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Nitrogen and Potassium in Narrow-Row Cotton

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ABSTRACT: Information on fertilizer management for cotton in narrow-row cropping system is scarce; therefore, studies are needed to improve nutrient stewardship for such systems. The aim of this study was to evaluate the effects of nitrogen and potassium application on yield and fiber quality of cotton under a narrow-row system. A field trial was carried out for three years, where the treatments were set up in an incomplete factorial arrangement [(4 × 4) + 1] under a randomized block design, with four N rates (20, 40, 60, and 80 kg ha^{-1}), four K_2O rates (0, 40, 80, and 120 kg ha^{-1}), and one control (no N or K_2O), for a total of 17 treatments, with four replicates. Urea and potassium chloride were applied on the soil surface 20 days after crop emergence. Varieties used were FMT 701 (2009/2010 and 2010/2011) and FMT 709 (2011/2012). Cotton yield and fiber quality parameters were measured. In the narrow-row cropping system, cotton lint yield was positively affected by N and K application. Cotton yield in relation to K applications was not dependent on N rates. Potassium application increased the micronaire index and fiber resistance, whereas high N rates reduced fiber resistance.

Keywords: *Gossypium hirsutum*, nitrogen, potassium, narrow-row cotton.

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INTRODUCTION

Cotton (*Gossypium hirsutum* L.) has been grown in different row spacing systems, such as conventional (≥0.9 m), narrow row (0.39 to 0.76 m), and ultra-narrow row (0.19 to 0.38 m), with populations ranging from 50,000 to 320,000 plants ha^{-1} (Silva et al., 2006). Narrow-row-space cotton, originally studied and cultivated in marginal lands of the American cotton belt and in Australia, was brought to Brazil as a development to shorten the season, hence reducing production costs (Yamaoka and Belot, 2011; Alves et al., 2012).

Growing cotton as a second crop in narrow-row after soybeans, in the same season, was a system initially suggested in Mato Grosso, Brazil, in 2009, with this configuration: (i) seeding time ranging from mid-January to early February, following the soybean harvest, (ii) row spacing from 0.45 to 0.5 m, and (iii) double the plant population used in conventional systems. Lower water availability and temperature during the second crop decreases yield per plant, but benefits cotton yield per hectare in response to higher population (Gottardo, 2012).

Narrow row spacing in cotton favors intensification of the cropping system, with the possibility of growing two crops within a season and its use in crop rotation. However, information on nutrient management in the narrow-row cropping system is scarce, and farmers apply the same fertilizer strategy used for conventional cotton with no further criteria (Carvalho et al., 2011c), which demonstrates the need for research in this area.

Nutrient application, especially N and K, is crucial for high yield cotton. Higher rates of N may be required in narrow row spacing due to higher populations compared to conventional systems. Nevertheless, excessive use of N can reduce yield because plants will grow taller and take longer to mature (Bell et al., 2003), which is not desired in narrow-row systems. Hence, N rates must be appropriate for avoiding excessive growth in a long cycle.

Application of high N rates in narrow-row cotton is restrictive since plants grow under low water and temperature as of May, reducing crop response to N, and excessive plant growth may require higher rates of plant growth regulator (Yamaoka and Belot, 2011). The narrow-row cotton did not require higher N rates compared to conventional spacing, and that recommended rates must be based on expected yield and on factors related to crop response to N (Carvalho et al., 2011b).

Cotton takes up great amounts of K, which plays an important role in plant development and fiber quality (Carvalho et al., 2011c). However, one hypothesis is that narrow-row cotton may demand more N and K during the boll filling stages in response to higher plant population and low availability of these nutrients because of water shortage in the soil, leading to the need for higher application rates. Research data on this subject have not been conclusive so far. The objective of this study is to evaluate the effect of N and K application on gross and lint yield and on fiber quality of cotton in narrow-row spacing systems.

MATERIALS AND METHODS

Field trial

The study was carried out in an experimental station in Itiquira, Mato Grosso, Brazil, located at 17° 09' S and 54° 42' W, 490 m asl, in a *Latossolo Vermelho Distrófico* (Santos et al., 2013), a Typic Haplorthox (Soil Survey Staff, 2014), of the *Cerrado* (Brazilian tropical savanna), where the climate type is Aw with dry winters, according to Köppen classification (Ribeiro and Walter, 1998), with average rainfall ranging from 1,200 to 1,800 mm per year and average temperature between 22 and 23 °C (Figure 1). Soil characteristics are shown in table 1.

