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Timing and Splitting of Nitrogen Side-Dress Fertilization of Early Corn Hybrids for High Grain Yield

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ABSTRACT: Currently, most nitrogen fertilizer is side-dressed when corn is in the four (V4) to eight (V8) expanded leaf stage. However, recent studies have shown that modern hybrids take up high amounts of nitrogen during grain filling. This indicates that a late nitrogen fertilization, at the time of crop flowering, may be important to optimize corn agronomic performance. This study aimed to evaluate the effect of the timing and splitting of nitrogen side-dress application on the agronomic performance of early corn hybrids in order to achieve high grain yield. The experiment was set in Lages, Santa Catarina, in the South of Brazil, during the 2014/2015 and 2015/2016 growing seasons. A randomized block design arranged in split plots was used. Two hybrids were tested in the main plots: P1680YH (very early) and P30F53YH (early). Six nitrogen side-dress systems were assessed in the split plots: control (without N), full N rate applied at V5, full N rate applied at V10, 1/2 N rate applied at V5 and 1/2 at V10, 1/3 N rate applied at V5, 1/3 at V10 and 1/3 at VT; and the whole N rate applied at VT. The nitrogen rate was 300 kg ha^{-1} N. Urea was used as the nitrogen source. Total grain yield and yield components, agronomic nitrogen use efficiency, and leaf area were determined. Grain yield ranged from 6,422 to 15,426 kg ha^{-1} in 2014/2015 and from 9,283 to 14,986 in 2015/2016. Nitrogen side-dress application performed one time at V5 or V10 or split into two or three applications at different growth stages had similar grain yield, number of ears per plant, kernels per ear, and 1,000 grain dry weight. Nitrogen side-dressed entirely at VT led to higher grain yield than the control. However, grain yield and agronomic nitrogen use efficiency were lower in this treatment than in the treatments involving the other growth stages of side-dress nitrogen. The early hybrid was higher yielding than the very early hybrid, regardless of the timing of nitrogen fertilization. Splitting of nitrogen fertilization up to tasseling was not an effective strategy to increase grain yield and agronomic nitrogen use efficiency of the corn hybrids P30F53YH and P1680YH.

Keywords: *Zea mays*, phenology, cultivar, productivity.

INTRODUCTION

Corn is a crop with high yield potential. This has been shown by the yields of 18.6 and 17.4 Mg ha^{-1} obtained by Menegati et al. (2012) and Schmitt et al. (2012), respectively, in experiments carried out in the South of Brazil. However, such yields are not achieved on most Brazilian farms. Average corn grain yield in Brazil was close to 5.5 Mg ha^{-1} in the 2016/2017 growing season (Conab, 2017). This is far below the potential crop yield and the average yield in the United States of America, with yields above 10 Mg ha^{-1} (USDA, 2017).

One of the main factors responsible for the low yield of corn is a low supply of nitrogen (N), because N is the nutrient most taken up by corn and with the largest impact on crop yield. Nitrogen is highly unstable in the soil. It can easily be lost through volatilization, leaching, and denitrification (Cantarella, 2007). Furthermore, corn has low N demand at the early growth stages of its cycle. It takes up only 5 to 10 % of total N from crop emergence to floral primordium differentiation, which occurs when the plant has five to six expanded leaves (Sangoi et al., 2016). These two factors make the timing of nitrogen fertilization an essential management strategy to optimize corn N use efficiency.

Currently, the Soil Chemistry and Fertility Commission of Rio Grande Sul and Santa Catarina (CQFS-RS/SC, 2016) recommends that most of the nitrogen applied be side-dressed when corn has four to eight expanded leaves, in one or two applications. Splitting of nitrogen side-dress fertilization is a strategy used to mitigate nitrogen losses when growers aim to achieve high yields, synchronizing N fertilization with the periods of greatest plant demand for the nutrient (Cantarella and Marcelino, 2008). Nevertheless, on soils with high clay content and N rates up to 120 kg ha^{-1}, nitrogen can be side-dressed in a single operation because N losses are low (Fountoura and Bayer, 2009).

Until the end of last century, late nitrogen applications, performed close to corn flowering, were not recommended, due to the low ability of the crop to take up the nutrient after tasseling (Sangoi et al., 2016). Nonetheless, experiments carried out by Silva et al. (2005a) in the Central Depression Region of Rio Grande do Sul showed that late nitrogen fertilizations, made between tasseling and silking, enhanced corn grain yield.

