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Potassium Fertilization for Long Term No-Till Crop Rotation in the Central-Southern Region of Paraná, Brazil

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ABSTRACT: Fertilization programs for annual crops in the state of Paraná, southern Brazil, are based on studies that focused on conventional tillage and were established more than 30 years ago. The primary purpose of this study was to assess potassium (K) fertilization on long-term (>30 years) no-tillage soybean, corn, wheat, and barley crops grown in rotation on Oxisols in the central-southern region of Paraná. A total of 47 experiments were carried out from 2008 to 2013, three of which addressed K calibration and the other 44, crop response to K fertilization. Critical K soil-test value and interpretation classes were established from the ratio between relative crop yield [RY = (yield without K/max yield) × 100] and soil K levels. Winter cereals were found to be more demanding of K than were soybean and corn; also, the former governed critical K soil-test value for crop rotation: 0.23 $cmol_c\ dm^{-3}$ in the 0.00-0.20 m soil layer. Recommended fertilization rates for soils in the low and medium soil K levels were established by using the build-up approach for soil correction; and those for the high and very high soil K levels were established by removing K at harvest and assessing economic return in crop response experiments. The K rates calculated for the high yield classes exceeded those currently recommended for use in Paraná.

Keywords: calibration, critical level, Mehlich-1.

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INTRODUCTION

The Brazilian state of Paraná (PR) encompasses a total 7.6 million hectares of soil under corn or soybean, approximately 90 % of which is under no-tillage (NT) management (Agrosoft, 2009). An overall corn and soybean output of 15.4 and 14.7 million Mg, respectively, make this state the second largest producer of these crops in Brazil (Conab, 2014). Paraná was one of the pioneering Brazilian states in using NT management in the 1970s. In fact, some areas have been under NT for a long time (Coamo, 2013), which has had marked effects on soil chemistry and fertility (Schlindwein and Anghinoni, 2000; Anghinoni, 2007).

No-tillage increases stratification of nutrients in the soil profile. It increases K accumulation in the surface layer (0.00-0.05 m) (Silveira et al., 2000; Almeida et al., 2005; Pauletti et al., 2009), which may influence K supply to crops and result in differences in K availability between soil layers (Schlindwein et al., 2011). The cation exchange capacity (CEC) of NT soils also increases in a stratum-dependent manner through an increase in organic C content (Bayer and Mielniczuk, 1997). This may affect K supply to soil indirectly via CEC saturation (Mielniczuk, 2005) and increase K requirements for an adequate supply of K to crops (Silva and Meurer, 1988).

One other important factor is the lack of fertilization recommendations for crop rotation systems, where different sensitivities of crops to nutrient availability in the soil and crop response to fertilization are essential with a view to ensuring high grain yields and efficient use of inputs. In Paraná and other Brazilian states, however, K fertilization relies on specific technical recommendations for individual crops (Embrapa, 2011; Embrapa, 2013a,b) that were established for conventional tillage systems over 30 years ago (Ocepar, 1987; Lantmann et al., 1996; Embrapa, 1999), a time at which crop yields were much lower than they are today in the central-southern region of PR [that is, 3.8 Mg ha^{-1} soybean and 12.2 Mg ha^{-1} corn; Agrária (2014)].

Technicians and producers frequently use alternative fertilizer recommendations tailored for other states such as RS and SC (CQFSRS/SC, 2004) or SP (Raij et al., 1997), which have also been established for conventional tillage, but adapted to NT management guidelines. However, the use of outdated recommendations for individual crops, together with the adoption of systems based on results obtained under different soil and climatic conditions, hardly provide an objective basis for ensuring high crop yields and highly efficient use of applied inputs.

We hypothesized that crops differ in K demand and that this fact leads to differences in critical soil-test values and in crop response to K fertilization, thus allowing one to anticipate the effects of fertilization on crop rotation systems. The primary purpose of this study was thus to determine critical soil-test K values and interpretation classes in soil with a view to developing K fertilization recommendations for soybean, corn, barley, and wheat crops grown in rotation on Oxisols under NT for more than 30 years in the central-southern region of Paraná.

MATERIALS AND METHODS

Site and experiments description

A total of 47 experiments were conducted in different municipalities in the central-southern region of Paraná, all located in areas managed by Cooperative Agrária. The soils were all Oxisols with mean clay content exceeding 600 g kg^{-1}, an organic matter content of 54 g kg^{-1}, and a cation exchange capacity at pH 7.0 of 15 cmol$_c$ dm^{-3}.

Three K rate calibration experiments were started in 2008 in the municipalities of Guarapuava, Pinhão, and Candói. The Guarapuava experiment was conducted in the experimental area of FAPA (Colônia Vitória, Entre Rios district) and the Pinhão and Candói experiments were performed in areas belonging to members of the cooperative. These experiments were arranged in a randomized block design using split plots with four replications. In the main plots (9.6 × 10 m), fertilizer was broadcast without incorporation, using various rates of potassium chloride (0, 80, 160, 320, and 640 kg ha^{-1} K_2O) prior to sowing the winter crops of 2008 in order to establish baseline K levels in the soil. Each plot was divided into two split plots, 4.8 × 10 m in size, in the summer of 2008/09, one of the split plots being resupplied with 60 kg ha^{-1} K_2O each season. The results of the K calibration experiments of 2008 and 2009, which were previously analyzed and interpreted by Vieira et al. (2013), were combined with those for 2010-2013 in order to consolidate previously recommended critical K levels.

A total of 44 K-response experiments were conducted from the winter of 2011 to the summer growing season of 2012/13 (11 with soybean, 10 with corn, 12 with wheat, and 11 with barley). All were performed on land owned by the rural cooperative in seven municipalities (Guarapuava, Pinhão, Candói, Roncador, Goioxim, Reserva do Iguaçu, and Campina do Simão). The experimental areas were selected in terms of soil-test K value (Mehlich-1) as determined from the cooperative's soil analysis data bank in order to cover the occurrence of K range levels in the region (interpretation classes of "medium", "high" and "very high") and use the relationship between yield and soil-test K values previously established by Vieira et al. (2013). The K response experiments were arranged in a randomized complete block design with three replications at 0, 30, 60, 120, and 240 kg ha^{-1} K_2O using potassium chloride that was applied to crop rows. The plots for the soybean and corn experiments consisted of four 5-m rows spaced 0.40 m apart for soybean and 0.80 m apart for corn; those for the wheat and barley experiments consisted of six 5-m rows spaced 0.17 m apart.

Management practices for adjusting soil acidity and the amounts of other nutrients were based on the official recommendations for the specific crops (Fontoura and Bayer, 2009; Embrapa, 2011; Embrapa, 2013a,b).