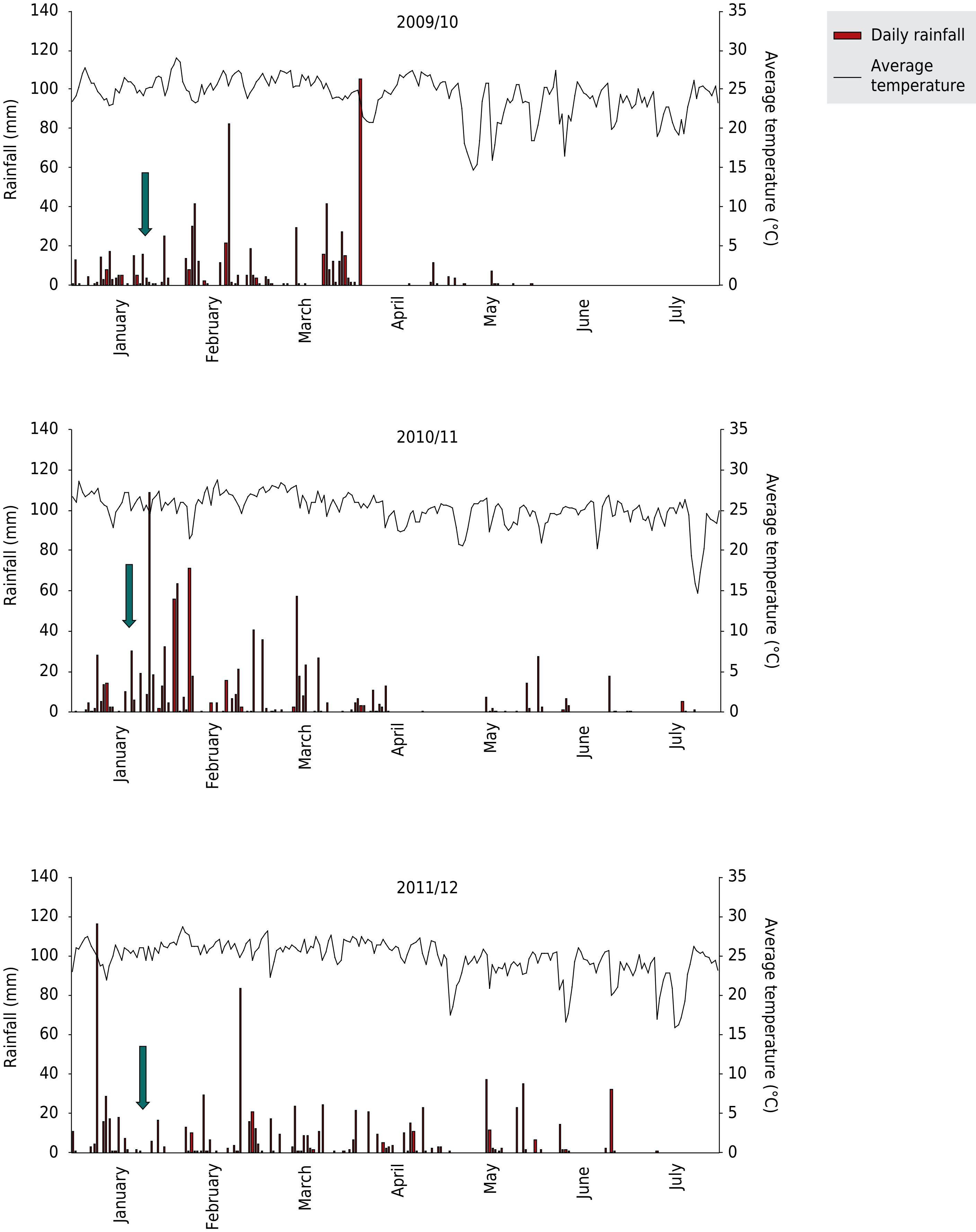

Figure 1. Daily values of rainfall and average temperature in the 2009/10, 2010/11, and 2011/12 crop seasons (arrows indicate seeding time).

Table 1. Soil properties of the 0.0-0.2 and 0.2-0.4 m layers before the beginning of the trial

Depth	pH($CaCl_2$)	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	CEC	m	V	OM	Clay	Sand	Silt
m		— mg dm^{-3} —		— cmol$_c$ dm^{-3} —					— % —		g dm^{-3}	— g kg^{-1} —		
0.0-0.2	4.9	3.3	36	2.1	1.5	0.0	5.5	9.2	0	40	38.9	635	215	150
0.2-0.4	4.3	1.5	19	0.6	0.5	0.5	5.7	7.3	30	16	30.4	-	-	-

Methods according to Claessen (1997). Extractants: P and K (Mehlich-1); Ca^{2+}, Mg^{2+}, and Al^{3+} (KCl 1 mol L^{-1}); H^+ (calcium acetate at pH 7); OM: organic matter (potassium dichromate); clay, sand, and silt (pipette method); CEC: cation exchangeable capacity; m: aluminium saturation; V: base saturation.

Land use in the area had been for cattle grazing (*Urochloa decumbens* L.) for 18 years prior to the start of the trial in the fall of 2008, at which time the following operations were performed: disking (14 × 32") to a 0.2 m depth, subsoiling to a depth of 0.3 m, liming (4 Mg ha^{-1}), and disking (14 × 32") to a 0.2 m depth. Afterwards, *Millet* sp. was sown as cover crop. The trial was set up in 2009 after desiccation of the cover crop, which was carried out for three consecutive seasons, the period of the experiment. Cotton was grown in the fall after summer fallow.

Treatments and experimental design

The field trial was set up in a completely randomized block design in an incomplete factorial arrangement [(4 × 4) + 1], with four N rates (20, 40, 60, and 80 kg ha^{-1}), four K_2O rates (0, 40, 80, and 120 kg ha^{-1}), and one additional treatment (control, no NK), with four replicates. Treatments were applied by hand using urea (45 % of N) as a source of N, and potassium chloride (60 % of K_2O) as a source of K, broadcasting these fertilizers 20 days after seedling emergence. Plots were 6.3 m wide by 6.0 m long. All treatment plots, except the control, received 30 kg ha^{-1} N plus 40 kg ha^{-1} K_2O in the planting furrow as a starter.

Field trial activities

For trial set-up, a disk seeder was used to mark the rows, then 0.1 m deep furrows were opened by hand and 70 kg ha^{-1} P_2O_5 plus 2.5 kg ha^{-1} B were applied, annually, via triple superphosphate and *Borogran* (oxi-sulphate B source), respectively. After that, the furrows were closed and the seeder was driven over the plots, seeding 10 cotton seeds per meter. In the 2010/11 and 2011/12 seasons, all plots received phosphogypsum application at the rate of 0.3 and 3.0 Mg ha^{-1}, respectively, prior to cotton seeding. The cotton variety used in the 2009/10 and 2010/11 seasons was FMT 701, while in the 2011/12 season, the variety was FMT 709. Seeds were treated with fungicides (carbendazin + thiram: 30 + 70 g/100 kg seeds; plus thiamethoxam: 70 g/100 kg seeds) and sowed on Jan. 25, 2010, Jan. 21, 2011, and Jan. 25, 2012 in the respective crop seasons. Weed, insect, and disease control was carried out according to regional recommendations. A growth regulator (mepiquat chloride) was applied as necessary.

Parameters and statistics

The nutritional status of the plants was evaluated annually via leaf analysis sampling, according to Zancanaro and Kappes (2012). Lab analysis for macronutrient content was performed according to Malavolta et al. (1997). Just before harvest, final population and plant height were measured in two rows of 4.0 m length at two different spots in each plot. At harvest (which took place on Jul. 29, 2010, Jul. 26, 2011, and Aug. 2, 2012, respectively), 20 ready-for-harvest bolls were collected from each plot to determine boll weight and lint percentage. In addition, all the bolls from plants present in two rows of 4.0 m length at two different spots in each plot were collected and weighed to determine gross yield. After that, a sample from each plot was sent for analysis of lint quality using the HVI method.

After harvest, soil samples were collected using a probe at twelve points in each plot (eight points in the rows plus four points between rows) at a depth of 0.2 m. Samples were analyzed according to Claessen (1997). Data were subjected to ANOVA and regression analysis using the software Assistat (Silva and Azevedo, 2002).

RESULTS AND DISCUSSION

Yield parameters

Throughout the period of this study, plant population was not affected by any of the treatments, and there was no interaction effect of the factors studied on any yield parameter (Table 2). Nevertheless, N and K rates positively affected plant height in the second year (2010/11), while K rates alone affected it in 2011/12. In both seasons, plant height was higher when N and K were applied as compared to the control. The linear response of this parameter to N rates (Figure 2a), which is in agreement with Carvalho et al. (2011a), who concluded that N rates (16, 64, 144, and 256 kg ha^{-1} N) caused a linear increase in plant height of narrow-row-space cotton (0.45 m).