More recently, Ciampitt and Vyn (2013) showed that modern corn hybrids take up 29 % more nitrogen after flowering than old hybrids. The same behavior was reported by Haegele (2013), who compared hybrids from the 1970s with modern hybrids and observed that current hybrids accumulated 40 % more N after flowering and took up 8.96 kg ha^{-1} more nitrogen throughout their cycle.

Newer corn hybrids have different patterns of nitrogen use during grain filling, requiring greater amounts of N after flowering to fill their kernels. An important trait that may be involved in the dynamics of nitrogen uptake is duration of the crop cycle. The tendency of breeding programs to stimulate early maturity and associate it with an increase in grain yield may have contributed to create more uniform nitrogen uptake at the crop vegetative development and grain filling stages (Silva et al., 2005a).

Planning for N fertilization during periods of higher N demand is essential for optimizing crop yield and decreasing the cost of nitrogen application. The earlier maturity and the higher yield potential of current hybrids increases corn nitrogen requirements, especially during the most advanced growth stages of the crop (Sangoi et al., 2016). Such characteristics have increased the advantages of splitting nitrogen side-dress fertilizations. Furthermore, environmental problems may arise from incorrect nitrogen applications performed entirely during the initial growth stages of corn, when the plant is not able to take up and assimilate the nutrient.

This study was carried out based on the hypothesis that splitting of nitrogen side-dress fertilization, with application of part of the N at tasseling, is a management strategy that increases grain yield, mainly in early cycle hybrids. The objective was to evaluate the effects of the timing of nitrogen side-dress fertilizer application and of splitting application on the agronomic performance of early corn hybrids in order to achieve high grain yield.

MATERIALS AND METHODS

This study was conducted in the municipality of Lages, state of Santa Catarina, in the highlands of southern Brazil, in the 2014/2015 and 2015/2016 growing seasons. The experimental site is at 27° 50′ 35″ S, 50° 02′ 45″ W, and 849 m a.s.l. The climate of the region is Cfb in the Köppen classification system, with mild summers; the average temperature of the hottest month is below 22 °C, winters are cold, and there is adequate rainfall throughout the year. The soil at the study site was a *Nitossolo Vermelho Distrófico* (Santos et al., 2013), which corresponds to a Rhodic Kandiudox (Soil Survey Staff, 2014).

A randomized block design was used, with treatments arranged in split plots. Two hybrids were tested in the main plots: P1680YH (very early), with thermal requirement of 1220 degree-days, and P30F53YH (early), with thermal requirements of 1556 degree-days. Six nitrogen side-dress systems were assessed in the split plots: control (without N); full N rate applied at V5; full N rate applied at V10; 1/2 N rate applied at V5 and 1/2 at V10; 1/3 N rate applied at V5, 1/3 at V10, and 1/3 at VT; and full N rate applied at VT. The nitrogen rate was 300 kg ha^{-1} N. Urea was used as the nitrogen source. Each split plot comprised six rows, with 0.7 m row spacing and 7 m length. All data were collected from the second and third row, in an area of 8.4 m^2.

The experimental area was fertilized with a mixture of phosphorus, potassium, and nitrogen on the day of sowing, based on results of soil analysis carried out yearly before sowing (Table 1) and in accordance with the CQFS-RS/SC (2004) recommendations to achieve a grain yield of 21 Mg ha^{-1}. The sources used to supply N, P, and K were urea (45 % N), triple superphosphate (46 % P_2O_5), and potassium chloride (60 % K_2O), respectively. The rates applied at sowing were equivalent to 30 kg ha^{-1} N, 340 kg ha^{-1} P_2O_5, and 170 kg ha^{-1} K_2O. Fertilizers were distributed on the soil surface close to the plant rows. Nitrogen was side-dressed according to the growth stages defined for each treatment.

The experiment was hand planted in a no-tillage system on October 22, 2014 and October 15, 2015. The plots were over-sown, dropping three seeds per hill, and then thinned to the desired density (90,000 plants ha^{-1}) when the plants had three expanded leaves (V3). Weeds were controlled with two herbicide applications. The first, immediately after sowing and prior to plant emergence, was a combination of atrazine (1,250 g a.i. per hectare) and metolachlor (1,250 g a.i. per hectare). The second, after corn emergence, when the plants were at V4, was tembotriona (100 g ha^{-1} of a.i.). Insects and diseases were controlled when necessary so as not to interfere with plant development.