Soil sampling and assessment

Soil samples for the K calibration experiments were collected on a yearly basis from the 0.00-0.10 and 0.00-0.20 m layers in May. Samples for the K response experiments were obtained from the same layers prior to starting the experiments and crop seeding. Samples were collected with a shovel using the method of taking samples perpendicular to the crop rows (CQFSRS/SC, 2004). Soil-test K value was determined by using the Mehlich-1 extraction method (Tedesco et al., 1995).

In the calibration experiments, yields were determined by harvesting a 30 m^2 area for winter cereals and 20 m^2 for summer crops; the plot area studied in the fertilization response experiments was 2.7 m^2 for winter cereals, 3.2 m^2 for soybean, and 6.4 m^2 for corn. Grain yield data were all adjusted to 13 % moisture.

Because crops, seasons, and locations differed among experiments, yields were expressed as relative grain yield (RY) and calculated in relation to the maximum yield (RY = 100) per season and location for the different crops:

$$RY\ (\%) = \frac{Crop\ yield\ without\ K\ fertilization}{Maximum\ yield}\ x\ 100 \qquad \text{Eq. 1}$$

In the fertilization response experiments, maximum yield was calculated from the curves of equations fitted to crop yield versus K rate, and coincided with the yield at maximum technical efficiency (MTE).

With a positive response to fertilizer application, the maximum yield was calculated from the fitted linear equation with provision for the highest K rate; with a negative response, the maximum yield corresponded to a zero K rate (i.e., no K application), which coincided with the intercept of the regression equation. With quadratic equations, the maximum yield was calculated as the K rate at which the first derivative of the quadratic equation was zero.

Fitting calibration curves and determination of critical soil-test K level and interpretation classes

Calibration curves were obtained by plotting the ratio of relative grain yield in the treatments without K fertilization to soil-test K (Mehlich-1) as determined in soil samples collected prior to sowing of each crop. In order to consolidate the calibration curve previously reported by Vieira et al. (2013) for the results of 2008 and 2009 with the calibration experiments conducted in this study, the results of three calibration experiments for the five-year period 2008-2012 were used in combination with those of the 44 fertilization response experiments (2011-2012/13).

It should be noted that white oat was included in the calibration curve and critical values sets, but not in the fertilization response or rate recommendation sets because of the small area devoted to this crop in recent years owing to its low economic returns relative to other winter cereals.

Data were fitted by using the Mitscherlich equation, an exponential expression used to reach a relative yield of 100 %, which is widely used for calibration (Cubilla et al., 2007; Villalba, 2008; Wendling et al., 2008; Schlindwein et al., 2011):

$$RY = R_{max}(1 - 10^{-b.Ksoil}) \qquad \text{Eq. 2}$$

where RY is the relative grain yield, R_{max} the maximum yield (RY = 100), b the effective coefficient of the nutrient, and $Ksoil$ the soil-test K value (cmol$_c$ dm^{-3}, Mehlich-1). The calibration curve was fitted through use of the software Table Curve 2D v. 5.

The critical soil-test K concentration in the soil, which represents the K value at 90 % of the maximum grain yield, was determined from the fitted calibration curve. This criterion is similar to that used with fertilization systems in RS and SC (CQFSRS/SC, 2004), and its use is justified by the fact that the yields ensuring maximum economic efficiency (MEE) are usually obtained at approximately 90 % of maximum performance.

Potassium interpretation classes were defined in terms of the soil-test critical K levels. Thus, the soils with one-half or less than the critical value were included in the “low” and “medium” soil-test classes, whereas those with twice or more the critical value were included in the “high” and “very high” soil-test classes. These interpretation classes spanned the following ranges of grain RY: <68 % (low), 68-90 % (medium), 91-99 % (high) and >99 % (very high). The likelihood of economic returns from K application in the different interpretation classes was calculated by assessing crop response to the application of 50 kg ha^{-1} K_2O and the average prices of grain and potassium chloride from October 2008 to September 2013. The mean price per Mg of soybean, corn, wheat, and barley was US$ 225.50, 101.50, 149.28, and 141.71 (US$ = R$ 3.50) respectively, and that of potassium chloride US$ 215.63 (US$ 359.43 per Mg of K_2O) (Agrolink, 2013; Mundi, 2013). Economic return was also assessed on the assumption of a 30 % lower average grain price.

Estimation of recommended K fertilization rates

The recommended K_2O rates for the crops grown on the soils in the low and medium K interpretation classes were estimated in terms of soil fertility build-up, which involved determining the rates needed to raise the soil-test K level to its critical value. This required measuring the increase in soil-test K value 7 months after application of the different K rates in the calibration experiments at Guarapuava, Pinhão, and Candói in order to determine the amount of K_2O needed to raise the K level to 0.01 cmol$_c$ dm^{-3}.

The recommended rates for crop fertilization of the soils in the high and very high K interpretation classes were based on the amounts needed to replenish the amounts of K exported in grains (20 kg K_2O Mg^{-1} soybean, and 6 kg K_2O Mg^{-1} corn, wheat, and barley). Adequate rates for the crops in succession in the rotation were estimated by assessing the economic efficiency of K application in each class from data for the 0.00-0.20 m soil layer in the crop fertilization response experiments. Thus, the rate and yield of maximum technical efficiency (MTE) and economic efficiency (MEE) were calculated from the fitted curve of grain yield against the applied K rate. As stated above, the MEE rate was estimated from the average price of grain and potash over the period from October 2008 to September 2013.

RESULTS AND DISCUSSION

Grain crop yields

Crop yields in the three K calibration experiments were 6.0, 16.2, 4.1, and 6.7 Mg ha^{-1} for soybean, corn, wheat, and barley, respectively (Table 1). These results testify to the high yield potential of the central-southern region of PR. Even without K fertilization, yields were high, with RY values greater than 90 %, indicating high K levels in the soils. The lowest RY values without K application in the three calibration experiments were obtained in Candói, where K fertilization increased grain yield by 750 kg ha^{-1} in soybean and 560 kg ha^{-1} in white oat.

The relative crop yields in the K response experiments are listed in tables 2 and 3. The soil-test K concentration in the 0.00-0.20 m soil layer at the 44 locations studied ranged from 0.20 to 0.67 cmol$_c$ dm^{-3}, with 19 locations below the critical value proposed by Vieira et al. (2013): 0.30 cmol$_c$ dm^{-3}, which is similar to the mean content of agricultural soils in the Guarapuava region. These results confirm the good natural K supply capacity of soils in Paraná, with the sole exception of sandy soils with a low CEC in the northwestern region (Caires, 2013). In addition to the good natural K content in basaltic soils of the Serra Geral formation, the high mean soil-test K values in agricultural soils of the central-southern region is a result of a long history of fertilization in combination with continuous K cycling resulting from intensive rotation of no-tillage cover and cash crops in the area, which is also suggested by the high organic matter contents (54 g kg^{-1}) and CEC$_{pH7.0}$ (15 cmol$_c$ dm^{-3}) of the soils – which together minimize potential K losses by erosion and leaching.

