SEÇÃO IV - FERTILIDADE DO SOLO E NUTRIÇÃO DE PLANTAS

POTASSIUM AVAILABILITY IN A HAPLUDALF SOIL UNDER LONG TERM FERTILIZATION[1]

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ABSTRACT

In a system in which fertilization is recommended, diagnosis of soil K availability and the establishment of critical levels are made difficult by the possibility of a contribution of non-exchangeable forms of K for plant nutrition. Due to its magnitude, this contribution is well diagnosed in long term experiments and in those which compare fertilization systems with positive and negative balances in terms of replacement of the K extracted by plants. The objective of this study was to evaluate K availability in a Hapludalf under fertilization for sixteen years with the addition of K doses. The study was undertaken in an experiment set up in 1991 and carried out until 2007 in the experimental area of the Soil Department of the Federal University of Santa Maria (Universidade Federal de Santa Maria - UFSM), in Santa Maria (RS), Brazil. The soil was a Typic Hapludalf submitted to four doses of K (0, 60, 120 and 180 kg ha^{-1} K$_2$O) and subdivided in the second year, when 60 kg ha^{-1} of K$_2$O were reapplied in the subplots in 0, 1, 2 and 3 times. As of the fifth year, the procedure was repeated. Grain yield above ground dry matter and total K content contained in the plant tissue were evaluated. Soil samples were collected, oven dried, ground, passed through a sieve and submitted to exchangeable K analysis by the Mehlich-1 extractor; non-exchangeable K by boiling HNO$_3$ 1 mol L^{-1} and total K by HF digestion. Potassium fertilization guidelines should foresee the establishment of a critical level as of which the recommended dose should accompany crop needs, which coincides with the quantity exported by the grain,

without there being the need for the creation of broad ranges of K availability to predict K fertilization. In adopting the K fertilization recommendations proposed in this manner, there will not be K translocation in the soil profile.

Index terms: potassium fertilization, potassium critical level, potassium export by plants.

RESUMO: *DISPONIBILIDADE DE POTÁSSIO EM ARGISSOLO COM HISTÓRICO DE ADUBAÇÃO*

Em um sistema de recomendação de adubação, o diagnóstico da disponibilidade de K do solo e o estabelecimento de níveis de suficiência são dificultados pela possibilidade de contribuição de formas não trocáveis de K para a nutrição das plantas. Devido à sua magnitude, essa contribuição é bem diagnosticada em experimentos de longa duração e que comparem sistemas de adubação com balanços positivos e negativos em termos de reposição do K extraído pelas plantas. Este trabalho teve como objetivo avaliar a disponibilidade de K em um Argissolo com histórico de 16 anos de adição de doses desse nutriente. O trabalho foi realizado em um experimento instalado em 1991 e conduzido até 2007, na área experimental do Departamento de Solos da Universidade Federal de Santa Maria (UFSM), em Santa Maria (RS). O solo foi um Argissolo Vermelho distrófico típico submetido a quatros doses de K (0, 60, 120 e 180 kg ha^{-1} K$_2$O), subdivididas no segundo ano, a partir do qual foram reaplicados 60 kg ha^{-1} de K$_2$O nas subparcelas em 0, 1, 2 e 3 vezes. A partir do quinto ano, o procedimento foi repetido. Avaliaram-se a produção de grãos e de matéria seca e o teor total de K contido no tecido. Amostras de solo foram coletadas, secas, moídas, passadas em peneira e submetidas à análise de K trocável, pelo extrator de Mehlich-1; de K não trocável, pelo HNO$_3$ 1 mol L^{-1} fervente; e de K total, pelo HF. Os programas de adubação potássica devem prever o estabelecimento de um nível de suficiência, a partir do qual a dose recomendada deve acompanhar as necessidades das culturas, que coincidem com a quantidade exportada pelos grãos, não sendo necessária a criação de amplas faixas de disponibilidade de K para predição da adubação. Adotando-se as recomendações de adubação potássica assim propostas, não haverá translocação de K no perfil do solo.

Termos de indexação: adubação potássica, nível de suficiência, exportação de potássio por plantas.