Table 1. Chemical properties of the soil in the experimental area during the 2014/15 and 2015/16 growing seasons, in Lages, Santa Catarina, Brazil

Layer	Clay	pH		OM	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}
		H_2O	SMP						
m	g kg^{-1}			g kg^{-1}	mg dm^{-3}		$cmol_c$ dm^{-3}		
				2014/15 growing season(1)					
0.00-0.20	560	5.2	5.7	60.0	4.4	186.0	5.79	2.47	0.2
				2015/16 growing season(2)					
0.00-0.20	530	5.1	5.2	50.0	5.0	195.0	7.0	2.45	0.3

(1) Analyses performed by the laboratory of Universidade do Estado de Santa Catarina. (2) Analysis performed by the laboratory of Universidade do Oeste de Santa Catarina. P and K were extracted with Mehlich-1. Ca^{2+}, Mg^{2+}, and Al^{3+} were extracted with KCl 1 mol L^{-1}.

Two leaf area determinations were performed, at the R1 growth stage (silking) and 56 days after, when the kernels were at R5 (hard mass stage), according to the scale proposed by Ritchie et al. (1993). Leaf area was estimated measuring the length (L) and largest width (W) of all photosynthetic active leaves (leaves that had more than 50 % green area), according to the method described by Borrás et al. (2003). Leaf area per plant (LA) was calculated using the following expression: LA = L × W × 0.75, where 0.75 is a correction coefficient used because leaves do not have a rectangular area.

All ears harvested from the second and third row of each split plot were used to determine grain yield and yield components (number of kernels per ear and 1,000 grain weight). The ears were shelled and the kernels were dried in a laboratory oven at the temperature of 65 °C until completely dry. Total grain weight was converted to kg ha^{-1} and expressed in the standard moisture of 13 % to calculate grain yield. Samples of 400 kernels per treatment were separated and oven dried at 65 °C for 72 h. After that, they were weighed; their weight was multiplied by 2.5, converted to moisture of 13 %, and used to express 1,000 grain weight. The number of kernels per ear was obtained through the relation among 1,000 grain weight, total grain weight, and the number of ears harvested in each experimental unit.

Temperature and rainfall data were collected at the Epagri Experimental Station, 10 km from the experiment. Soil moisture was monitored with tensiometers. The experiment was irrigated when soil water tension was below -0.4 Mpa, to maintain soil moisture close to field capacity.

Average monthly temperature ranged from 16.2 to 20.8 °C in 2014/15 and from 16.7 to 20.9 °C in 2015/16. The month of October had the lowest thermal sums, with values of 180 and 140 growing degrees (GD) in 2014/15 and 2015/16, respectively. January had the highest thermal sums, with 363.7 and 360.7 GD for the growing seasons of 2014/15 and 2015/16, respectively.

Agronomic nitrogen use efficiency was determined according to Fageria et al. (2006), using the following formula: AE = (PGcf - PGsf)/QNa, expressed in kg kg^{-1}, in which AE is the agronomic efficiency; PGcf is the grain yield with nitrogen fertilization; PGsf is the grain yield without nitrogen fertilization; and QNa é is the application rate of side-dressed nitrogen.

The data were examined by analysis of variance using the F test. The F values were considered significant at the error probability level of 5 % ($p<0.05$). When the treatment differences were significant, averages were compared by Tukey's test, at the significance level of 5 %.

RESULTS AND DISCUSSION

Rainfall was high in both growing seasons of the experiment, with a total volume throughout the crop cycle of 1,005 mm in 2014/15 and 1,035 mm in 2015/16. During crop vegetative development between the V5 and VT growth stages, when nitrogen fertilization was side-dressed, rainfall reached volumes of 393 mm during the 2014/15 growing season and 506 mm during the 2015/16 growing season. Irrigation was applied three times in 2014/15 from November to December. In the second growing season, the experiment was irrigated two times during the second half of January. Nearly 30 mm of water were applied each time.

The grain yield ranged from 6,422 to 15,426 kg ha^{-1} in 2014/2015 and from 9,283 to 14,986 kg ha^{-1} in 2015/2016. Average yields of the experiment were 12,665 and 12,817 kg ha^{-1} for the first and second growing season, respectively. The variation among treatments regarding grain yield was higher in 2014/2015 than in 2015/2016.