Potassium levels at the time soybean was sown resulted in a negative yield response of this crop in most growing seasons and locations. Only in three of the 11 soybean experiments conducted in the 2011/12 and 2012/13 seasons did K fertilization increase grain yield (Table 2). The negative effects of fertilization may have resulted from the way potassium fertilizer was applied to the soil (that is, as potassium chloride to crop rows), which may have led to an excess of chlorine in the soil and to the

Table 1. Grain yield range and relative grain yield (RY) for soybean, corn, wheat, barley, and white oat, and soil-test K value (Mehlich-1, 0.00-0.20 m layer), as obtained in calibration experiments with different K_2O rates applied in 2008

Crop	Guarapuava			Pinhão			Candói		
	Yield(1)	RY(2)	Soil-test K	Yield	RY	Soil-test K	Yield	RY	Soil-test K
	Mg ha^{-1}	%	cmol$_c$ dm^{-3}	Mg ha^{-1}	%	cmol$_c$ dm^{-3}	Mg ha^{-1}	%	cmol$_c$ dm^{-3}
Soybean	3.7-6.0	91-100	0.25–0.65	3.6-4.5	89-100	0.47-0.73	3.9-4.6	84-98	0.14-0.57
Corn	15.9-16.2	99-100	0.35–0.66	13.2-14.9	88-92	0.57-0.83	14.6-15.5	94-100	0.15-0.39
Wheat	-	-	-	3.8-4.1	92-94	0.57-0.87	-	-	-
Barley	6.2-6.7	93-96	0.29-0.56	5.2-5.8	91-96	0.50-0.65	4.5-5.1	90-99	0.15-0.39
White oat	-	-	-	-	-	-	2.0-2.5	78-87	0.14-0.49

(1) Lowest and highest crop yield in the experiment. (2) Lowest and highest relative yield in the treatments without re-application.

Table 2. Soil-test K values at two soil depths, fitted equations for soybean and corn yields as a function of K rate, relative yield in the treatment without K, maximum technical efficiency (MTE) rate, and maximum economic efficiency (MEE) rate in different crops and sites

Experimental site	Harvest	Equation	r^2	Soil-test K		Interpretation class	Without K	MTE		MEE
				0.00-0.10 m	0.00-0.20 m		RY	Rate	Yield	Rate
				——— $cmol_c\ dm^{-3}$ ———			%	——— $kg\ ha^{-1}$ ———		
				Soybean						
Murakami 1	2011/12	$\hat{y} = 4369\ \ 6.25^{*} x + 0.011^{**} x^2$	0.96	0.32	0.24	High	100	0	4369	0
Jaster	2012/13	$\hat{y} = 5002 + 2.91 x - 0.013^{*} x^2$	0.84	0.35	0.27	High	97	111	5164	51
Candói	2011/12	$\hat{y} = 3434 - 6.08 x + 0.027^{*} x^2$	0.80	0.35	0.31	High	100	0	3434	0
Guarapuava 1	2011/12	$\hat{y} = 4416 + 4.94 x - 0.018^{*} x^2$	0.72	0.39	0.38	High	93	139	4759	94
Murakami 2	2012/13	$\hat{y} = 6057 - 6.12^{*} x + 0.013^{*} x^2$	0.92	0.42	0.42	High	100	0	6057	0
Guarapuava 2	2012/13	$\hat{y} = 5891 - 7.74^{**} x + 0.026^{**} x^2$	0.98	0.58	0.43	High	100	0	5891	0
Roncador 1	2011/12	$\hat{y} = 3732 - 0.82 x - 0.005^{*} x^2$	0.81	0.60	0.49	Very High	100	0	3732	0
Pinhão	2011/12	$\hat{y} = 3064 - 0.72 x$	0.27	0.70	0.56	Very High	100	0	3064	0
Murakami 3	2012/13	$\hat{y} = 3497 - 2.16 x$	0.56	0.85	0.62	Very High	100	0	3497	0
Roncador 2	2012/13	$\hat{y} = 3427 + 1.23 x - 0.009^{*} x^2$	0.80	0.68	0.66	Very High	99	67	3468	0
Murakami 4	2011/12	$\hat{y} = 4671 - 4.34^{*} x + 0.013^{**} x^2$	0.96	0.78	0.67	Very High	100	0	4671	0
				Corn						
Murakami 1	2011/12	$\hat{y} = 14\,898 + 1.16^{*} x$	0.82	0.24	0.22	Medium	98	240	15 175	0
Pinhão 1	2011/12	$\hat{y} = 12\,742 - 1.23 x$	0.07	0.46	0.26	High	100	0	12 742	0
Roncador 1	2012/13	$\hat{y} = 15\,773 + 12.92 x - 0.065^{*} x^2$	0.73	0.46	0.26	High	96	100	16 419	73
Goioxim	2012/13	$\hat{y} = 12\,452 + 20.74 x - 0.096^{*} x^2$	0.69	0.44	0.35	High	92	108	13 568	89
Roncador 2	2011/12	$\hat{y} = 10\,690 - 0.31 x$	0.01	0.54	0.37	High	100	0	10 690	0
Candói	2012/13	$\hat{y} = 11\,843 + 11.34^{*} x - 0.058^{*} x^2$	0.89	0.55	0.39	High	96	98	12 399	67
Pinhão 2	2012/13	$\hat{y} = 13\,855 + 1.24 x$	0.05	0.76	0.47	Very High	98	240	14 154	0
Guarapuava 1	2011/12	$\hat{y} = 14\,862 + 25.46^{*} x - 0.158^{**} x^2$	0.98	0.50	0.50	Very High	94	81	15 889	69
Guarapuava 2	2012/13	$\hat{y} = 14\,962 + 10.91^{**} x - 0.053^{**} x^2$	0.99	0.81	0.52	Very High	96	104	15 529	70
Murakami 2	2012/13	$\hat{y} = 14\,229 - 5.05 x$	0.50	0.64	0.54	Very High	100	0	14 229	0

accumulation of chloride ions in plants, or from salting of the soil from the effect of high salt content of the fertilizer (Ernani et al., 2007) diminishing plant emergence and density (Salton et al., 2002). Previous studies showed the maximum acceptable K_2O rates for application to soybean crop rows ranged from 80 (Embrapa, 2013b) to 50 kg ha^{-1} (Raij, 2011).