INTRODUCTION

Soil analysis as a way of predicting fertilization in the Southern region of Brazil began in the 1940s (Mohr, 1950). Nevertheless, calibration only intensified as of the 1960s, and the first tables relating results of analyses with doses of fertilizers were used at the end of this decade (UFRGS, 1968; UFRGS, 1973). In these tables, fertilization correction was foreseen to elevate the initial nutrient content of the soils and, as of that point, for annual maintenance fertilization. This was adopted both for P and for K. In this context, the content of 60 mg dm^{-3} of K extracted by Mehlich-1 was the critical level for soils in the State of Rio Grande do Sul (RS). As of that time, the recommendation tables continued to be improved by new results of research conducted for this purpose. In the updating of the recommendation tables undertaken in 1987 (Siqueira et al., 1987), the K critical level was increased to 80 mg dm^{-3}. In 2004, the Fertilization and Liming Manual for the States of

RS and Santa Catarina (SC) (CQFS-RS/SC, 2004) promoted a change in the recommendation system for K, establishing classes in accordance with the Cation Exchange Capacity (CEC) at pH 7.0 (CEC$_7$), with the studies of Silva & Meurer (1988) and Meurer & Anghinoni (1993) as a reference. Thus, CTC$_7$ values less than 5, from 5.1 to 15 and greater than 15 cmol$_c$ dm^{-3} correspond to critical levels in the soil of 45, 60 and 90 mg dm^{-3}, respectively. This separation in classes permitted the re-establishment of the critical level of 60 mg dm^{-3} for most of the soils planted in RS and SC since they have CTC$_7$ from 5.1 to 15 cmol$_c$ dm^{-3} (Rheinheimer et al., 2001). However, there is evidence that it is difficult to fit soils in availability classes because in most cases they are not satisfactory indexes for estimating the soil supply capacity (Rouse & Bertramson, 1949; Mohr, 1959; Oliveira et al., 1971; Nachtigall & Vahl, 1991; Meurer & Anghinoni, 1993; Melo et al., 2004; Bortoluzzi et al., 2005; Brunetto et al., 2005; Kaminski et al., 2007). Thus, in soils rich in micaceous minerals, the K

content is naturally high, while in kaolinitic soils, the content varies from high to low. However, that does not mean that both have similar K content extracted by Mehlich-1 to express their productive potentials. Thus, the recommendation of the dose of K fertilizer based on availability classes has not provided the expected responses (Vidor & Freire, 1971; Patella, 1980; Scherer, 1998a; Brunetto et al., 2005). This is expressed by the diversity of values estimated to define the critical level, which seems to be associated with the group of crops and the type of soil used in the calibration experiments. As such, Scherer (1998a) and Borkert et al. (1993) in Oxisols ($CTC_7 \cong$ 14 $cmol_c$ kg^{-1}), one in Santa Catarina and another in Paraná, estimated values for K critical levels of approximately 60 mg kg^{-1}. In the same way, Brunetto et al. (2005), in two Ultisols ($CTC_7 \cong$ 6 $cmol_c$ kg^{-1}) estimated K critical levels near 40 mg kg^{-1}. Both the values are less than that recommended by the CQFS-RS/SC (2004), even though the soils are included in the same CTC_7 class. Thus, it is believed that the low response of the crops to K fertilization is related to the contribution of non-exchangeable forms of K which are not estimated by the routine chemical extractors, which would give support to the supply capacity of these soils (Mohr, 1959; Oliveira et al., 1971; Nachtigall & Vahl, 1991; Silva et al., 1995; Melo et al., 2004; Bortoluzzi et al., 2005; Kaminski et al., 2007). However, various studies indicate that availability of non-exchangeable forms depends more on the demand of the plants for the nutrient rather than on soil properties like texture and mineralogy. For its part, demand is controlled by the availability of the other nutrients or other soil fertility factors that facilitate the development and productivity of the crops (Simonsson et al., 2007).

Some soils of the Southern region of Brazil have K reserves in non-exchangeable forms which are potentially available to the plants. The magnitude of these reserves may influence fertilization management, due to the capacity of K release during the crop cycle, which is greater than the quantity estimated by the Mehlich-1 extractor. This may be an indication that there is no need for establishing ranges of availability to regulate the doses of the fertilizer since there are no K sinks, even with the presence of 2:1 minerals (Bortoluzzi et al., 2005). The high recovery of added K and the non-establishment of ranges may simplify the model for the definition of doses based solely on the quantity exported by the crops. For that reason, studies related to the K dynamic in long term experiments are important for monitoring the behavior of availability of the nutrient in the soil, checking its critical level in accordance with the crop grown, providing greater reliability in fertilizer recommendation.