Grain yield was affected by the growth stage of the corn at the time of nitrogen side-dress fertilization and by the hybrid cycle (Table 2). There were no significant differences between treatments where nitrogen was fully applied at V5 or at V10 in either growing season, nor in those treatments where the fertilizer application was split in two times (1/2 in V5 and 1/2 in V10) or three (1/3 in V5, 1/3 in V10, and 1/3 in VT). In the first year, the highest absolute yield value was registered when nitrogen was side-dressed with 1/3 in V5, 1/3 in V10, and 1/3 in VT, achieving a yield of 14,764 kg ha^{-1}, which represented more than 500 kg of additional grain per hectare compared to the other treatments. However, such numerical differences were not statistically significant. In 2015/2016, the highest yield value was detected when nitrogen fertilization was divided into two applications, at the V5 and V10 growth stages, achieving a yield of 13,965 kg ha^{-1}. Nonetheless, the yield values and the numerical differences among treatments were lower than in 2014/2015.

In the present study, corn yield response to nitrogen fertilization according to the growth stage of the plants did not confirm the observations reported by DeBruin and Buntzen (2014), who concluded that splitting of N side-dress application is fundamental to maximize crop yield. The yield response also did not support the remarks made by Yamada and Abdala (2000) and Fernandes and Libardi (2007) that when high nitrogen rates are used to achieve high yield levels, there is a need to split N side-dress applications to optimize the nutrient use efficiency.

The control treatment without N side-dress had the lowest yields in both growing seasons, confirming the importance of nitrogen for corn development. Nevertheless, even the yields registered in the control treatment, without nitrogen side-dress fertilization, were above the Brazilian average. This response was more pronounced in the second growing season, when the grain yield of the control was over 9,000 kg ha^{-1}. The high organic matter content of the soil where the trial was conducted (55 g kg^{-1}), the application of 30 kg of mineral N during sowing, and the well-established no-tillage system (more than

Table 2. Yield of two corn hybrids as affected by the growth stage of plants at the time of nitrogen side-dress fertilization in Lages, Santa Catarina, Brazil

Growth stage at time of nitrogen side-dress	Yield			
	kg ha^{-1}			
	P30F53YH[1]	P1680YH[2]		
	2014/2015 growing season		Average	CV (%)
V5[3]	15,426	12,734	14,080 ab[4]	10.9
V10	14,824	13,667	14,245 ab	
1/2 V5 + 1/2 V10	14,821	12,145	13,483 ab	
1/3 V5 + 1/3 V10 + 1/3 VT	14,840	14,689	14,764 a	
VT	12,484	10,989	11,737 b	
Control (Without N)	8,946	6,422	7,684 c	
Average	13,556 a	11,774 b		
CV (%)	11.1			
	2015/2016 growing season		Average	CV (%)
V5	14,986	12,812	13,899 a	7.25
V10	14,487	12,901	13,694 ab	
1/2 V5 + 1/2 V10	14,590	13,339	13,965 a	
1/3 V5 + 1/3 V10 + 1/3 VT	15,247	12,664	13,955 a	
VT	13,313	10,743	12,028 b	
Control (Without N)	9,283	9,439	9,361 c	
Average	13,651 a	11,983 b		
CV (%)	12.8			

(1) Early cycle hybrid. (2) Very early cycle hybrid. (3) V5 = five expanded leaf stage; V10 = ten expanded leaf stage; VT = tasseling, according to the growth stage scale proposed by Ritchie et al. (1993). Single application at the rate of 300 kg ha^{-1} N. (4) Averages followed by the same lowercase letter in the column or row do not differ significantly by the Tukey test at the significance level of 5 %.

15 years) in the experimental area may have contributed to the control yield values higher than 6,000 kg ha^{-1} in 2014/2015 and 9,000 kg ha^{-1} in 2015/2016.

In both growing seasons, the application of all the nitrogen in VT reduced corn grain yield compared to the treatments where nitrogen side-dress was applied in V5 or V10, in one-time or split application. This happens because corn takes up nearly 75 % of N between the stages of floral primordium differentiation and tasseling. During this period, N is essential to ear differentiation and spikelet development of the female inflorescence (Sangoi et al., 2016).

However, the treatment with one-time nitrogen fertilization during crop tasseling (VT) had higher yield than the control in both growing seasons. Nitrogen side-dress application at VT promoted a yield increase of 4,053 and 2,667 kg ha^{-1} in the combined average of the hybrids in the first and second growing season, respectively. Such data corroborated the observations of Silva et al. (2005b), DeBruin and Butzen (2014), and Ning et al. (2014), showing that modern hybrids have considerable capacity to take up nitrogen during grain filling. The hybrid P30F53YH was higher yielding than P1680YH in the average of nitrogen side-dress fertilization during the growth stages, in both growing seasons. Early hybrids have higher yield potential than very early hybrids because they have a longer period to develop ears and fill the kernels (Sangoi et al., 2014).