Corn responded favorably to K fertilization (MTE rate > 0) at 7 of the 10 experimental locations. However, the mean yield increase at MTE compared to absence of K fertilizer was only 5 %, which represents an additional 660 kg ha^{-1} on average.

Table 3. Soil-test K values at two soil depths, fitted equations for wheat and barley yields as a function of K rate, relative crop response in the treatment without K, maximum technical efficiency (MTE) rate, and maximum economic efficiency (MEE) rate for different crops and sites

Experimental site	Year	Equation	r^2	Soil-test K		Interpretation class	Without K	MTE		MEE
				0.00-0.10 m	0.00-0.20 m		RCR	Rate	Yield	Rate
				$cmol_c\ dm^{-3}$			%	$kg\ ha^{-1}$		
				Wheat						
Rodeio	2011	$\hat{y} = 2235 + 3.62\ x - 0.009\ x^2$	0.67	0.30	0.20	Medium	85	206	2507	69
Santa Clara	2011	$\hat{y} = 3940 + 5.50^{*}\ x - 0.017^{*}\ x^2$	0.90	0.27	0.23	Medium	90	159	4377	90
Guarapuava	2011	$\hat{y} = 4321 + 2.28\ x$	0.65	0.34	0.24	High	89	240	4867	0
Pinhão 1	2012	$\hat{y} = 2629 + 0.57\ x - 0.002\ x^2$	0.64	0.33	0.25	High	98	180	2680	0
Santa Rita	2011	$\hat{y} = 5061 + 5.29^{*}\ x - 0.015^{**}\ x^2$	0.94	0.33	0.28	High	92	173	5518	94
Guarapuava	2012	$\hat{y} = 4129 + 12.69^{**}\ x - 0.094^{**}\ x^2$	0.99	0.47	0.29	High	91	68	4559	55
Murakami 1	2012	$\hat{y} = 2291 + 1.17^{*}\ x$	0.73	0.58	0.29	High	89	240	2571	0
Roncador	2012	$\hat{y} = 2787 + 0.04\ x$	0.01	0.40	0.37	High	100	240	2796	0
Murakami 2	2012	$\hat{y} = 2853 + 4.47\ x - 0.012^{*}\ x^2$	0.64	0.50	0.47	Very High	87	193	3284	88
Santana	2011	$\hat{y} = 4273 + 0.39\ x$	0.16	0.61	0.56	Very High	98	240	4367	0
Campo Bonito	2011	$\hat{y} = 4490 + 4.46\ x - 0.009^{*}\ x^2$	0.82	0.70	0.62	Very High	89	237	5019	109
Pinhão 2	2012	$\hat{y} = 3226 - 1.88\ x$	0.53	0.71	0.64	Very High	100	0	3226	0
				Barley						
Rodeio	2011	$\hat{y} = 1816 + 14.65^{*}\ x - 0.093^{**}\ x^2$	0.96	0.30	0.20	Medium	76	79	2395	65
Santa Clara	2011	$\hat{y} = 5410 + 5.75\ x - 0.020^{*}\ x^2$	0.84	0.27	0.23	Medium	93	142	5816	79
Guarapuava	2011	$\hat{y} = 5127 + 2.51\ x - 0.011\ x^2$	0.51	0.34	0.24	High	97	117	5274	0
Pinhão 1	2012	$\hat{y} = 3056 + 8.59\ x - 0.031\ x^2$	0.32	0.33	0.25	High	84	140	3657	99
Santa Rita	2011	$\hat{y} = 3219 + 11.10\ x - 0.036^{*}\ x^2$	0.67	0.33	0.28	High	79	154	4072	119
Guarapuava	2012	$\hat{y} = 4843 + 4.73^{*}\ x - 0.015^{*}\ x^2$	0.89	0.47	0.29	High	93	160	5221	75
Murakami 1	2012	$\hat{y} = 2302 + 3.93^{*}\ x - 0.017^{*}\ x^2$	0.88	0.58	0.29	High	91	118	2533	41
Murakami 2	2012	$\hat{y} = 3347 + 7.57\ x - 0.025^{*}\ x^2$	0.82	0.50	0.47	Very High	86	149	3911	99
Santana	2011	$\hat{y} = 5372 + 3.01\ x - 0.005\ x^2$	0.27	0.61	0.56	Very High	93	289	5807	45
Campo Bonito	2011	$\hat{y} = 5613 + 5.02\ x - 0.013^{*}\ x^2$	0.69	0.70	0.62	Very High	92	193	6098	96
Pinhão 2	2012	$\hat{y} = 2730 + 4.71\ x - 0.013^{*}\ x^2$	0.86	0.71	0.64	Very High	86	188	3173	87

Wheat and barley were more demanding of K than were soybean and corn; thus, the relative mean yields for wheat, barley, soybean, and corn in the treatments without K fertilization were 91, 89, 99, and 97 %, respectively. The increased K demand of the soil sown with winter cereals is consistent with the decreased critical soil K value for soybean (Sfredo and Borkert, 1991) relative to wheat (Muzilli and Lantmann, 1978) in Paraná since the late 1990s (Lantmann et al., 1996).

Critical soil-test K value

The calibration curve of grain yield *versus* soil-test K values, and the fitted equations and critical values for the 0.00-0.10 and 0.00-0.20 m layers are in the figure 1. The calibration curves were fitted to groups of crops with a similar response of grain yield to soil-test K levels. Thus, the winter cereals (wheat, barley, and white oat) were fitted separately from the summer crops (soybean and corn).

