.9	28.7	16.7	96.6
48.1	19.6	3.7	28.6	28.1	21.7	26.1	16.5	92.4
37.1	32.7	2.9	27.3	26.3	20.3	26.2	16.4	89.3
Part C								
59.8	9.0	2.3	28.9	26.8	21.2	25.2	17.1	90.3
58.8	**8.4**	**4.2**	**28.6**	**26.6**	**23.0**	**28.0**	**17.2**	**94.8**
56.6	8.3	6.2	29.0	29.3	22.7	28.7	17.9	98.6
54.9	8.2	7.8	29.1	28.4	23.4	29.9	18.1	99.8
49.8	7.7	10.9	31.6	28.8	23.3	30.2	18.0	100.3
$HSD_{0.01}$**				2.0	1.9	2.0	2.2	4.1

* This treatment belongs to parts A, B and C

** $HSD_{0.01}$ – critical difference significant at $p \leq 0.01$ calculated by the Tukey's HSD test

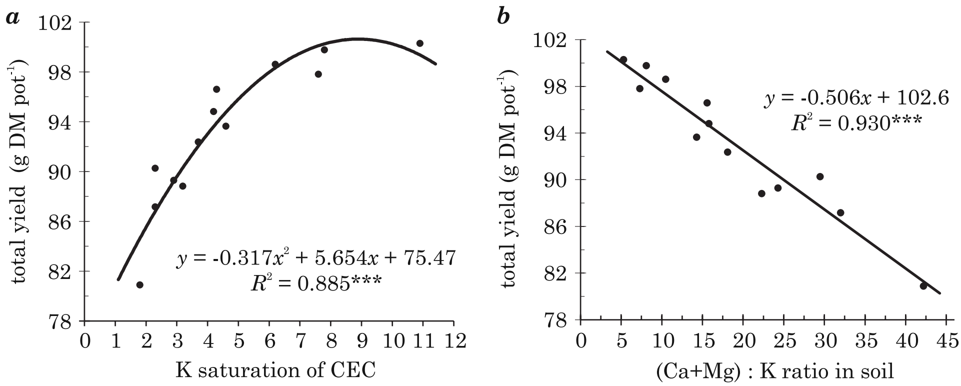

Fig. 1. Total yield of annual ryegrass as affected by percentage K saturation of CEC and (Ca+Mg) : K ratio in soil ($mmol_c$); *** correlation significant at 0.01 level

maximum yield of grass. A further increase in K saturation (to 10.9%) did not exert a significant influence on ryegrass yield, and it contributed to an undesirable drop in Mg concentration in grass (Zalewska et al. 2017). A steep decrease in plant weight was noted when the saturation level of K was decreased to 2.3% (the Ca : Mg : K ratio in this treatment was 6.6 : 1 : 0.26). The results of this study suggest that a decrease in K saturation below 4% could induce a significant reduction in grass yield. The present findings are consistent with the results of earlier studies by Zalewska (2005*a*,*b*, 2008). In most cases, a significant decrease in crop yield was reported when K saturation was below 4%. In soils with balanced pH, the percentage of K held by the CEC had a decisive impact on yield, in particular in crops grown for green fodder such as oats, grasses, sunflower and carrots. When K saturation was raised above 5%, crop yield continued to increase, but this was accompanied by an undesirable increase in the concentration of K and lower levels of Mg and Ca in green fodder. In oilseed rape grown for seeds, an increase in the soil's base saturation level of K from 5% to 8% (Mg saturation was 8% and Ca saturation approximated 55%) was justified because it significantly increased seed yield without contributing to excessive accumulation of K in generative plant parts (Panak, Zalewska 1988).

The increase in the soil's saturation level of Mg from 4.8% to 12.3% (fertilization treatments – part B) also contributed to an increase in the weight of annual ryegrass plants. Despite the absence of significant differences in yield between treatments, the increase in Mg saturation to 12% was fully justified because it improved the quality of green forage. Plants from the above treatment were characterized by a significantly lower concentration of K and higher content of Mg (Zalewska et al. 2017). A further increase in the Mg saturation (to 19.6% and 32.7%), which took place mostly at the expense of saturation levels of K and Ca, led to a highly significant decrease in the total yield of ryegrass. This probably resulted from the simultaneous drop in the saturation level of K below 4% in those treatments.