The number of ears produced per plant was affected by the interaction between the hybrid and growth stage at which nitrogen fertilization was applied during the first growing season (Table 3). The hybrid P1680YH had a smaller number of ears per plant in the control, whereas this variable did not exhibit significant differences among treatments with and without nitrogen side-dress fertilization for the hybrid P30F53YH. Gott et al. (2014), studying the effects of time and the source of nitrogen fertilization in late planted corn, also found a smaller number of ears per plant for the hybrid P3646H in the control without N than in the treatments with nitrogen fertilization.

Table 3. Number of ears per plant of two corn hybrids as affected by the growth stage of plants at the time of nitrogen side-dress fertilization in Lages, Santa Catarina, Brazil

Growth stage at time of nitrogen side-dress	Ears per plant (No.)			
	P30F53YH[(1)]	P1680YH[(2)]		
	2014/2015 growing season		Average	CV (%)
V5[(3)]	0.93 aA[(4)]	0.90 aA	0.91	3.71
V10	0.93 aA	0.88 aA	0.90	
1/2 V5 + 1/2 V10	0.95 aA	0.92 aA	0.94	
1/3 V5 + 1/3 V10 + 1/3 VT	0.96 aA	0.90 aA	0.93	
VT	0.90 aA	0.88 aA	0.88	
Control (without N)	0.92 aA	0.75 bB	0.83	
Average	0.93	0.87		
CV (%)	8.03			
	2015/2016 growing season		Average	CV (%)
V5	0.97	0.91	0.94 ns	3.93
V10	0.97	0.91	0.94	
1/2 V5 + 1/2 V10	0.96	0.94	0.95	
1/3 V5 + 1/3 V10 + 1/3 VT	0.97	0.93	0.95	
VT	0.94	0.93	0.94	
Control (Without N)	0.92	0.94	0.93	
Average	0.95 ns[(5)]	0.93		
CV (%)	6.03			

(1) Early cycle hybrid. (2) Very early cycle hybrid. (3) V5 = five expanded leaf stage; V10 = ten expanded leaf stage; VT = tasseling, according to the growth stage scale proposed by Ritchie et al. (1993). Single application at the rate of 300 kg ha^{-1} N . (4) Averages followed by different lowercase letters in the row and uppercase letters in the column are significantly different by the Tukey test at the significance level of 5 %. (5) Not significant ($p \geq 0.05$).

In 2014/2015, the hybrid P30F53YH produced a larger number of ears per plant than P1680YH when nitrogen side-dress was not carried out. In the treatments with nitrogen fertilization, there was no difference between hybrids for number of ears. Such a response may be explained by the earlier cycle of P1680YH. Very early hybrids have higher nitrogen demand during crop vegetative development and are more sensitive to a lack of this nutrient used to transform their axillary buds into ear primordia (Sangoi et al., 2016).

There was no significant effect of the time of nitrogen side-dress fertilization and the hybrid cycle on the number of ears produced per plant in 2015/2016. A similar response was reported by Kappes et al. (2009) studying nitrogen sources and application times. This probably occurred because the number of ears produced per plant is not strongly affected by management practices but is a trait inherent to each genotype (Souza et al., 2001).

In 2014/2015, the number of kernels produced per ear was lower in the control than in other treatments with nitrogen fertilization (Table 4). In 2015/2016, the highest number of kernels per ear was recorded when nitrogen fertilization was split in V5 and V10, being significantly higher than the treatment with fertilization in VT and the control treatment. Silva (2001) and Meira et al. (2009), testing different times of urea fertilization, only detected reductions in the number of rows per ear and number of kernels per row in the control without N. There was no difference between the two hybrids in the number of kernels per year in either growing season.

The 1,000 grain weight value was significantly less in the control than in the treatments with N side-dress application in the average of the two hybrids (Table 5). Even when all nitrogen was side-dressed in VT, 1,000 grain weight was similar to the remaining treatments with nitrogen fertilization. This is indirect evidence of the capacity of modern hybrids to take up nitrogen during grain filling. Silva et al. (2005b), Gomes et al. (2007), Cruz et

Table 4. Number of kernels per ear of two corn hybrids as affected by the growth stage of plants at time of nitrogen side-dress fertilization in Lages, Santa Catarina, Brazil