The NPK supply on narrow-row-space cotton in the Cerrado of the state of Goiás was studied by Carvalho et al. (2011b), which found no interaction effect on plant height, but only an isolated effect from N rates (40, 80, and 120 kg ha^{-1} N) on a linear increase in plant height in the second year of the study. Authors emphasized that increasing plant

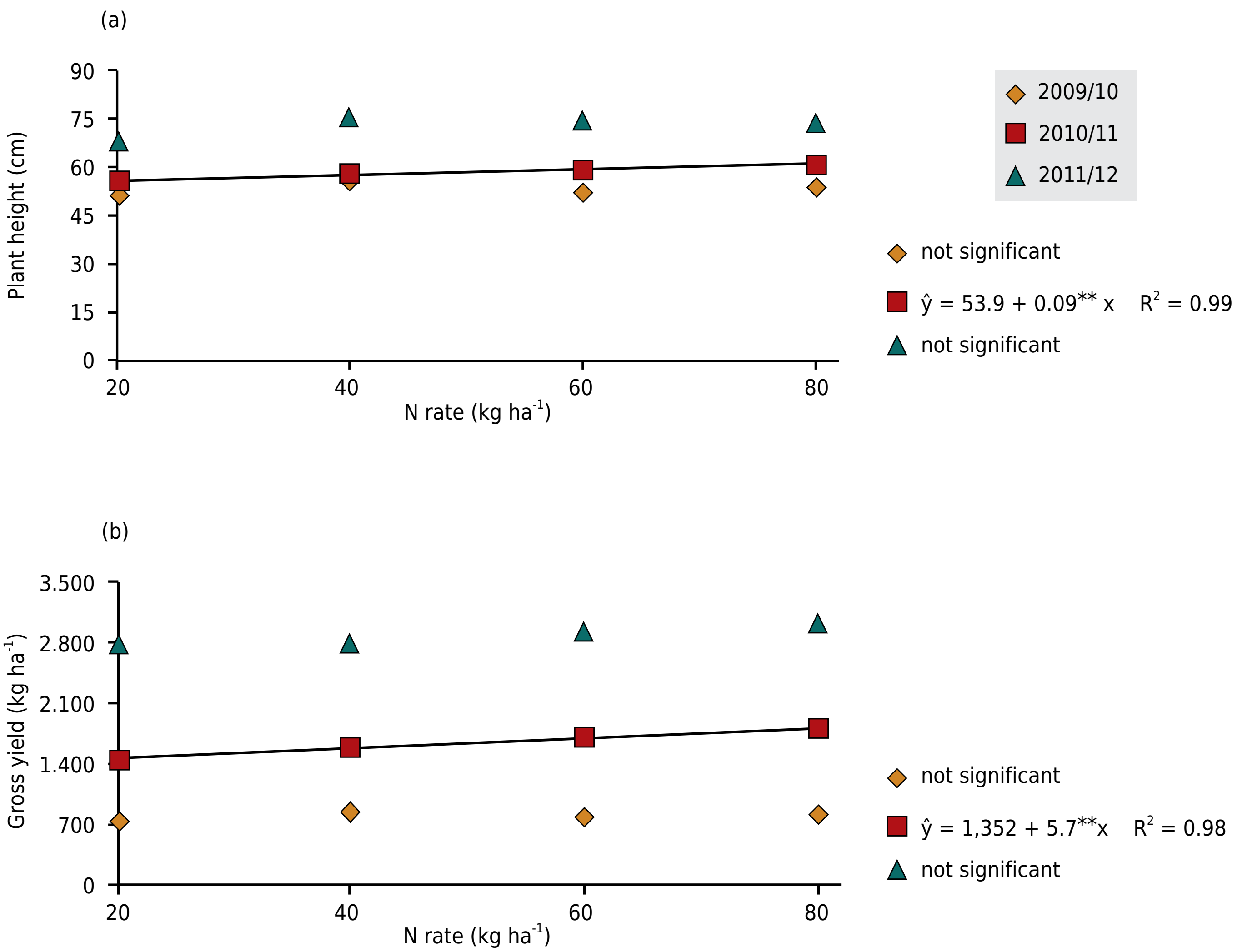

Figure 2. Plant height and gross yield of narrow-row-space cotton in response to nitrogen rates applied in the 2009/10, 2010/11, and 2011/12 crop seasons. **: significant at 1 % by F test.

height for narrow-row-space cotton is not desirable because it interferes with harvest. Furthermore, high N rates lead the plants into continuous growth, lengthening the cycle and reducing yield (Bell et al., 2003). Other studies found similar results of N rates leading to taller plants (Bogiani et al., 2011; Gottardo, 2012; Galhardo et al., 2013).

Increasing K rates promoted linear response in plant height in the 2010/11 and 2011/12 crop seasons (Figure 3a), but no effect was observed in the first year (2009/10). Furthermore, Kaneko et al. (2014) did not observe any effect of K rates (0, 60, 80, 100, and 120 kg ha^{-1} K_2O) on plant height of narrow-row-space cotton, in agreement with other studies (Bogiani et al., 2011; Carvalho et al., 2011b; Freitas et al., 2011; Galhardo et al., 2013). The results for plant height observed in this study (Table 2) are considered adequate for narrow-row-space cotton to be harvested using the stripper system, as pointed out by Silva et al. (2010): 0.53, 0.58, and 0.72 m in 2009/10, 2010/11, and 2011/12, respectively.

Gross yield of narrow-row-space cotton was positively influenced by K rates (years 1 and 2) and N rates (year 2) as well (Table 2). The effect of N rates on gross yield, and a linear model

Table 2. Analysis of variance, coefficients of variation (CV), and mean values for plant population (PP), plant height (PH), boll weight (BW), lint percentage (LP), gross yield (GY), micronaire (Mic), strength (Str), mean length (Len), short fiber index (SFI), elongation (Elg), uniformity index (Unf), and maturity (Mat) of cotton fiber in a narrow-row-space system in response to nitrogen and potassium application, in the 2009/10, 2010/11, and 2011/12 crop seasons

Factor	DF	PP	PH	BW	LP	GY	Mic	Str	Len	SFI	Elg	Unf	Mat
		plants ha^{-1}	cm	g	%	kg ha^{-1}	µg pol^{-1}	g tex^{-1}	in	%			
							2009/10						
N rate	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
K_2O rate	3	ns	ns	*	**	**	**	ns	ns	ns	ns	ns	ns
N × K_2O	9	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Factorial *vs* control	1	ns	ns	ns	*	**	**	ns	ns	ns	ns	ns	ns
Rep	3	*	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Residue	48	-	-	-	-	-	-	-	-	-	-	-	-
CV (%)	-	8.4	11.3	8.0	1.7	13.3	5.1	3.5	2.1	7.9	5.2	1.0	1.0
Mean	-	183,415	53.1	4.65	44.5	772	4.2	32.4	1.1	7.6	7.5	85.7	87.0
							2010/11						
N rate	3	ns	*	ns	ns	**	ns	**	ns	ns	ns	ns	ns
K_2O rate	3	ns	**	**	*	**	**	**	ns	ns	ns	ns	ns
N × K_2O	9	ns	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns
Factorial *vs* control	1	ns	**	ns	**	**	**	*	**	ns	ns	ns	ns
Rep	3	ns	**	ns	**	ns	ns	**	ns	ns	ns	ns	*
Residue	48	-	-	-	-	-	-	-	-	-	-	-	-
CV (%)	-	15.9	9.6	5.2	1.7	9.0	2.8	2.0	1.1	2.2	5.7	0.7	0.9
Mean	-	181,683	57.7	4.22	38.9	1,590	4.0	33.5	1.2	7.0	6.2	87.0	86.0
							2011/12						
N rate	3	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
K_2O rate	3	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
N × K_2O	9	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Factorial *vs* control	1	ns	**	*	*	**	**	ns	ns	ns	ns	ns	**
Rep	3	ns	ns	ns	ns	**	ns	ns	ns	ns	*	ns	ns
Residue	48	-	-	-	-	-	-	-	-	-	-	-	-
CV (%)	-	7.86	11.2	8.6	3.5	16.5	4.8	3.6	2.1	10.6	5.7	0.9	0.6
Mean	-	173,284	71.8	4.82	44.7	2,823	4.9	30.4	1.2	6.5	6.8	85.0	87.7

DF: degrees of freedom; CV: coefficient of variation. **, *, ns: significant at 1 %, 5 % and not significant, respectively, by F test.