In experiments performed on various plant species, the percentage of the CEC occupied by Mg and the exchangeable Mg : K ratio often significantly influenced crop yield. In an experiment conducted on yellow lupine, the highest green forage yield was noted with Mg saturation of 10% and K saturation of 5% (ZALEWSKA 2003). A decrease in the saturation level of Mg below 10% with a simultaneous increase in the K saturation above 5% resulted in a significant drop in lupine yield. In a study on sunflowers, the highest green forage yield was noted in soil with the Mg saturation level of 8.4% and K saturation level of 4.2% (ZALEWSKA 2008). When the Mg saturation of the CEC was lowered to 5%, the green forage yield of sunflower decreased significantly. In an experiment with carrots, a decrease in the percentage of the CEC occupied by Mg to 5.7% with a simultaneous increase in the K saturation to 13.5% also led to a significant drop in the weight of roots and leaves (ZALEWSKA 2005*a*). The decrease in yield was probably caused by fluctuations in the Mg : K ratio in soil, which inhibited the Mg uptake by plants. Many researchers agree that the exchangeable Mg : K ratio in soil should be maintained at minimum 2 : 1, whereas the saturation level of Mg should be at least 10%. The above Mg : K ratio and Mg saturation level guarantee high yields of crop plants with favourable mineral composition (MCLEAN, CARBONELL 1972, ZALEWSKA 2003, 2008).

In part A of the experiment, where the soil's saturation level of Ca was increased (from 41% to 71%) with a simultaneous decrease in the percentage of the CEC occupied by Mg, K and H, the highest yield was achieved when the Ca saturation reached 41.3%, Mg saturation – 14.7%, K saturation – 7.6% and H saturation – 36.3% (Ca : Mg : K : H ratio of 2.8 : 1 : 0.52 : 2.5). A significant decrease in the weight of annual ryegrass plants was noted when the saturation level of Ca increased above 58.8% and the saturation level of K decreased below 4.2%. The results of this study suggest that a base saturation of 64% is sufficient to guarantee satisfactory ryegrass yield. The decrease in the K saturation below 4% was the key factor responsible for the drop in grass yields in treatments with higher Ca saturation levels.

The results of the present experiment indicate that the Ca:Mg ratio has a limited influence on plant yield. In fertilization treatments B, a change in the Ca : Mg ratio from 2.5 : 1 to 13.2 : 1 had no significant effect on the yield of annual ryegrass. In treatments C, characterized by a similar Ca : Mg ratio (approximately 6.5 : 1), significant differences in the weight of ryegrass plants were observed. In those treatments, the saturation level of K was the key factor determining ryegrass yield. Those results indicate that saturation levels of all four major cations (Ca, Mg, K and H) should be taken into consideration when interpreting the results of soil analyses and formulating fertilization guidelines. A single cation ratio has a limited influence on crop yield. Other authors also reported low correlations between the Ca : Mg ratio and plant yield (LIEBHARDT 1981, KELLING et al. 1996, SCHONBECK 2001). STEVENS et al. (2005) revealed that the growth of cotton (*Gossypium hirsutum* L.), lint yield, micronaire and fiber strength did not differ significantly in soils where Ca : Mg ratios ranged from 7.6 : 1 to 2.5 : 1.

The results of correlation and regression analyses point to very strong relationships between ryegrass yield and the (Ca+Mg) : K ratio in soil ($R^2 = 0.93$). The increase in the value of the above ratio from 5 to 42 was accompanied by a proportional decrease in ryegrass biomass (Figure 1b). The value of the analyzed ratio is determined by the concentrations of the three major exchangeable cations, therefore, it could be a more effective parameter for describing the chemical fertility of soil than the ratio between two cations only (e.g. Ca : Mg).

According to some researchers, the BCSR concept is not useful for formulating fertilizer recommendations, and some of them even claim that basic cation saturation ratios have a limited influence on the chemical, physical and biological fertility of soils (Kopittke, Menzies 2007). These views are easy to refute because the BCSR concept defines not only the ratios of basic cations in soil, but also the per cent saturation of the CEC with Ca, Mg and K, which provides information about the concentrations of available K, Mg and Ca in soils with a particular CEC. A single ratio between selected cations in soil, e.g. Ca : Mg, has a limited influence on soil fertility, but the soil's saturation levels of all major cations is an important indicator of soil productivity.

The results of this study, which investigated annual ryegrass, and earlier findings (Zalewska 2005*a*,*b*, 2008, Zengin et al. 2009, Zalewska et al. 2017) indicate that in soils with the saturation levels of around 65% Ca, 10% Mg, 5% K and 20% H (optimal saturation according to the BCSR), the yields of the tested plants were always similar to maximum yields, and their mineral composition was favourable.

CONCLUSION

The percentage of the CEC occupied by K, Ca, Mg and H and the mutual ratios between these cations significantly influenced the yield of annual ryegrass. The results of this study do not support the use of a single, optimal basic cation saturation ratio in the soil's exchange complex. Changes in the Ca, Mg and K saturation did not always exert a significant effect on the yield of annual ryegrass. The results of this study indicate that high yields of annual ryegrass with balanced mineral composition can be achieved when 50-60% of the soil's exchange complex is occupied by Ca, 8-12% by Mg and 4-5% by K. A rise in K saturation above 5% increased ryegrass yield, but it also led to deterioration in the quality of green forage due to excessive accumulation of K and lower concentrations of Mg and Ca in grass. A significant decrease in the yield of annual ryegrass was noted when the saturation level of K dropped below 4%.

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