The objective of the present study was to evaluate K availability in a Hapludalf under K fertilization for sixteen years.

MATERIAL AND METHODS

The study was undertaken in the experimental field of the Soil Department of the Federal University of Santa Maria (Universidade Federal de Santa Maria - UFSM), in Santa Maria (RS). The experiment was set up in 1991 in a Typic Hapludalf (Argissolo Vermelho distrófico típico) (Embrapa, 2006), with a sandstone substrate. At the 0-20 cm layer, the soil presented 180 g kg^{-1} of clay, composed of kaolinite, interstratified illite-smectite (Moterle, 2008) and kaolinite-smectitee (Bortoluzzi et al., 2007) type minerals; 240 g kg^{-1} of silt; 580 g kg^{-1} of sand; 17 g kg^{-1} of organic matter; pH in water of 5.1; exchangeable Ca + Mg 3.5 $cmol_c$ dm^{-3}; CTC_7 of 6.4 $cmol_c$ kg^{-1}; exchangeable Al 0.65 $cmol_c$ dm^{-3}; available P 3.2 mg kg^{-1} and available K 50 mg kg^{-1}.

In implantation of the experiment, 3.0 Mg ha^{-1} of dolomitic lime was applied and incorporated to elevate the pH in the water of the soil to 6.0. Treatments were arranged in subdivided plots with a randomized block experimental design with four replications, applied on the summer crops. The experiment was divided into cycles of four annual crops. At the beginning of the experiment and in the years 1995, 1999 and 2002, four doses of K_2O (0, 60, 120 and 180 kg ha^{-1} of K_2O) were applied on the main plot, with dimensions of 6 x 16 m. On the second crop, the main plot was divided into four subplots, with dimensions of 4 x 6 m, on which 60 kg ha^{-1} of K_2O were added on three of them; on the third crop, the same dose in two subplots was added; and on the fourth crop, K was added only on one subplot. As of the fifth (1995) and ninth year (1999), a dose of 60 kg ha^{-1} of K_2O was reapplied on the subplots, except for the year 2002, where the initial doses were applied on the main plots. In the first four years of the experiment (1991 to 1994) after each fertilization, the soil was turned with the aid of a rotary hoe, and crop residues removed from the soil surface layer. In 1995, a no-till planting system was adopted and the K doses were applied on the soil surface. In the year 2003, the subplots were excluded and the main plots that received 0, 60, 120 and 180 kg ha^{-1} of K_2O came to receive 0, 30, 60 and 90 kg ha^{-1} of K_2O (T0, T30, T60 and T90 respectively). These doses were applied to the soybean (*Glycine max,* L. Merrill) (04/05 harvest), castor bean (*Ricinus communis,* L.) (06/07 harvest) and wheat (*Triticum aestivum,* L.) (07 harvest) crops. On the soybean (05/06 harvest) and black oat (*Avena strigosa,* Scherb) (05 and 06 harvest) crops, K was not added. On the soybean crop (04/05 harvest), three irrigations by sprinkling were performed, totaling 100 mm during the crop cycle.

The summer crops planted throughout the experiment were: soybeans, in the 91/92, 92/93, 93/94, 94/95, 95/96, 96/97, 97/98, 03/04, 04/05 and 05/06 harvests; corn (*Zea mays*, L.), in the 99/00 and 01/02 harvests; sorghum (*Sorghum bicolor,* L. Moench*)*, in