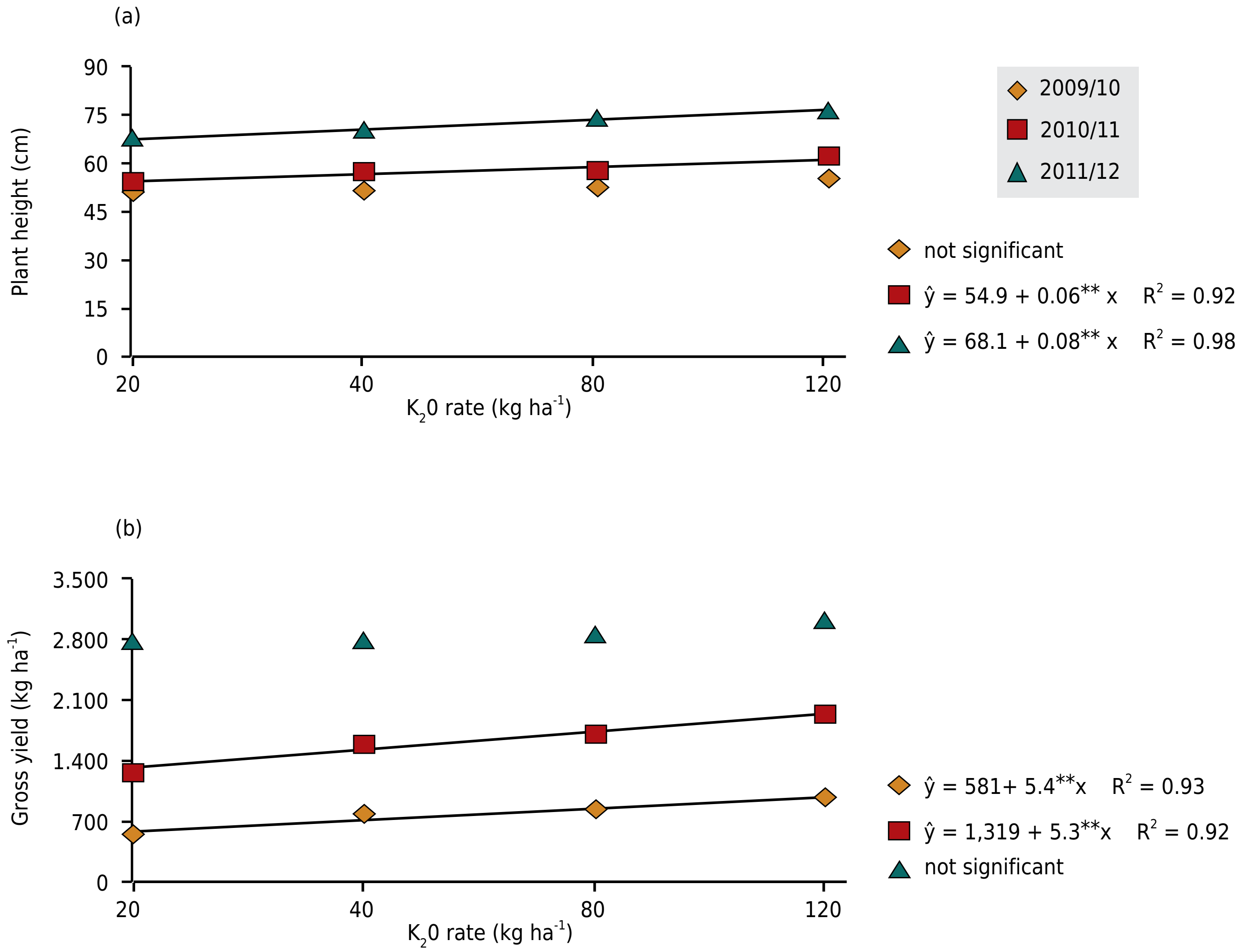

Figure 3. Plant height and gross yield of narrow-row-space cotton in response to potassium rates applied in the 2009/10, 2010/11, and 2011/12 crop seasons. **: significant at 1 % by F test.

fitted to data of the 2010/11 season allows calculation of 5.7 kg of gross yield per kg of N applied (Figure 2b). The highest values of gross yield observed with 80 kg ha^{-1} N represented an increase of 24 % as compared to the lowest rate applied (20 kg ha^{-1} N). Such results are in agreement with other studies (Bogiani et al., 2011; Gottardo, 2012; Galhardo et al., 2013) that observed higher values for gross yield of narrow-row cotton in response to N rates.

Effect of NPK supply on the yield of narrow-row cotton grown after soybean harvest was studied by Carvalho et al. (2011b), which found an increase of 8.4 % from the lowest (40 kg ha^{-1} N) to the highest (120 kg ha^{-1} N) rate of N applied. The authors concluded that narrow-row cotton did not demand more N than conventional cotton and that rate recommendation should be based on expected yield and other factors limiting response to N fertilization.

Regarding the effects of K rates on gross yield, linear models fitted to data show that 3.4 and 5.3 kg ha^{-1} of cotton yield were obtained per kg ha^{-1} of K_2O applied in the 2009/10 and 2010/11 crop seasons, respectively (Figure 3b). The higher values of gross yield observed with 120 kg ha^{-1} K_2O represented an increase of 81 and 54 % in the first two years of the study, respectively, as compared to the control. Such a significant positive response is in agreement with the fact that K is the nutrient that is most taken up and its supply is crucial for plant development and high yields, as pointed out by Carvalho et al. (2011c).

Other studies reported the positive effect of K supply on narrow-row cotton yield (Bogiani et al., 2011; Freitas et al., 2011). In contrast, Carvalho et al. (2011b), Sofiatti et al. (2013), and Kaneko et al. (2014) did not observe higher yields of narrow-row cotton from increasing K rates. According to the last two studies cited, the reasons might be: (i) K recycling from deeper layers of the soils by cover crops in rotation, and (ii) soil K level was already adequate for high yield (63 mg dm^{-3} in the top 0.2 m). In the third year of this study, no effect on lint percentage or gross yield was observed in response to N or K application (Table 2). This may be explained by the residual effect of previous applications in the first two years.