Wheat, barley, and oat were more demanding of K than were the summer crops; thus, they exhibited a critical soil-test value of 0.33 $\text{cmol}_c\ \text{dm}^{-3}$ in 0.00-0.10 m layer and 0.23 $\text{cmol}_c\ \text{dm}^{-3}$ in

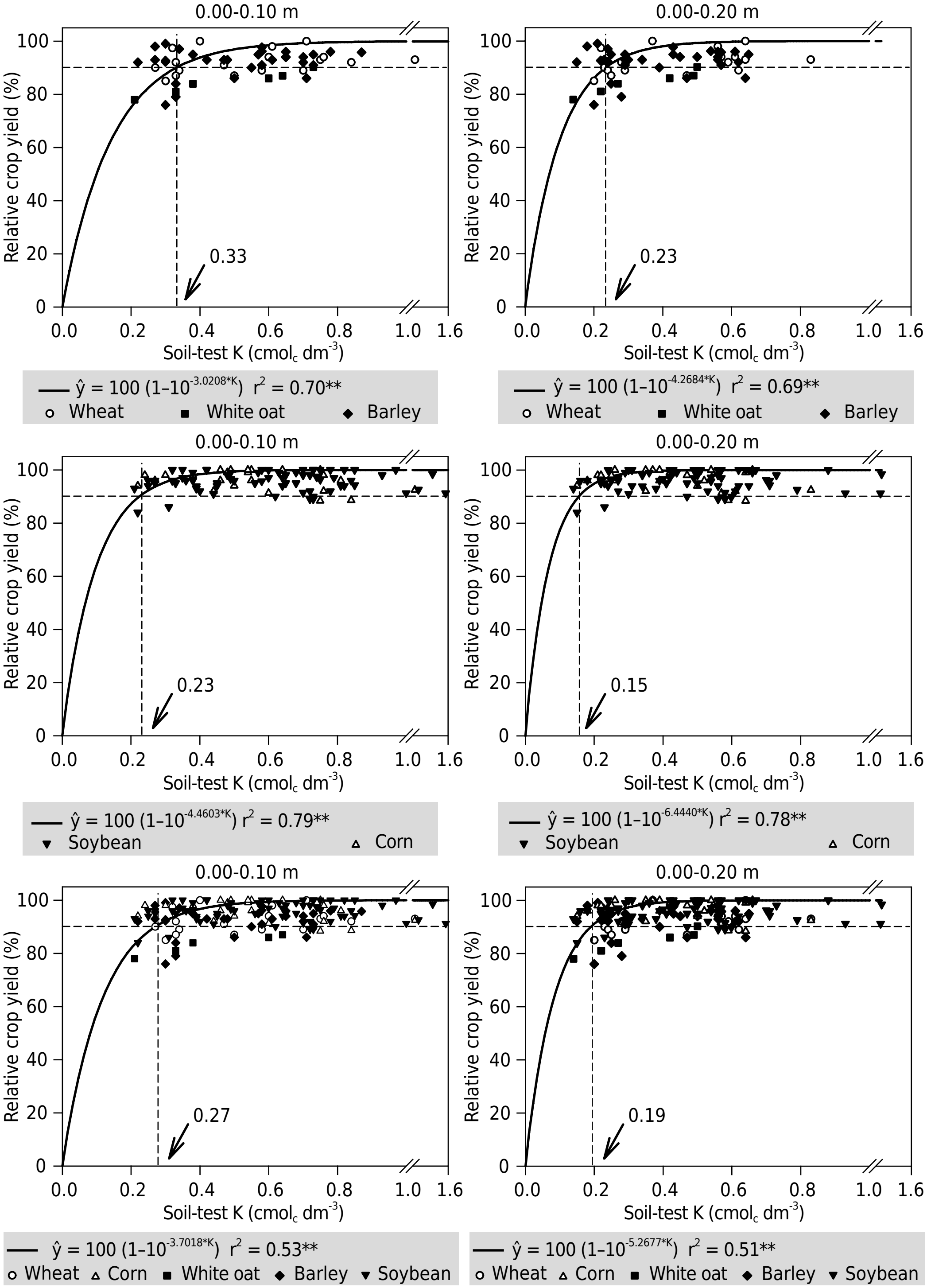

Figure 1. Relationship between soil-test K (Mehlich-1) in the 0.00-0.10 and 0.00-0.20 m layers and white oat, wheat, barley, soybean, and corn yields (0.01 $\text{cmol}_c\ \text{dm}^{-3}$ K equivalent to 3.91 mg dm^{-3}). **: significant ($p<0.01$).

the 0.00-0.20 m layer at RY = 90 % (Figure 1). These critical soil K values are lower than the values previously determined by Vieira et al. (2013) for the respective layers (0.40 and 0.30 $cmol_c$ dm^{-3}) if the results of only the calibration experiments from 2008 to 2009 are considered. The critical soil K values for soybean and corn were 0.23 $cmol_c$ dm^{-3} in the 0.00-0.10 m layer and 0.15 $cmol_c$ dm^{-3} in the 0.00-0.20 m layer. A weak response of these crops to K fertilization and lower critical values in the soil were previously observed in different studies and locations [e.g., critical values of 0.10 and 0.16 $cmol_c$ dm^{-3} in the 0.00-0.20 m layer for soybean in Paraná (Borkert et al., 1993) and Santa Catarina (Scherer, 1998), and 0.11 $cmol_c$ dm^{-3} in the 0.00-0.10 m layer for soybean and corn in Rio Grande do Sul (Brunetto et al., 2005). Vieira et al. (2015) also found decreased critical values for soybean and corn in the central-southern region of Paraná when evaluating crop response to P in the soil. They ascribed the increased P demand of winter cereals to drought and cold during cultivation, restricting diffusion of nutrients in the soil.

Compared to the current official recommendations for K fertilization in Paraná, the estimated critical soil K value for wheat and barley (0.33 $cmol_c$ dm^{-3}) is slightly higher than the recommended content for the 0.00-0.10 m layer in no-tillage soils: 0.30 $cmol_c$ dm^{-3} (Embrapa, 2011; Embrapa, 2013a). The recommendation of K fertilization for soybean (Embrapa, 2013b) is based on a critical value of 0.30 $cmol_c$ dm^{-3} for the 0.00-0.10 m layer (i.e., on a much higher content than the 0.23 $cmol_c$ dm^{-3} found in this study).

Critical soil-test K value in the states of RS and SC is not crop specific (CQFSRS/SC, 2004); rather, a single critical value of only 0.23 $cmol_c$ dm^{-3} for soils with CEC >15 $cmol_c$ dm^{-3} in the 0.00-0.10 m layer of long-term NT soils – which is the typical CEC range for soils in the central-southern region of Paraná – has been reported. This value is identical to the critical soil K value found in this study for soybean and corn in the 0.00-0.10 m layer, but 30 % lower than the critical soil K value for winter cereals in the same layer: 0.33 $cmol_c$ dm^{-3}. Thus, if the critical soil K values for Rio Grande do Sul and Santa Catarina are applied to soils in the central-southern region of Paraná, the value estimated as critical will be insufficient (under the critical value required).

Potassium interpretation classes

Potassium interpretation classes were established from the critical soil-test K value for the most K demanding crops (winter cereals), namely: 0.23 $cmol_c$ dm^{-3} for the 0.00-0.20 m layer and 0.33 $cmol_c$ dm^{-3} for the 0.00-0.10 m layer. It should be noted that, since a study previously conducted in the same region showed soil nutrient content and acidity in the 0.00-0.20 m layer to be better correlated with crop yields than the same variables in the 0.00-0.10 m layer (Fontoura et al., 2015), the K fertilization recommendations discussed below are based on the results for soil samples from the 0.00-0.20 m layer.