the 00/01 harvest; common jackbean (*Canavalia ensiformis,* DC.), in the 02 harvest and castor bean in the 06/07 harvest. The winter crops planted were: black oats in the years 91, 92, 93, 94, 95, 96, 97, 99, 03, 05 and 06; oats + common vetch (*Vicia sativa,* L.), in 2000 and 2001 and wheat in 2004 and 2007. The soil remained fallow in the winter of 98 and in the 98/99 harvest. Nitrogen and P were added to each crop, in accordance with the recommendation from the Soil Fertility Commission (Comissão de Fertilidade do Solo - CFS-RS/SC, 1995) and the Soil Chemical and Fertility Commission (Comissão de Química e Fertilidade do Solo - CQFS-RS/SC, 2004). Nitrogen and P were added on the castor bean crop in accordance with the recommendation from Milani & Severino (2006). In the present study, the results of soil analyses during the period from 1991 to 2007, and the grain yield and dry matter of the crops undertaken during the period from 2004 to 2007 were used. For each crop, the grains of the summer species and the green matter of the above ground part of the winter species were collected in an area of 24 m^2 in each experimental unit and dried in a forced air laboratory oven at 65 °C. Afterwards, the samples were ground and prepared for analysis of the total K in the plant tissue, in accordance with the method proposed by Tedesco et al. (1995). After each collection of the summer crops, soil was collected in the 0–10 cm layer, dried, ground, passed through a sieve with a 2 mm screen and reserved. Then, the soil was prepared and extraction of available K by Mehlich-1 (Tedesco et al., 1995), non-exchangeable K by boiling HNO$_3$ and total K by concentrated HF (Pratt, 1965) were performed. In July 2007, in the main plots, a trench was opened of approximately 40 x 40 x 40 cm and soil was collected at every 1 cm to the depth of 10 cm, every 2.5 cm to the depth of 20 cm and every 5 cm to a depth of 40 cm. The soil was dried, ground and K was extracted by Mehlich-1, in accordance with the method proposed by Tedesco et al. (1995). The quantities exported were obtained by the product of the content in the grains and the grain yield, with the exception of the soybeans 04/05, for which the content in the soybean grains from 05/06 was used.

The results of grain yield and of dry matter of the above ground part were submitted to analysis of variance, and when the effects were significant, the means were compared by the Tukey test at a significance level of 5 %. The relative yield (*rr*) was obtained using the equation:

$$rr = \frac{rt}{rm} \ 100 \qquad\qquad (1)$$

where the *rt* is the yield of the treatment and *rm* is the maximum yield. The results of the relative yield were adjusted using the Mitscherlich model:

$$y = a \ (1 - b^x) \qquad\qquad (2)$$

in which *yw* represents the relative yield, *a* and *b* are constants and *x* is the K content extracted by Mehlich-1. The K critical level in the soil was estimated at a relative yield of 90 %.

RESULTS

Cultivation of plants in the control treatment (T0) throughout the 16 years (1991-2007), reduced the soil K content extracted by Mehlich-1 (Table 1). In 1991, the original content in the soil was 50 mg kg^{-1}, passing to 27 mg kg^{-1} in 2007 since there was no addition of the nutrient during the period. At the greatest dose (T90), where 990 kg ha^{-1} of K$_2$O was added over 16 years, representing an annual average addition of 62 kg ha^{-1} of K$_2$O, the soil K content increased from 50 mg kg^{-1} to 68 mg kg^{-1} (Table 1). However, if one considers the soil samples undertaken in 1993 when the K content was 80 mg kg^{-1}, the content diminished. In contrast, in the treatment with the addition of 660 kg ha^{-1} of K$_2$O over 13 years, representing an annual average dose of 41 kg ha^{-1} of K$_2$O (T60), the K content extracted by Mehlich-1 oscillated in comparison to the content obtained in 1993, but was always greater than the original 50 mg kg^{-1}. When the additions of K were less than the exports from the crops, the content in the soil diminished, as in the T30 treatment. Thus, one observes that the K contents estimated by Mehlich-1 reduced in all the treatments throughout the years, being most pronounced in the treatments where there were no additions or the additions were less than the exports by the crops.

In a similar way, the forms of K denominated as non-exchangeable, estimated by the extractor of boiling 1.0 mol L^{-1} HNO$_3$, reduced throughout the cropping in the treatments where contents of the nutrient were low. That suggests that when the consumption of K by the plants is greater than the added dose of the nutrient (Table 1), this form of the nutrient in the soil is also a bioavailable source. In the control treatment, the non-exchangeable K content passed from 130 mg kg^{-1} in the year 1991 to 64 mg kg^{-1} in 2007 (Table 1). The total K content extracted with HF, for its part, remained constant in the treatment with the maximum dose, but numerically less.