The values for gross yield observed in this study are below the yield attainable for narrow-row cotton in Mato Grosso, based on the most recent seasons (Conab, 2015). This may be related to the low soil fertility at the beginning of the trial, the time of seeding, the weather conditions, and to the row spacing applied. In the first year, a severe drought that occurred in April 2010 as plants were filling their bolls had a significant impact on yield (Figure 1). This is important to mention because weather conditions in the season can greatly impact yield, and water is the most limiting factor. Hence, to grow cotton in a narrow-row system as a second crop, even before analyzing nutrient supply, it is important to evaluate the soil capability to supply water to the crop throughout the cycle, and lower yields may be expected compared to conventional systems.

In all seasons, a significant effect of treatments over the control was observed on lint percentage (Table 2). In the first two years, K rates affected lint percentage positively and by the quadratic model that was fitted, it was possible to calculate the K rate that promoted the maximum values for each season: 45.4 % at 115 kg ha^{-1} K_2O in the 2009/2010 crop season, and 39.2 % at 50 kg ha^{-1} K_2O in the 2010/2011 crop season (Figure 4a). Nevertheless, Carvalho et al. (2011b) showed no response of lint percentage to K rates (40, 80, and 120 kg ha^{-1} of K_2O), but instead a positive response to N. Other studies corroborate the results of this study where no effect of N rates was observed on lint percentage (Carvalho et al., 2011a; Gottardo, 2012; Galhardo et al., 2013).

Boll weight was positively affected by K rates in 2009/10 and 2010/11 (Table 2), while in 2011/12 there was significant difference between treatments and control for this variable. As observed for plant height, K rates resulted in a linear response of boll weight (Figure 4c), which is in agreement with Freitas et al. (2011), who studied the effect of K rates (0, 40, 80, 100, and 120 kg ha^{-1} of K_2O) on narrow-row-space cotton. Potassium is a nutrient that plays a direct role in metabolism of carbohydrates, which is directly related to the fiber components. However, some studies present opposite results: Carvalho et al. (2011b), Galhardo et al. (2013), and Kaneko et al. (2014) reported no effect of K rates on boll weight. Regarding N rates, no effect was observed on boll weight, as also found by Carvalho et al. (2011a,b), which may be related to its role as a nutrient in the plant. Unlike K, in which one of the functions is to help with transport of carbohydrates into the bolls, N is responsible for adjusting the plant cycle and promoting fiber quality, especially related to strength, length, and micronaire (Carvalho et al., 2011c), that is, it makes no direct contribution to fiber weight.

Fiber quality

In the 2009/10 and 2010/11 crop seasons, micronaire was positively affected by K rates (Table 2), and a significant effect was observed between all treatments compared to the control. In the third year, only the latter effect described was observed. The micronaire presented a linear response to K rates in the first two seasons (Figure 4b), which is in agreement with Carvalho and Ferreira (2006) and Carvalho et al. (2011c), who reported better fiber quality in response to K application since its supply helps to regulate the cycle, sustain leaf activity, and promote higher deposit of cellulose inside the fibers, which has a direct impact on micronaire. Despite the benefits of K supply to fiber quality, as also reported by Carvalho and Bernardi (2005) and Echer (2008), definition of the right rate of K is important because high rates of this nutrient may negatively affect uptake of other cations, especially Mn.

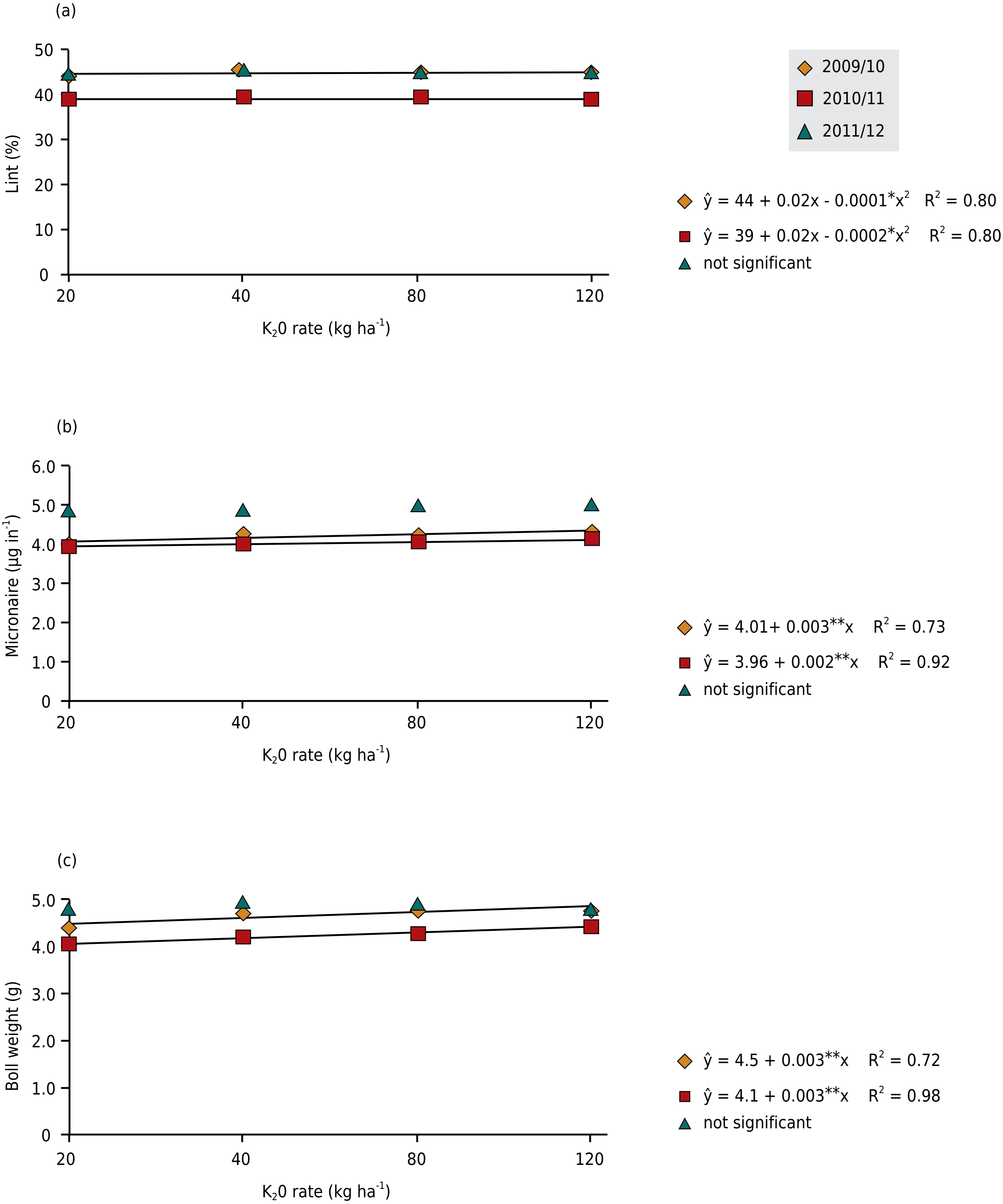

Figure 4. Lint percentage, micronaire, and boll weight of narrow-row-space cotton in response to potassium rates applied in the 2009/10, 2010/11, and 2011/12 crop seasons. ** and *: significant at 1 and 5 %, respectively, by F test.