Interpretation classes were associated with the following soil-test K values: <0.12 $cmol_c$ dm^{-3} (low), 0.12-0.23 $cmol_c$ dm^{-3} (medium), 0.24-0.46 $cmol_c$ dm^{-3} (high) and >0.46 $cmol_c$ dm^{-3} (very high). As can be seen from figure 2, these classes were closely related to the probability of the crops responding to K application – mainly for winter cereals – and hence useful for the intended purpose. The likelihood of economic return in response to K application in the very high K class was very low or zero, and increased with decreasing soil-test value.

The economic returns in the experiments of crop response were highest for the soils in the medium K interpretation class; in addition, returns decreased as the soil K level increased, thus confirming a medium, low, and very low likelihood of the crops grown on soils in the respective increasing K classes responding to K fertilization. At current grain prices, the economic return on application of 50 kg ha^{-1} K_2O to the four crops taken together was only positive for the medium K class (16 US$ ha^{-1}). Although economic returns were positive in 47 % of the experiments in the high and very high classes, the mean return was negative (–5.43 and –6 US$ ha^{-1}, respectively). With a grain price 30 % lower than the average, the economic return for the medium availability class was still positive (5.71 US$ ha^{-1}), which further supports the distribution of available levels among the proposed classes.

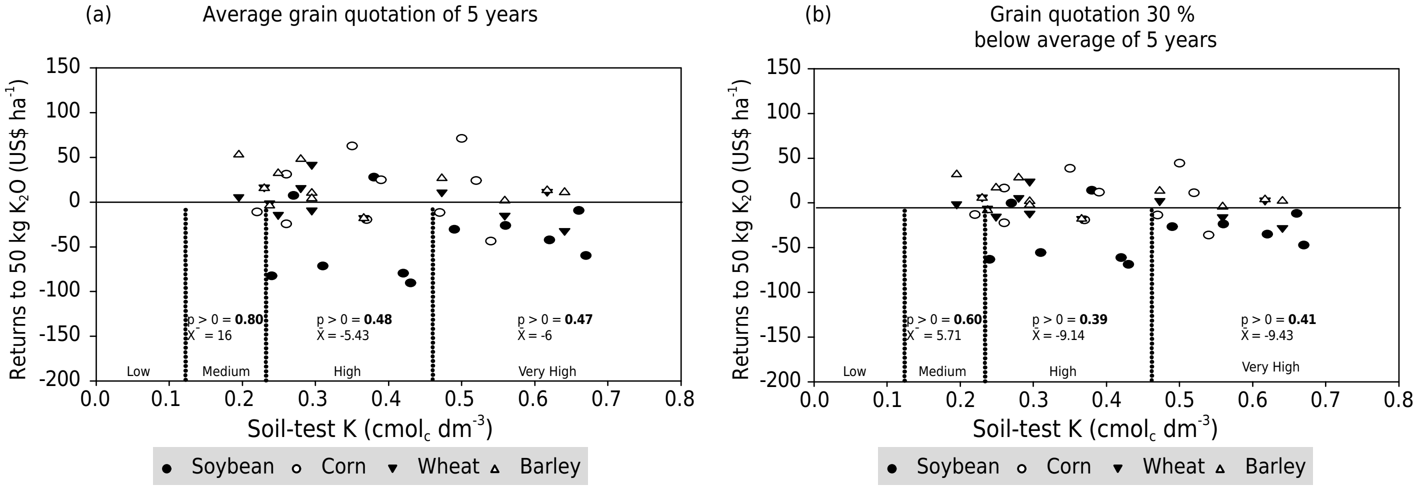

Figure 2. Net returns from K fertilization for different interpretation classes and prices of commodities and fertilizers. Quotation for soybean, corn, wheat, and barley: US$ 225.50, 101.50, 149.28, and 141.71 Mg^{-1} (a); and US$ 157.71, 71.14, 104.57 and 99.14 Mg^{-1} (b). Quotation for K fertilizer: US$ 359.43 Mg^{-1} K_2O. (US$ = R$ 3.50). *: p>0 = Ratio of the number of trials with a positive increase to total trials in each interpretation class.

Potassium fertilization recommendation

After soil-test K ranges were determined from the calibration curves, the recommended rate for each crop and K class were estimated. The rates for the low and medium classes were calculated from the relationship between soil K values in the 0.00-0.20 m soil layer seven months after fertilization and the K_2O rates used in the calibration experiments (Figure 3). The fertilizer rate needed to increase the soil-test value by 0.01 cmol$_c$ dm^{-3} K was 11.1 kg ha^{-1} K_2O in Guarapuava and Pinhão, and 9.1 kg ha^{-1} K_2O in Candói. These values are lower than the requirement of 20.3 kg ha^{-1} previously determined by Schlindwein et al. (2013) for the 0.00-0.20 m soil layer in the highlands of Rio Grande do Sul, and also lower than the value determined by Wendling et al. (2008) for the 0.00-0.10 m soil layer in Paraguay: 19.6 kg ha^{-1}.

Potassium fertilizer rates were estimated by multiplying the mean for the three locations (10.4 kg ha^{-1} K_2O for each 0.01 cmol$_c$ dm^{-3}) by the difference between the critical soil-test K value and intermediate value for the medium class, and the highest value for the low class, because only a few soils in the region contained less than 0.12 cmol$_c$ dm^{-3} K. Thus, the soils in the low K class required 115 kg ha^{-1} K_2O for their K content to be raised from 0.12 to 0.23 cmol$_c$ dm^{-3}, and those in the medium class required 55 kg ha^{-1} K_2O for the content to be increased from 0.175 to 0.23 cmol$_c$ dm^{-3}.

Correction rates in most current recommendations of K fertilizer use in Brazil are based on a build-up philosophy and have been established for soils with K values below the critical value (Sousa and Lobato, 1996; Ribeiro et al., 1999; CQFSRS/SC, 2004; Embrapa, 2013b) even though the optimum rate differs according to the particular soil and climate conditions in each location.

In Paraná, the recommended measure for corrective K fertilization for soils with a soil-test value below 0.08 cmol$_c$ dm^{-3} and a clay content above 400 g kg^{-1} (Embrapa, 2013b) is prior broadcast application of 140 kg ha^{-1} K_2O plus a replenishment rate on crop rows to compensate for the extraction of K in proportion to expected yield. The recommended correction rates determined in this study are similar to the recommended fertility correction rates for the states of Rio Grande do Sul and Santa Catarina, namely: 120, 60, and 30 kg ha^{-1} K_2O for soils with very low (<0.078 cmol$_c$ dm^{-3}, CEC$_{pH7.0}$ > 15 cmol$_c$ dm^{-3}), low (0.079-0.153 cmol$_c$ dm^{-3}) and medium K availability (0.154-0.230 cmol$_c$ dm^{-3}), respectively.