Grain production for soybeans, wheat and castor beans were sensitive to reduction in the soil K content (Table 2). This is because in 2004, when evaluation of the data presented here was begun, the contents of soil K were 26, 36, 53 and 68 mg kg^{-1} in the treatments T0, T30, T60 and T90, respectively, and the lowest production coincided with the lowest contents in the soil. However, an increase in production was observed when the K content in the soil increased by around 10 mg kg^{-1}, resultant of the addition of annual average quantities of 30 kg ha^{-1} of K$_2$O (Table 2).

Table 1. Potassium content of the main plot extracted by Mehlich-1, 1 mol L^{-1} HNO$_3$ and HF before the set up of the experiment in 1993, 1997 and 2007

Year	Treatment	Potassium aplied, K$_2$O		Potassium extracted		
				Mehlich-1	HNO$_3$	HF
		kg ha^{-1}	kg ha^{-1} ano^{-1}	mg kg^{-1}		
1991		Native field soil		50	130	1.104
1993[1]	T0	0	0	43	96	-
	T30	60	20	48	86	-
	T60	120	40	61	103	-
	T90	180	60	80	112	-
1997[2]	T0	0	0	34	94	-
	T30	120	17	47	103	-
	T60	240	34	68	116	-
	T90	360	51	82	127	-
2005	T0	0	0	25	84	-
	T30	300	20	33	98	-
	T60	600	40	55	103	-
	T90	900	60	75	117	-
2007	T0	0	0	27	64	905
	T30	330	21	37	70	895
	T60	660	41	49	88	961
	T90	990	62	68	110	1.073

[1] Data obtained by Veduin (1994). [2] Data obtained by Saggin et al. (1998).

Table 2. Grain yield of commercial crops and dry matter of cover crops arising from the potassium application on the soil

Dose K$_2$O	Inicial K content[1]	Soybeans (04/05) Yes	Oats (05) No	Soybeans (05/06) No	Oats (06) No	Castor bean (06/07) Yes	Wheat (07) Yes
kg ha^{-1}	mg kg^{-1}	kg ha^{-1}					
0	26	2.785 c[1] (26)[2]	4.616 b	1.176 c (26)	5.519 c	595 d (29)	1.091 b (22)
30	37	3.437 b (36)	5.953 a	1.683 b (37)	6.398 bc	1.513 c (38)	1.951 a (32)
60	50	3.660 ab (53)	6.437 a	1.896 a (50)	7.553 a	1.719 b (49)	2.100 a (52)
90	65	3.880 a (68)	5.969 a	1.817 a (64)	6.963 ab	1.920 a (64)	2.050 a (65)
CV (%)		4.8	6.3	2.4	6.8	16.8	16.7

[1] Means followed by the same letter are not statistically different by the Tukey test at the level of 5 %. [2] Numbers between parentheses represent the potassium content extracted by Mehlich-1 after cropping; Yes: with the application of K$_2$O on the crop; No: without the application of K$_2$O on the crop.

Potassium content in the grains, with the exception of wheat, increased with the elevation of K content in the soil, accompanying the increase in yield (Table 3). The lowest content was found in the control treatments. In the other treatments, K content in the plants grew to the extent that availability grew, up to T60, or 50 mg kg^{-1} of K in the soil (Table 3). The quantities of K exported by grains of crops were greater where availability in the soil and yield were greater, as can be inferred by the results presented in tables 2 and 3. Balance between the quantity added and exported, estimated for the last four years of cropping, show a deficit of 50 kg ha^{-1} of K$_2$O in the T30 treatment; equilibrium in the T60 treatment (164 vs. 163) and a surplus in the T90 treatment (248 vs. 178).

Table 3. Potassium content in the grain and quantities exported by wheat, soybeans and castor beans and content and quantity recycled by the above ground part of black oats