Fiber resistence was influenced by all factors, and even interaction of the factors of N and K application rate, in the 2010/11 crop season (Table 2). The rest of the parameters evaluated in regard to fiber quality were not affected by the interaction of N and K rates. Higher N rates caused linear reduction in fiber resistence when associated with 40 and 120 kg ha^{-1} K_2O (Table 3). In contrast, for the effect of K rates, it was only possible to fit regression models for low rates of N. For the application of 20 kg ha^{-1} N, a quadratic model best described the response of fiber resistence to K rates, showing that a value of 34.8 g tex^{-1} could be obtained with the application of 75 kg ha^{-1} K_2O. For the application of 40 kg ha^{-1} N, a linear model was adjusted. For the other rates of N and K, regression analysis did not show any significance.

The short fiber index, elongation, and uniformity index were not influenced by treatments during the period of the study (Table 2). However, a significant effect was observed for elongation in 2010/11 and the uniformity index in response to NK application in 2011/12, compared to the control. Bogiani et al. (2011), Gottardo (2012), and Sofiatti et al. (2013) did not observe any effect of NK application on the length and uniformity index of narrow-row cotton.

According to official classifications from the Brazilian Ministry of Agriculture (Brasil, 2002), using overall mean values as a reference and considering weather conditions, the fiber harvested in this study was classified as high strength (>31 g tex^{-1}), high elongation (6.8 to 7.6 %), medium micronaire (4.0 to 4.9 µg pol^{-1}), high uniformity index (>85 %), low short fiber index (6.0 to 9.0 %), and mature (86 to 100 %).

Nutritional parameters

No interaction of N and K rates on leaf nutrient concentration was observed in this study. Nevertheless, leaf N concentration was significantly affected by K rates and by all treatments, compared to the control, in the first year of the study (Table 4). Nitrogen application did not affect leaf N concentration, as reported by other studies such as Gottardo (2012) and Carvalho et al. (2011b). In contrast, the results of this study showed a linear increase in leaf N concentration in response to K rates applied (Figure 5a), which is in agreement with Bogiani et al. (2011). This effect may be explained by the synergy between N and K as related to nitrate translocation in the plant (Ferreira et al., 2007).

Leak P concentration was not affected by any treatment (Table 4), also as reported by Bogiani et al. (2011). In this study, annual application of 70 kg ha^{-1} P_2O_5 was enough to supply P to plants. The NPK supply to narrow-row cotton was studied by Carvalho et al. (2011b), who observed synergy between N and P as leaf P concentration increased along with the N rates applied.

Table 3. Strength of fiber from narrow-row-space cotton in response to nitrogen and potassium rates, in the 2010/11 crop season

N rate	Control	K_2O rate				Equation	R^2
		0	40	80	120		
kg ha^{-1}		kg ha^{-1}					
		Strength of fiber (g tex^{-1}) (2010/11)					
Control	32.8	-	-	-	-		
20	-	32.4	34.3	34.3	33.7	$\hat{y} = 32.5 + 0.06\,x - 0.0004^{*}\,x^2$	0.98
40	-	33.3	33.8	34.8	34.2	$\hat{y} = 33.5 + 0.009^{*}\,x$	0.60
60	-	32.8	34.0	33.0	33.3	$\hat{y} = \bar{y} = 33.3$	-
80	-	33.0	32.1	34.1	32.8	$\hat{y} = \bar{y} = 33.0$	-
Equation	-	$\hat{y} = \bar{y} = 32.9$	$\hat{y} = 35.1 - 0.03^{**}\,x$	$\hat{y} = \bar{y} = 34.0$	$\hat{y} = 34.4 - 0.02^{*}\,x$		
R^2	-	-	0.70	-	0.58		

**, *: significant at 1 and 5 %, respectively, by F test.

Leak K concentration was positively affected by K rates and all treatments, as compared to the control, in every crop season of this study (Table 4). This result does not agree with Bogiani et al. (2011) and Carvalho et al. (2011b), who reported no significant effect of K application on leaf K concentration. The original level of K in the soil (Table 1), classified as medium by Sousa and Lobato (2004), plus the K rates applied yearly were not enough to keep leaf K concentration at the level of sufficiency (13.7 to 18.2 g kg^{-1} K), as estimated by DRIS (Kurihara et al., 2013) in the first year of the study (Figure 5b). Throughout the period of this study, the average of leaf K concentration increased gradually, which is related to annual K fertilizer application, although it was not sufficient to reduce or avoid crop response. Hence, gross yield was still affected by K rates applied every year.

Leaf Ca concentration was affected by N rates in 2009/10 and by K rates in 2011/12 (Table 4). Also, a significant effect on Ca leaf content was observed from all treatments, compared to the control. Leaf calcium concentration values decreased with the increase in K rates (Figure 5c), as also observed by Bogiani et al. (2011), and with the increase in N rates (Figure 6a), but still remained above the sufficiency level of 16.9 g kg^{-1} Ca proposed by Kurihara et al. (2013).

Leaf Mg concentration was affected by K rates in 2009/10 and 2010/11, and by N rates in 2010/11 (Table 4). As described for Ca, leaf Mg concentration values decreased with the increase in K rates (Figure 5d). High K rates could decrease cation uptake, especially Mg,

Table 4. Analysis of variance, coefficients of variation (CV), and mean values for leaf macronutrient concentration in narrow-row-space cotton and soil potassium availability in response to nitrogen and potassium application, in the seasons 2009/10, 2010/11, and 2011/12 crop seasons

Factor	DF	N	P	K	Ca	Mg	S	K
		g kg^{-1}						mg dm^{-3}
				2009/10				
N rate	3	ns	ns	ns	**	ns	**	ns
K_2O rate	3	*	ns	**	ns	**	**	**
N x K_2O	9	ns	ns	ns	ns	ns	ns	ns
Factorial *vs* control	1	*	ns	**	ns	*	*	**
Rep	3	ns	**	ns	**	**	ns	ns
Residue	48	-	-	-	-	-	-	-
CV (%)	-	8.4	9.2	21.0	8.9	15.5	14.9	18.5
Mean	-	27.3	1.3	3.4	27.2	6.7	3.0	31.7
				2010/11				
N rate	3	ns	ns	ns	ns	**	ns	ns
K_2O rate	3	ns	ns	**	ns	*	ns	**
N x K_2O	9	ns	ns	ns	ns	ns	ns	ns
Factorial *vs* control	1	ns	ns	**	ns	**	*	**
Rep	3	ns	**	*	**	ns	**	ns
Residue	48	-	-	-	-	-	-	-
CV (%)	-	5.4	16.2	12.0	11.7	10.4	11.3	16.6
Mean	-	39.3	2.6	14.4	19.0	5.8	4.6	54.1
				2011/12				
N rate	3	ns	ns	ns	ns	ns	ns	ns
K_2O rate	3	ns	ns	**	**	ns	ns	**
N x K_2O	9	ns	ns	ns	ns	ns	ns	ns
Factorial *vs* control	1	ns	ns	**	*	*	ns	**
Rep	3	ns	**	**	ns	ns	*	ns
Residue	48	-	-	-	-	-	-	-
CV (%)	-	7.4	12.0	14.4	8.3	13.2	10.9	12.1
Mean	-	38.7	2.9	20.2	27.0	6.1	3.8	46.5

DF: degrees of freedom; CV: coefficient of variation. **, *, ns: significant at 1 %, 5 % and not significant, respectively, by F test.