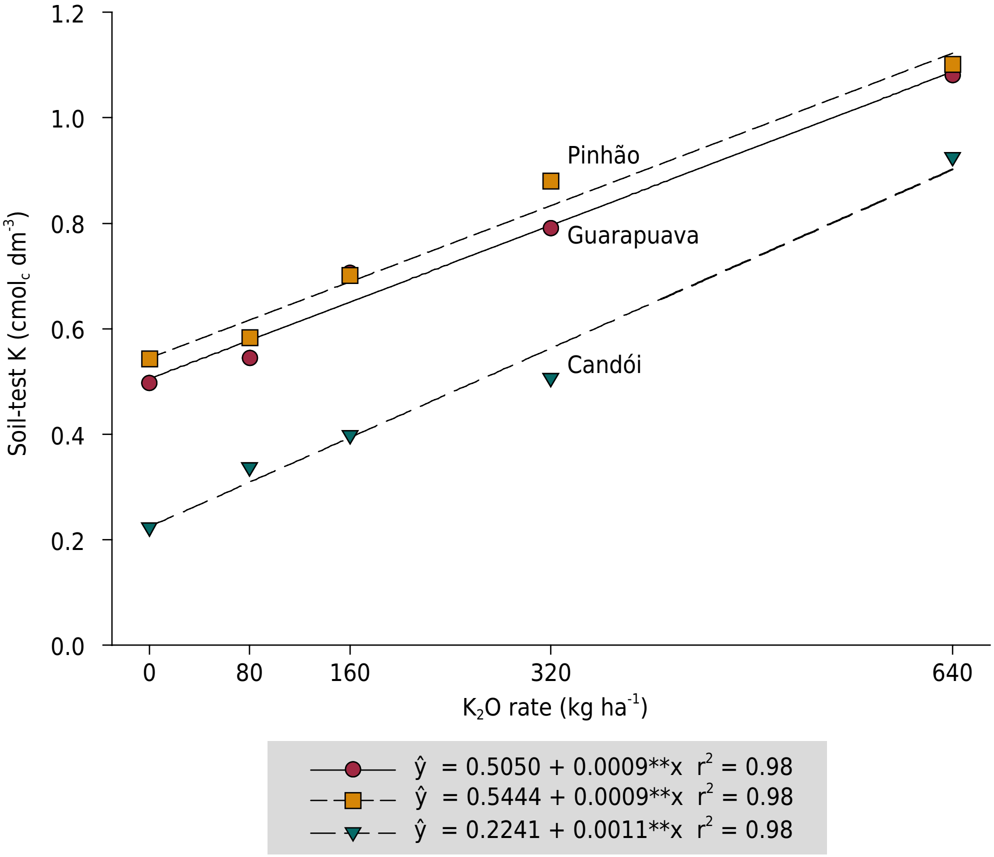

Figure 3. Soil-test K seven months after K_2O application in Guarapuava, Pinhão, and Candói, PR, Brazil.

The K rates for the high and very high classes were estimated from K export in grain, based on the mean experimental yield and mean K grain concentration, and the maximum economic efficiency as determined in the K fertilization response experiments (Tables 2 and 3).

With soybean, K fertilization led to a positive economic return in only two experiments in the high availability class; whereas MEE for the very high class did not respond positively to K application in any experiment (Table 2). This suggests that K fertilization of soybean in soils in the high and very high classes must be carefully adjusted and that using rates below the replenishment level for grain export or early application of fertilizer to soil for cropping winter cereals are effective practices.

Potassium fertilization for corn was economically positive in three of five experiments on soils in the high availability class. The MEE rates for this class were very similar to the amounts of K exported by grains. Unexpectedly, half of the experiments in the very high class exhibited a positive response (MEE rate of 70 $kg\ ha^{-1}$). This result suggests that soils in the high and very high classes benefit from use of the replenishment rate to grow corn.

Grain yield in wheat and barley increased with increasing K fertilization in all experiments on soils in the medium class (MEE rates of 76 $kg\ ha^{-1}$, Table 3). In the high class, K fertilization of wheat was economically viable in only two of the six locations, with a mean MEE rate similar to the replenishment fertilization rate (25 $kg\ ha^{-1}$) for an expected yield of 3.5 $Mg\ ha^{-1}$. In contrast, barley grown on soils in the high class responded positively to fertilization in five of the six experiments (MEE rate of 64 $kg\ ha^{-1}$, which is much higher than the replenishment rate). Maximum economic efficiency rates exceeding the replenishment rate were also observed in the very high class, which indicates that the crops responded to K application even in soils with high soil-test K values.

Combined analysis of the results of soil K correction and crop response to K fertilization revealed that the recommended correction rate for crops in soil-test K values below the critical value was 115 and 55 kg ha^{-1} for low and medium classes, respectively – plus the K replenishment rate for export in grain (Table 4). For soils in the high and very high classes, replenishment fertilization is suggested for all crops; the rate, however, can be reduced for summer crops (particularly soybean) given that they failed to respond to K application to soils in the very high class.

The recommended K rates for soybean grown on soils in all interpretation classes are higher than those recommended for Paraná (Embrapa, 2013b). The difference can probably be ascribed to differences in expected yield between studies; in fact, the replenishment rate for the high class, 80 kg ha^{-1} K_2O, was based on an expected yield of 4 Mg ha^{-1} (Table 4), whereas the replenishment rate for soils in Paraná, 40 kg ha^{-1}, was estimated for a yield of 2 Mg ha^{-1}. The recommended K rates for soybean in Paraná (Embrapa, 2013b) were also lower in the low and medium classes as a result of using 90 kg ha^{-1} K on soils with K levels below 0.10 cmol$_c$ dm^{-3} and 70 kg ha^{-1} K on soils with soil-test values range of 0.10-0.20 cmol$_c$ dm^{-3}. However, the recommended critical value and rates were calculated from the results of experiments conducted in the 1980s and 1990s (OCEPAR, 1987; Sfredo and Borkert, 1991; Embrapa, 1999) on soils under conventional tillage, with crop yields around 60 % lower than current values.