Dose K_2O	Soybeans. 05/06		Castor beans. 06/07		Black oats. 05		Black oats. 06		Wheat. 07	
	Content	Exported	Content	Exported	Content	Recycled	Content	Recycled	Content	Exported
kg ha^{-1}	kg Mg^{-1}	kg ha^{-1}	kg Mg^{-1}	kg ha^{-1}	kg Mg^{-1}	kg ha^{-1}	kg Mg^{-1}	kg ha^{-1}	kg Mg^{-1}	kg ha^{-1}
0	17.5 c	20.7	3.2 c	4.4 c	7.4 b	35.1 c	7.6 c	41.9 b	3.87 [ns]	4.2 b
30	19.2 c	32.3	8.2 b	12.4 b	10.2 b	60.1 b	11.1 bc	70.4 b	3.82	7.5 a
60	20.3 ab	38.5	10.5 a	18.4 a	13.9 a	89.5 a	14.2 ab	107.3 a	3.74	7.8 a
90	20.5 a	38.2	11.8 a	22.7 a	15.8 a	93.3 a	17.7 a	123.2 a	3.90	8.0 a
CV (%)	5.1	3.7	7.6	1.2	16.9	9.3	16.1	16.1	6.4	17.4

[1] Means followed by the same letter do not differ statistically by the Tukey test to the level of 5 %. [ns]: not significant at 5 %.

DISCUSSION

The addition of nutrients via fertilization has the purpose of elevating its content in the soil, guaranteeing a supply for the plants. However, when its reduction occurs, perceptible by the estimate from chemical extractors, it is an indication that the content of the nutrient is being exhausted in its available form because the fertilizations are not sufficiently balanced to maintain the content in the soil and support plant demand, nor to guarantee satisfactory yields from the crops. These presuppositions, in relation to K, are supported by the results presented, through which it may be inferred that the use of fertilizers must meet plant demand, maintaining the critical levels in the soil, but may be reduced, or even suspended, when the content in the soil reaches the availability class considered high. In this availability class, there is the indication that the plants no longer respond to the addition of K, as was observed in table 2; soil with K content above 50 mg kg^{-1} did not provide for yield increases in the plants grown. The logic of the fertilization recommendation systems, based on soil analysis, counsels increasing the content when it is less than the critical levels, maintaining it in the class of sufficient availability, but also reducing it when it is found at levels above the critical level, which is monitored by periodic analysis of the soils in the cropped areas.

Thus, in this study, the addition of doses of K less than the quantities exported by the annual crops caused a reduction of available K in the soil (extracted by Mehlich-1) and also of non-exchangeable forms (Table 1). For that reason, it may be concluded that the largest K sink in the soil is the plant itself which is cultivated, since there are not considerable quantities of K adsorbed in the soil, as occurs, for example, with phosphorus. Also the contents remained constant when the quantity added coincided with that exported by the crops and increased when the quantity added went beyond that exported. Nevertheless, this balance and maintenance of availability depends on the K reserves in the soil, in addition to the exchangeable K and biocycling, which on many occasions represents a supply from the surface layers by the scavenging undertaken by the roots in the deepest layers, which depends on the mineralogy and the properties of each soil (Simonsson et al, 2007).

As this soil has CTC_7 of 6.4 cmol$_c$ kg^{-1}, the critical level established by the CQFS-RS/SC (2004) is 60 mg kg^{-1}, and the fertilization recommendation for soils in this availability class with a view toward a yield of 4,000 kg ha^{-1} of grains of soybeans is 95 kg ha^{-1} of K_2O, consisting of 45 kg ha^{-1} for yield maintenance of 2,000 kg ha^{-1}, plus 50 kg ha^{-1} necessary for doubling this grain yield and 95 kg ha^{-1} more in the second year for a later new soil analysis, seeking to monitor the alterations of content in the soil. These quantities are similar to double of what was added through four crop cycles and not only maintained yields at maximum quantities, but also added to the content in the soil, suggesting that the recommended quantities of K for RS and SC need to be reviewed. Moreover, Scherer (1998b), in an Oxisol in Santa Catarina, observed that the dose of 60 kg ha^{-1} K_2O is sufficient for obtaining maximum yield from soybeans and maintaining the K content near the critical level. Nevertheless, it should be highlighted that this was his lowest dose in the experiment; therefore it could be even less, since the grain yield was approximately 2500 kg ha^{-1}. Similar results were obtained by Borkert et al. (1993), Oliveira et al. (1971) and Vidor & Freire (1971).