Growth stage at time of nitrogen side-dress	Kernels per ear (No.)			
	P30F53YH[1]	P1680YH[2]		
	2014/2015 growing season		Average	CV (%)
V5[3]	472	462	467 a[4]	9.4
V10	428	472	450 a	
1/2 V5 + 1/2 V10	439	409	424 a	
1/3 V5 + 1/3 V10 + 1/3 VT	437	487	462 a	
VT	403	405	404 a	
Control (without N)	313	308	310 b	
Average	415 ns[5]	424		
CV (%)	10.9			
	2015/2016 growing season		Average	CV (%)
V5	430	474	452 ab	5.9
V10	441	456	448 ab	
1/2 V5 + 1/2 V10	446	466	456 a	
1/3 V5 + 1/3 V10 + 1/3 VT	452	438	445 ab	
VT	426	389	407 b	
Control (without N)	327	353	340 c	
Average	420 ns	429		
CV (%)	10.3			

[1] Early cycle hybrid. [2] Very early cycle hybrid. [3] V5 = five expanded leaf stage; V10 = ten expanded leaf stage; VT = tasseling, according to the growth stage scale proposed by Ritchie et al. (1993). Single application at the rate of 300 kg ha^{-1} N. [4] Averages followed by the same lowercase letter in the column do not differ significantly by the Tukey test at the significance level of 5%. [5] Not significant (p≥0.05).

al. (2008), and Haegele (2013) found similar results. These authors observed that corn 1,000 grain weight did not differ among treatments that received nitrogen fertilization, regardless of the time and number of N applications. Nevertheless, we expected that the greater fractioning of nitrogen fertilization, applying 1/3 of the N rate at tasseling, would prolong grain filling, resulting in heavier kernels and higher yield. Our data did not confirm that expectation (Tables 2 and 5).

The hybrid P30F53YH had higher 1,000 grain weight than P1680YH in the average of six nitrogen fertilizer applications over both growing seasons (Table 4). Production of heavier kernels contributed to the greater yield values of the early hybrid compared to the very early genotype (Table 2). The hybrid cycle can directly affect definition of grain yield and its components. There are hybrids that are more responsive and efficient in converting the N fertilizer applied into kernel production.

In both growing seasons, leaf area of the two hybrids, measured at silking (R1) and 56 days after, was similar among treatments with nitrogen side-dress fertilization performed totally in V5 or V10 and in the treatments where N fertilization was split in two or three times (Table 6). When the evaluation was performed at silking, the control and the treatment with all the nitrogen side-dressed in VT had the smallest leaf areas. In the evaluation carried out 56 days after R1, only the control had lower values than the other treatments.

A reduction in leaf area during grain filling decreases interception of solar radiation and crop photosynthetic efficiency (Sangoi et al., 2014). More limited light interception also has a negative impact on the non-structural carbohydrate stem content (Vieira, 2012) and the number of fertilized ovules (Sangoi et al., 2012). Therefore, the lower leaf area at silking shown by the treatment without N fertilization and by the treatment of all the

Table 5. A thousand grain weight of two corn hybrids as affected by the growth stage of plants at the time of nitrogen side-dress fertilization in Lages, Santa Catarina, Brazil

Growth stage at time of nitrogen side-dress	1,000 grain weight			
	g			
	P30F53YH[(1)]	P1680YH[(2)]		
	2014/2015 growing season		Average	CV (%)
V5[(3)]	395	344	370 a[(4)]	3.7
V10	407	346	376 a	
1/2 V5 + 1/2 V10	402	358	380 a	
1/3 V5 + 1/3 V10 + 1/3 VT	395	361	378 a	
VT	390	332	361 a	
Control (without N)	341	295	318 b	
Average	388 a	339 b		
CV (%)	7.2			
	2015/2016 growing season		Average	CV (%)
V5	402	349	376 a	3.87
V10	398	356	377 a	
1/2 V5 + 1/2 V10	394	353	374 a	
1/3 V5 + 1/3 V10 + 1/3 VT	405	360	383 a	
VT	384	334	359 ab	
Control (without N)	354	324	339 b	
Average	390 a	346 b		
CV (%)	3.77			

[(1)] Early cycle hybrid. [(2)] Very early cycle hybrid. [(3)] V5 = five expanded leaf stage; V10 = ten expanded leaf stage; VT = tasseling, according to the growth stage scale proposed by Ritchie et al. (1993). Single application rate of 300 kg ha^{-1} N. [(4)] Averages followed by the same lowercase letter in the column or row do not differ significantly by the Tukey test at the significance level of 5 %.