The rates for corn in the low and medium classes were 200 and 140 kg ha^{-1} (expected yield 14 Mg ha^{-1}), respectively, and hence much higher than the currently recommended rates for this crop in PR soils in the low (60-70 kg ha^{-1}), medium (40-60 kg ha^{-1}), and high classes (30-40 kg ha^{-1}) (Oliveira, 2003). However, these recommended rates were determined at unknown expected yields.

Our recommended rates for corn are lower than the K fertilizer recommendations for Rio Grande do Sul and Santa Catarina (CQFSRS/SC, 2004). Thus, the rates for corn as a first crop in these two states consist of ⅔ of the correction rate and the K replenishment rate plus 20 %; in addition, they were established for an expected yield of 4 Mg ha^{-1} plus 10 kg ha^{-1} K_2O for each additional Mg of grain to be produced, representing an increase of 67 % over the amount of K exported in grains. Thus, for an expected yield of 14 Mg ha^{-1}, a rate of 210 kg ha^{-1} K_2O is recommended for soil-test K values below 0.078 cmol$_c$ dm^{-3} and a rate of 160-170 kg ha^{-1} for soil-test values range of 0.079-0.230 cmol$_c$ dm^{-3}.

The K fertilizer recommendations for wheat (Embrapa, 2011) and barley (Embrapa, 2013a) used in Paraná are identical, and were estimated from the recommended fertilization practices for wheat (Oliveira, 2003). These recommendations involve applying 60-80 kg ha^{-1} K_2O to soil-test values below 0.10 cmol$_c$ dm^{-3} and 40-60 kg ha^{-1} K_2O to soil-test values from

Table 4. K_2O rates for soybean, corn, wheat, and barley on Oxisols in different interpretation K classes under no-tillage in the central-southern region of Paraná, Brazil

Interpretation class	Soil-test K	Crop$^{(1)}$			
		Soybean	Corn	Wheat	Barley
	cmol$_c$ dm^{-3}	kg ha^{-1}			
Low	< 0.12	195	200	135	140
Medium	0.12-0.23	135	140	75	80
High	0.24-0.46	80 (R)$^{(2)}$	85 (R)	20 (R)	25 (R)
Very high	> 0.46	<80 (R)	<85 (R)	20 (R)	25 (R)

$^{(1)}$ Recommended rates for expected yields of 4,000, 14,000, 3,500 and 4,000 kg ha^{-1} in soybean, corn, wheat, and barley, respectively. $^{(2)}$ R: replacement value as a function of nutrient content in harvested grains: 6 kg K_2O Mg^{-1} corn, wheat, and barley; 20 kg K_2O Mg^{-1} soybean.

0.11 to 0.30 $\text{cmol}_c\ \text{dm}^{-3}$ – values which are lower than those calculated in this study (Table 4). Our estimated rates are similar to those recommended for the states of RS and SC; as an exception, the recommended rate for soil-test value below 0.12 $\text{cmol}_c\ \text{dm}^{-3}$ (i.e., soils in the low class) is 20 kg ha^{-1} higher than that recommended by CQFSRS/SC (2004).

Potassium fertilization for crop rotation

The recommended K fertilizer rates for crops grown on soils containing amounts of K exceeding the critical level (i.e., soils in the high and very high interpretation classes) were similar to those for other regions, which is logical since all were based on the amount of K removed in grains. Interestingly, the expected response of crops grown on soils in the high or very high classes was low; therefore, fertilization may be economically unfeasible in the short term. However, in soils with high or very high classes– a typical situation after 30 years under no-tillage – K fertilization no longer focuses on monocultures and on maximizing economic efficiency at harvest, but rather on continuity of nutrient cycling within the crop rotation system and on maintaining soil K contents by replenishing K removed in grains.

Based on crop yields, economic returns from K fertilization, system fertilization philosophy, and the practicality of agricultural operations, K fertilization is proposed for the sequence of four crops in rotation used in the central-southern region of Paraná (Table 5). In soils in the high and very high classes, K replenishment fertilization for soybean could be moved up to the previous winter cereal (wheat or barley). The crop yields obtained in response to K rates (Tables 2 and 3) support this proposal. In fact, no positive economic returns from soybean were observed in response to K application in soils in the high class; however, wheat and barley exhibited the maximum economic efficiency rates in soils in the high and very high classes, and the rates invariably exceeded the K replenishment levels.

In this proposal, correcting the soil K content in the low and medium interpretation classes is recommended for the first winter cultivation because these crops are more responsive to K fertilization; in addition, replenishment fertilization could be maintained in the following summer crop (second crop) in order to ensure better K distribution in the soil. In soils with high or very high interpretation classes, moving up soybean replenishment fertilization for the previous winter crop and maintaining replenishment fertilization for corn are recommended. If the second crop is corn, correcting the soil K content for the preceding cover crop is recommended. By the time the third crop is sown, the soil-test K values in the low and medium classes must have been maintained and even raised to high interpretation class by fertilization of the first crop. Therefore, replenishment fertilization of the winter cereal plus the fertilization of the summer crop (in the case of soybean) in advance are recommended.

Table 5. K_2O rates for a sequence of four crops (soybean, corn, wheat, and barley) in rotation on Oxisols in different interpretation K classes under no-tillage in the central-southern region of Paraná

Interpretation class	Soil-test K	Crop sequence							
		1st crop		2nd crop		3rd crop		4th crop	
		Wheat/ Barley	Cover crop	Soybean	Corn	Wheat/ Barley	Cover crop	Soybean	Corn
	$\text{cmol}_c\ \text{dm}^{-3}$	kg ha^{-1}							
Low	< 0.12	115+RW(1)	115	RS	RC	RW+RS	–	–	RC
Medium	0.12-0.23	55+RW	55	RS	RC	RW+RS	–	–	RC
High	0.24-0.46	RW+RS	–	–	RC	RW+RS	–	–	RC
Very high	> 0.46	RW+RS	–	–	RC	RW+RS	–	–	RC

RW, RS, and RC: replacement value as a function of nutrient content in harvested grains of the winter crops (RW), soybean (RS), and corn (RC): 6 kg K_2O Mg^{-1} corn, wheat, and barley; 20 kg K_2O Mg^{-1} soybean.

CONCLUSIONS

Wheat, barley and white oat are the crops with the highest potassium demand from soil, and hence those having the highest critical soil-test K values. These crops exhibited a stronger response to K fertilization than did soybean and corn in soils under long-term no-tillage.

Based on the differential crop response observed, fertilization of soybean can be moved up to the previous winter cereal in high or very high interpretation K classes. However, this measure is not recommended in soils in the low or medium class.

The recommended potassium rates for soybean, corn, wheat, and barley in soils under long-term no-tillage in the central–southern region of Paraná are higher than the current official fertilization rates for individual crops in Paraná.

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