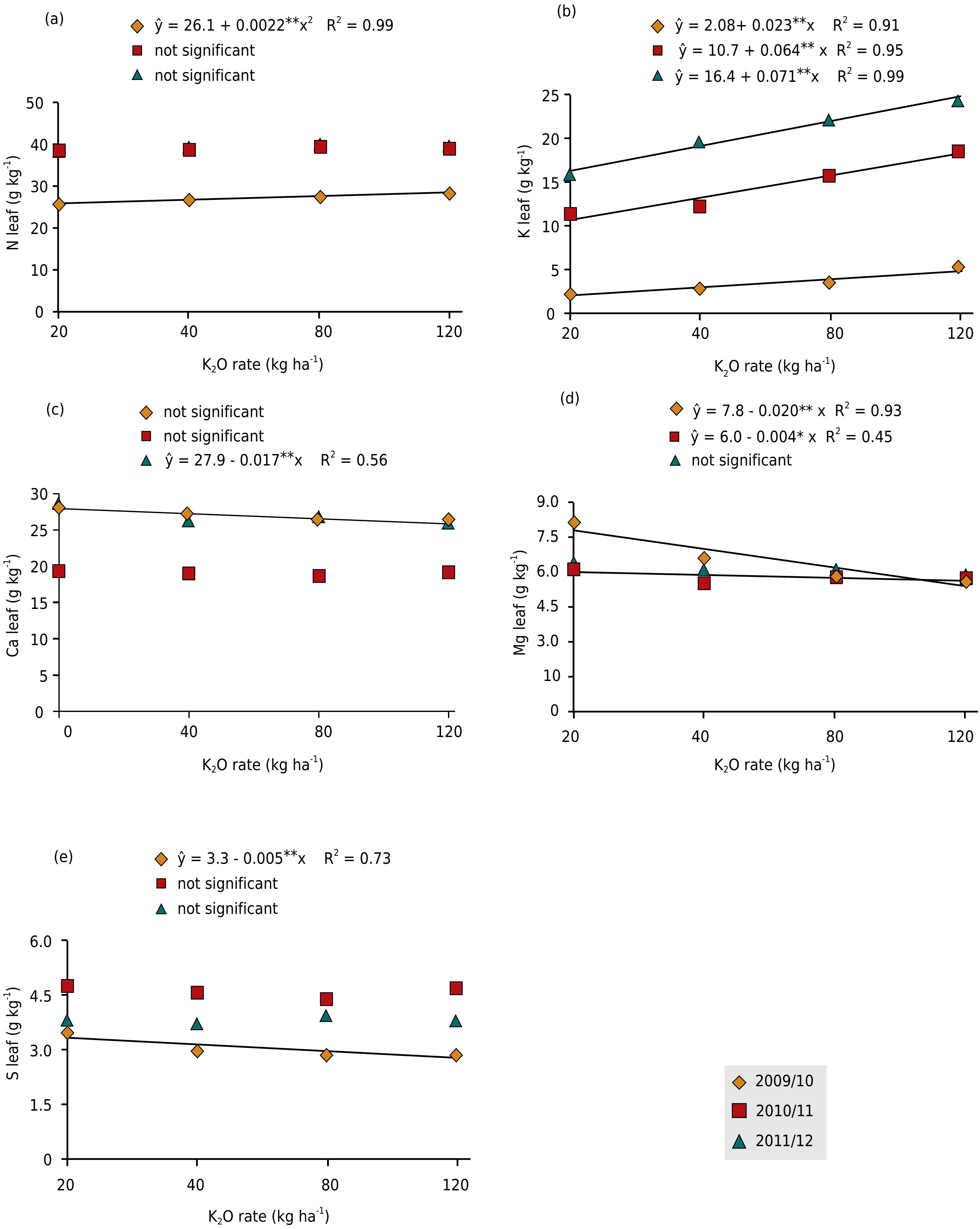

Figure 5. Leaf concentration of nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) in narrow-row-space cotton in response to potassium rates applied in the 2009/10, 2010/11, and 2011/12 crop seasons. ** and *: significant at 1 and 5 %, respectively, by F test.