N rate side-dressed at tasseling contributed to the lower yields of these treatments (Table 2). There was an expectation that supplying 1/3 of the N rate in VT would delay leaf senescence, resulting in production of heavier kernels and higher yield. The lack of significant differences in crop leaf area 56 days after silking between treatments with a single application of 300 kg ha^{-1} N in V5 or V10 and the treatment in which N side-dress was split in three applications of 100 kg ha^{-1} in V5, V10, and VT (Table 6) shows that this supposition was not confirmed. Therefore, the leaf area behavior at R1 corroborated the similarity observed among these treatments regarding 1,000 grain weight (Table 5) and yield (Table 2).

The agronomic nitrogen use efficiency (AE) was affected by the plant growth stage when nitrogen fertilizer was applied during the two growing seasons (Table 7). The application of all the nitrogen in VT led to lower AE than in the other treatments with side-dress applications made in a single operation or split into application at the growth stages of V5, V10, and VT. Late nitrogen fertilizations decrease nitrogen use for ear development because approximately 75 % of N is taken up by corn from primordium floral differentiation to tasseling (Sangoi et al., 2016). Therefore, plants in more advanced growth stages have lower capacity to take up and translocate N to the kernels (Silva et al., 2005b). The agronomic nitrogen use efficiency was low regardless of the growth stage at which N was side-dressed. It did not exceed 27 kg of grain per kg of nitrogen. Carvalho et al. (2011) tested agronomic nitrogen use efficiency with the application of 144 kg ha^{-1} of N and found that the hybrid P30F53 achieved 34.1 kg of grain per kg of nitrogen. Mota et al. (2015), evaluating the agronomic efficiency of common urea, obtained AE values of 42 and 35 kg of grain per nitrogen unit in the first and second growing season, respectively. The high nitrogen rate used in the experiment (300 kg ha^{-1}), the high soil organic matter content (5 to 6 %), and the lower than expected yield contributed to the low AE values.

The main hypothesis that generated this study was that splitting nitrogen side-dress fertilizer application, with some application at tasseling, is a management strategy that

Table 6. Leaf area of two corn hybrids as affected by the growth stage of plants at the time of nitrogen side-dress fertilization in Lages, Santa Catarina, Brazil

Growth stage at time of nitrogen side-dress	2014/2015 growing season		
	Leaf area during the reproductive stage		
	cm²		
	Silking (R1)	56 days after silking	Average
V5[1]	8,346 a[2]	5,771 a	7,059
V10	7,857 a	5,871 a	6,864
1/2 V5 + 1/2 V10	8,123 a	5,151 ab	6,637
1/3 V5 + 1/3 V10 + 1/3 VT	8,026 a	5,510 ab	6,768
VT	6,075 b	4,901 ab	5,488
Control (without N)	6,670 b	4,048 b	5,359
Average	7,516	5,209	
		2015/2016 growing season	
V5	7,976 a	4,663 a	6,320
V10	7,833 a	5,003 a	6,418
1/2 V5 + 1/2 V10	8,172 a	4,657 a	6,415
1/3 V5 + 1/3 V10 + 1/3 VT	7,995 a	5,223 a	6,609
VT	6,415 b	4,606 a	5,511
Control (without N)	6,080 b	2,807 b	4,444
Average	7,411	4,493	

(1) V5 = five expanded leaf stage; V10 = ten expanded leaf stage; VT = tasseling, according to the growth stage scale proposed by Ritchie et al. (1993). Single application rate of 300 kg ha^{-1} N. (2) Averages followed by the same lowercase letter in the column do not differ significantly by the Tukey test at the significance level of 5 %.

would prolong duration of leaf area, favor the production of heavier kernels, and increase corn yield. The data presented in tables 2, 4, and 5 did not confirm the hypothesis. Five factors that may have led to this response are the lower than expected yields in the experiment, the high rate of nitrogen side-dress application, the high organic matter and clay content in the experimental area, the mild atmospheric temperatures, and the regular rainfall distribution of the region where the experiment was carried out.

The fertilizer recommendations (N-P-K) used in the experiment aimed to achieve yield levels of 21 Mg ha^{-1}. However, the yields recorded did not surpass 15.5 t ha^{-1} in either growing season in any of the treatments (Table 2). The reports of the positive effects of late side-dress applications on corn yield made by DeBruin and Buntzen (2014) were obtained in association with grain yields above 20 Mg ha^{-1}. A high yield level of corn increases crop demand for nitrogen and enhances the possibility of having yield gains from splitting of nitrogen side-dress fertilization (Fountoura and Bayer, 2009).