In the T0 and T30 treatments, the quantity of K exported by the soybean grains estimated for the 04/05 harvest (Tables 2 and 3) and determined in the 05/06 harvest (Table 3) was 69.5 and 98.2 kg ha^{-1} of K_2O, there being a deficit, considering what was added and what was exported, which makes one suppose that the yield was maintained at the expense of non-exchangeable K, which explains a reduction of up to 50 % in the initial content, although there was also a

supply of K recycled by the oats crop, as also reported by Simonsson et al.(2007). As the uptake capacity of the plants is proportional to the quantity made available during the cycle, this resulted in a greater uptake than their physiological need, characterizing "luxury consumption". Reductions of the non-exchangeable forms may also occur when there are sufficient additions of K, as observed by Moody & Bell (2006) and Kaminski et al. (2007) and verified in the T60, but what would control this depletion are the other fertility conditions that accelerate crop development (Simonsson et al., 2007). The castor bean crop seems to be more demanding in K, or less efficient in uptake from the soil, because its yield increased with the increase in the available K content up to the limit of this experiment, as well as the quantity exported by the grains (Tables 2 and 3). Its grain yield increased by 918 kg ha^{-1} with the addition of only 30 kg ha^{-1} of K_2O, where the K content was 38 mg kg^{-1}. Wheat also responded to the addition of 30 kg ha^{-1} of K_2O, when the soil content was 32 mg kg^{-1} (Table 2), however, it did not respond to greater doses of the nutrient. In this treatment, the K content in the soil is classified as "low" by the CQFS-RS/SC (2004) and it would recommend double the dose applied.

These data show the difficulty of establishing K critical levels for all soils and crops since the species have different needs for the nutrient. Moreover, high yields are reached when the quantity added is near the quantity exported, for the plants present high capacity for recovering the added K since in this soil it is not adsorbed with greater energy than the capacity of plants in taking it up (Bortoluzzi et al., 2005; Simonsson et al., 2009).

In the soils where responses to additions of K are obtained, it is generally large for the first dose and very small, when existent, for subsequent doses, as presented in table 2, also verified by Scherer (1998b) e Borkert et al. (1993). Thus, in calibration studies, when more demanding crops are included, the estimated critical levels are higher, for the statistical adjustment models used "drive" critical levels higher, which come to be adopted as true. However, when only responsive and less demanding crops are included, these contents are less. Therefore, when yield data of soybean and corn grains, plus dry matter of the above ground part of oats were joined, in a ten year experiment, in soil similar to that of this experiment, Brunetto et al. (2005) estimated the critical level of K at 42 mg kg^{-1}. However, in this study, when yield data recovered for the entire period of the experiment (1991–2007) were included, including other crops like castor beans, wheat and canola, the critical levels were estimated at 51 mg kg^{-1} (Figure 1) and the value near 60 mg kg^{-1} was maintained, guaranteeing yield only with replacement doses, which would be variable in accordance to the need of each species grown. For that reason, it may be established that there is no need for the correction of soil K content up to a limit

considered as high, as adopted by the CQFS-RS/SC (2004); rather, the maintenance of this content with maintenance or replacement fertilization guarantees the content in the soil and maintains high yields (Table 2), as long as the balance between addition and exportation, added to the losses of the system, is positive.

Species with a high capacity for accumulating K, like oats, mobilize large quantities in the above ground part, and when the plant dry matter is maintained on the soil surface, the K is quickly released to the soil, presenting a half-life in the plant dry matter of only two weeks (Giacomini et al., 2003). This promotes the accumulation of the nutrient in the upper millimeters of the surface soil, and may serve as a source for subsequent crops. In this experiment, the quantity recycled by oats in the years 2005 and 2006 varied from 40 to 100 kg ha^{-1} of K_2O, representing values similar to the quantities recommended for the average yield of soybeans in the region. The cycling of K simply concentrates the nutrient in the region of decomposition of the straw and does not represent additions of "new K", since the source is the soil itself, regardless of the layer and, for that reason, it is not a recomposition of the quantities of K exported by the grain, since these quantities are depleted in subsurfaces, as was seen in the experiment (Figure 2). These results were also found by Simonsson et al. (2007) in field experiments, in which even without additions of K, they found an increase in the content in the soil surface layer, and a reduction of the content in the subsurface soil layers.