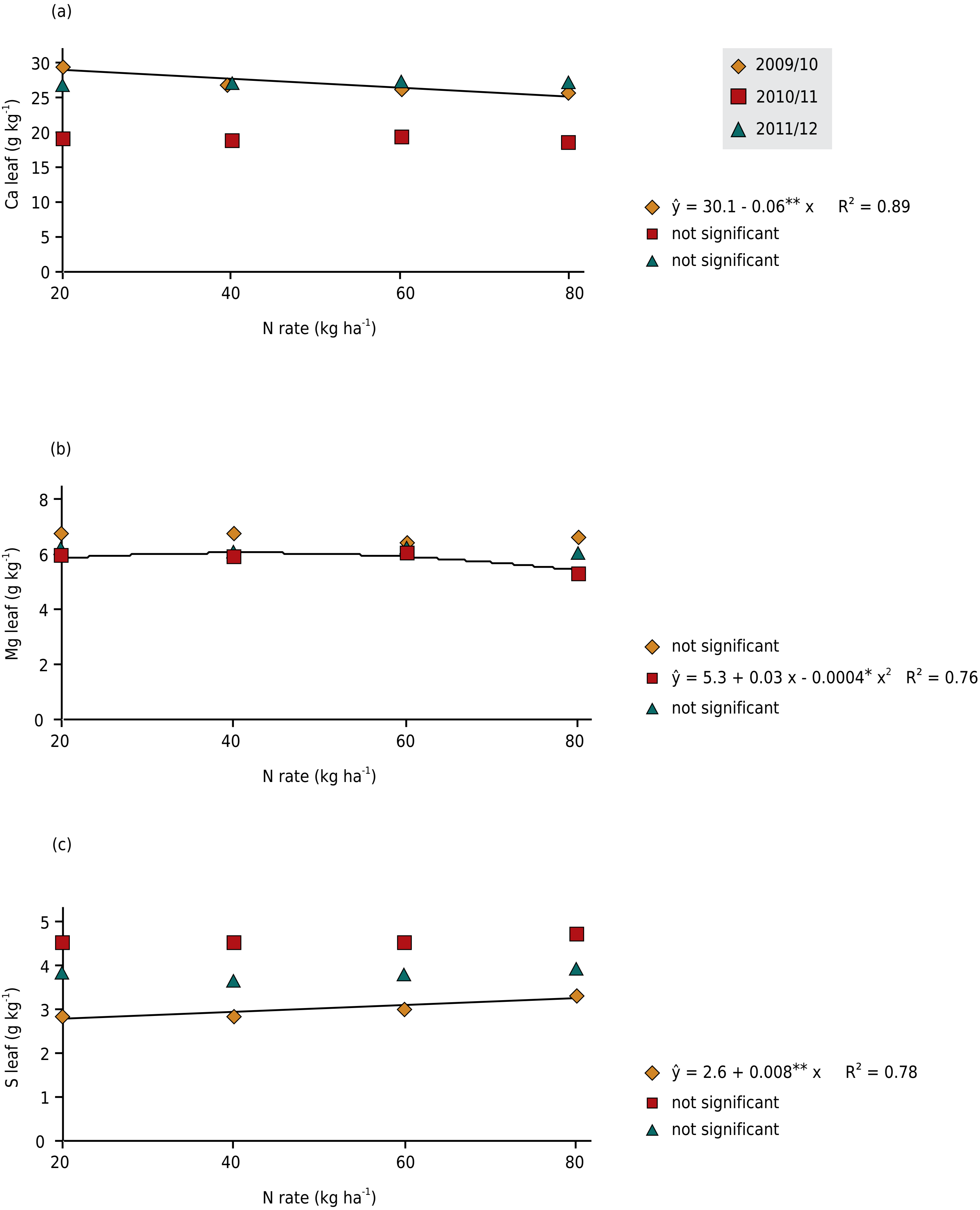

Figure 6. Leaf concentration of calcium (Ca), magnesium (Mg), and sulfur (S) in narrow-row-space cotton in response to nitrogen rates applied in the 2009/10, 2010/11, and 2011/12 crop seasons. ** and *: significant at 1 and 5 %, respectively, by F test.

were reported by Carvalho and Ferreira (2006). Competition between K and Mg for the same absorption sites in the root can lead to lower uptake of such nutrients and lower yields, but when soil cation levels are adequate, roots can take up nutrients more easily (Rosolem and Bogiani, 2014). Nevertheless, no visual symptoms related to Mg deficiency were identified in the trial, and leaf Mg concentration remained in the sufficiency range of 2.7 to 3.4 g kg^{-1} Mg (Kurihara et al., 2013). A quadratic model was fitted to leaf Mg concentration in response to N rates, and the maximum value was calculated as 6.1 g kg^{-1} Mg at the rate of 45 kg ha^{-1} N (Figure 6b), which is in agreement with Mengel and Kirkby (2001). The authors found that high levels of cations in the soil, especially K and NH_4^+, can reduce Mg uptake by the plant. This parameter was also affected by all treatments compared to the control for every season of the study.

The N and K rates affected leaf S concentration only in 2009/10 (Table 4). A linear decrease in leaf S was observed with the increase in K rates (Figure 5e), as also presented by Bogiani et al. (2011). According to the authors, this fact may be explained by a decrease in Ca and Mg uptake, due to competition for the same sites in the roots, leading to a decrease in S uptake while it was acting as a companion ion to the cations. The effect of treatments compared to the control was also observed for leaf S concentration in the first and second year of the trial.

Although no visual symptom of S deficiency was observed in the study, leaf S concentration was lower than the sufficiency range described by Kurihara et al. (2013), 3.8 to 5.4 g kg^{-1}, in the first year. Lower leaf S values associated with narrow-row spacing in cotton were observed by Ferrari et al. (2014). In addition, a synergetic effect was observed between N and S due to the linear increase in leaf S concentration in response to N rates applied (Figure 6c). Both nutrients are part of amino acids and this interaction shows the need for S in soils that are high yielding and responsive to N, as pointed out by Yamada et al. (2006). It is also likely that higher N rates promoted root development, which may have contributed to more S uptake from deeper layers. This hypothesis can be confirmed by the lack of synergetic effect in the last years of this study when 0.3 and 3 Mg ha^{-1} of phosphogypsum were applied in the second and third year, respectively.

The level of available K in the top 0.2 m of the soil was affected by K rates applied in every season of the study, and also by the treatments compared to the control (Table 4). Unlike Bogiani et al. (2011), a linear increase in K content was observed with an increase in K rates (Figure 7).

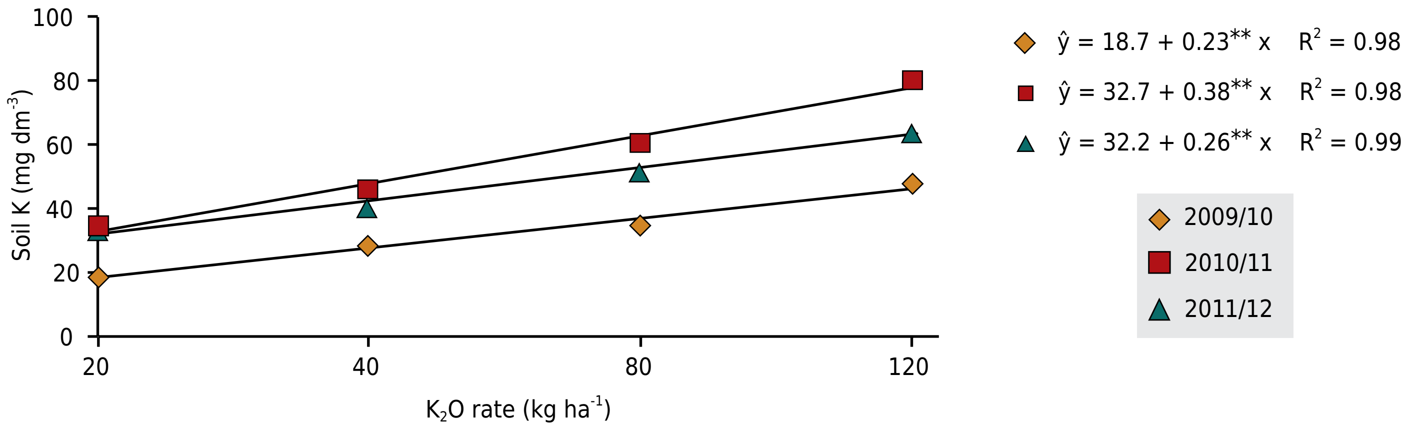

Figure 7. Soil potassium availability in the 0.0-0.2 m layer in response to potassium rates applied in the 2009/10, 2010/11, and 2011/12 crop seasons. **: significant at 1 % by F test.

CONCLUSIONS

Potassium application is a key practice for cotton grown in narrow row systems. Cotton uptakes high amounts of K, that can be affect by low soil K availability due to no application or low water content in the soil. High K rates applied to cotton in narrow row systems, grown as a second crop after soybeans, sustains higher yields and fiber quality.

The use of high N rates for cotton grown in narrow row with higher plant population, as compared to conventional systems, is not a requirement for higher yields, although it can reduce fiber quality. More plants in the field will compete for light, water, and nutrients, which will compensate plant height and yield.

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