The agronomic advantages of splitting nitrogen fertilization at different growth stages are higher under soil and environment conditions that favor N losses by nitrate leaching and ammonia volatilization before plants can take up the nutrient (Cantarella, 2007). The experiment was set up in an Oxisol that had clay content of 560 g kg^{-1} in the two growing seasons. Clay-rich soils have greater capacity to retain nitrogen, especially NH_4, compared to sandy soils. Furthermore, they have higher capacity to store water throughout the soil profile, reducing water percolation and limiting NO_3^- leaching to deeper soil layers (Bortolini, 2000). Rainfall was well distributed during the crop cycle in both growing seasons. Therefore, the textural properties of the soil where the experiment was conducted probably mitigated nitrate loss by leaching, increasing N availability to corn in all the plant growth stages in which nitrogen fertilization was side-dressed.

Table 7. Agronomic nitrogen use efficiency (AE) of two corn hybrids as affected by the growth stage of nitrogen side-dress fertilization in Lages, Santa Catarina, Brazil

Growth stage at time of nitrogen side-dress	AE			
	P30F53YH[1]	P1680YH[2]		
	2014/2015 growing season			CV (%)
V5[3]	21.6	21.0	21.3 a[4]	
V10	19.6	24.1	21.9 a	
1/2 V5 + 1/2 V10	19.6	19.1	19.3 ab	13.5
1/3 V5 + 1/3 V10 + 1/3 VT	19.6	27.6	23.6 a	
VT	11.8	15.2	13.5 b	
Control (without N)	-	-	-	
Average	18.4 ns[5]	21.4		
CV (%)	28.9			
	2015/2016 growing season		Average	CV (%)
V5	19.0	11.2	15.1 a	
V10	17.4	11.5	14.4 a	
1/2 V5 + 1/2 V10	17.7	13.0	15.3 a	17.6
1/3 V5 + 1/3 V10 + 1/3 VT	19.9	10.7	15.3 a	
VT	13.4	4.4	8.9 b	
Control (without N)	-	-	-	
Average	17.5 ns	10.2		
CV (%)	86.8			

[1] Early cycle hybrid. [2] Very early cycle hybrid. [3] V5 = five expanded leaf stage; V10 = ten expanded leaf stage; VT = tasseling, according to the growth stage scale proposed by Ritchie et al. (1993). Single application rate of 300 kg ha^{-1} N. [4] Averages followed by the same lowercase letter in the column do not differ significantly by the Tukey test at the significance level of 5 %. [5] Not significant ($p \geq 0.05$).

Hot and dry climates promote nitrogen losses (Ernani, 2008). Nitrogen side-dress applications were made in November, December, and January, when corn reached the growth stages of V5, V10, and VT, respectively. The monthly average temperature ranged from 17.6 to 20.8 °C during the 2014/2015 and 2015/2016 growing seasons. In addition, there was even distribution of rainfall throughout the crop cycle, and the experiment was irrigated when needed to maintain soil moisture close to field capacity. Thus, thermal and moisture conditions were not favorable to ammonia losses through volatilization.

The climatic and edaphic factors observed during the two growing seasons were not favorable to nitrogen losses by nitrate leaching and ammonia volatilization. The soil of the experimental area probably supplies similar amounts of nitrogen to the plants, regardless of the time of nitrogen fertilization and the manner of splitting applications. Situations of low crop response to nitrogen application indicate that the major factor limiting high yield is not N availability (Amado et al., 2013). The average yields above 7 Mg ha^{-1} of the control treatment without N support this hypothesis (Table 2). Similar results were found by Argenta et al. (2003) and Sangoi et al. (2007). They obtained corn yields higher than 7 Mg ha^{-1}, without side-dressing N, in soils with high organic matter content.

Split application of nitrogen side-dress, with a late N fertilizer application at tasseling, was not an effective management practice to increase corn grain yield. This response was due to the use of a clayey soil with high organic matter, associated with the climate conditions of mild temperatures and well distributed rainfall. The best time to perform nitrogen side-dress fertilization depends on several factors, including soil type, moisture, temperature, rainfall during the growing season, yield level, and hybrid cycle. Therefore, other experiments need to be conducted under different soil and climate conditions in order to investigate if splitting of N side-dress fertilization, associated with the nitrogen supply at crop flowering, are viable strategies to enhance Brazilian corn yield.

CONCLUSIONS

Splitting nitrogen side-dress fertilization into two or three applications does not increase grain yield and agronomic N use efficiency compared to fertilization performed in one-time application in V5 or V10 when high nitrogen rates are applied, regardless of the hybrid cycle.

The timing of nitrogen side-dress fertilization and the manner of splitting application are flexible and have low impact on corn agronomic performance in Rhodic Kandiudox (*Nitossolo Vermelho Distrófico*) with high organic matter content.

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