Vertical distributions of K may reinforce the explanation of the variations in the contents in terms
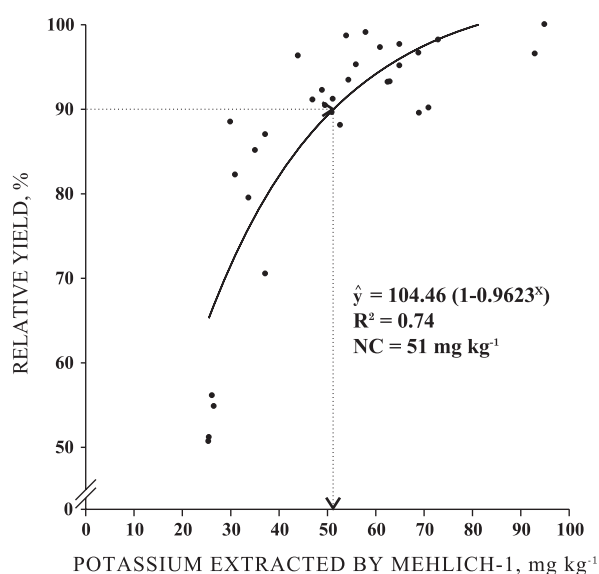
Figure 1. Relative yield and potassium content in the soil extracted by Mehlich-1 for grain crops grown in the period from 1991 to 2007.

POTASSIUM EXTRACTED BY MEHLICH-1, mg kg^{-1}
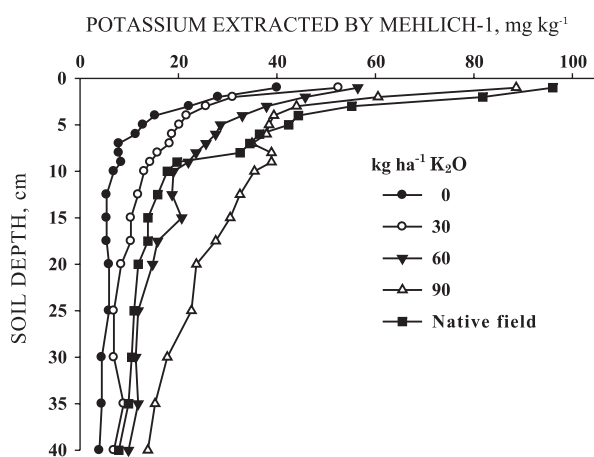
Figure 2. Vertical distribution of potassium extracted by Mehlich-1 in native field soil and submitted to the addition of K$_2$O doses, after fifteen years of cropping in a Hapludalf soil (Argissolo Vermelho distrófico típico).

of the K balance (added/exported) (Figure 2). Thus, considering the quantity of K in natural pasture adjacent to the experiment and not submitted to grazing as the original, therefore without the addition or exportation of the nutrient, it may be seen that in the T0 and T30 treatments, there was K depletion up to the 40 cm sampled; in the T60, the contents remained similar to the "original"; and increased in the T90. Maintenance of the contents of the control and contribution through cycling of oats may be explained by the greater volume of soil used by the roots. Thus, in soils where there is no physical impediment to root growth, the soil in the deeper layers is used by the roots and provides K in degrees similar to the soil of the surface layers. Moreover, to the extent that the supply of K increases, or the addition/exportation balance tends to equality, the contents in depth draw near to the content of the control treatment, a native field. But when the balance is greater than one, as in T90, the contents of this nutrient in the soil in the deeper layers increase (Figure 2). In this situation, in addition to there not being an increase in crop yield, K migration in the soil profile, which is not desirable, may represent economic and environmental losses. For that reason, when quantities are added which are greater than that exported by the plants, one is not only making a contribution to reach a high or very high content, for these situations, instead of representing a condition of good fertility, may lead to the loss of the added nutrient. In addition, the presence of impediment to root growth, whether of a physical order, like compaction of the subsurface, or chemical, like the presence of exchangeable Al a few centimeters below the surface, may lead to mistaken interpretations of experiment results, such as the establishment of elevated critical levels or of the need for the elevation of fertilizer doses to obtain high yields.

CONCLUSIONS

1. Potassium fertilization guidelines should foresee the establishment of a critical level as of which the recommended dose should accompany crop needs, which coincide with the quantity exported by the grain, without the need for the creation of wide ranges of K availability for predicting fertilization.

2. Adopting the recommendations for K fertilization thus proposed, there will not be translocation of K in the soil profile.

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