

Sowing date and maize response to the splitting of nitrogen side-dressing fertilization

Fecha de siembra y respuesta del maíz al fraccionamiento de la fertilización nitrogenada en la superficie

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ABSTRACT

The splitting of nitrogen side-dressing fertilization with the application of a nitrogen dose at maize tasseling may increase grain yield, mainly when the crop is sown at the most favorable date to achieve high productivity. This research was carried out to evaluate the effect of sowing date on the response of maize to the splitting of nitrogen side-dressing fertilization at different growth stages. Two sowing dates were tested: preferential (10/15/2015 and 09/20/2016) and late (12/5/2015 and 12/5/2016). Six nitrogen side-dressing management treatments were evaluated at each sowing date: control without N; complete nitrogen rate applied at phenological stages V5, V10 and VT; ½ N rate at V5 + ½ N rate at V10; and ½ N rate at V5 + ½ N rate at V10 + ½ N rate at VT. The N rate was equivalent to 300 kg ha⁻¹. Grain yield ranged from 8.9 to 15.3 t ha⁻¹ in Lages and from 7.4 to 16.4 t ha⁻¹ in Atalanta. There were no significant differences in grain yield and agronomic efficiency of nitrogen use (AE) among the treatments with the entire N side-dressing fertilization at V5 and V10 and those when the nutrient was split into two or three times, regardless of sowing date. AE was higher when the crop was sown at the preferential sowing date than in the late sowing date, regardless of N side-dressing application. The splitting of nitrogen fertilization up to the crop tasseling did not increase maize grain yield or AE.

Key words: *Zea mays* L., growth stage, sowing period, fractionation.

RESUMEN

El fraccionamiento de la fertilización nitrogenada en la superficie, con la aplicación de una parte de nitrógeno en el panojamiento, puede aumentar el rendimiento de los granos de maíz, principalmente cuando el cultivo se siembra en la fecha más favorable para obtener una alta productividad. El objetivo de esta investigación fue evaluar los efectos de la fecha de siembra sobre la respuesta del maíz al fraccionamiento de la fertilización nitrogenada en la superficie y a los estados fenológicos. Se evaluaron dos fechas de siembra: preferencial (15/10/2015 y 20/09/2016) y tardía (5/12/2015 y 5/12/2016). En cada fecha de siembra fueron analizados seis tratamientos de aplicación de nitrógeno en la superficie: testigo sin N; aplicación de dosis completa de N en V5, V10 y VT; ½ aplicación de N en V5, + ½ aplicación de N en V10; y ½ de la aplicación de N en V5 + ½ de la aplicación de N en V10 + ½ de la aplicación de N en VT. La dosis de nitrógeno utilizada fue de 300 kg ha⁻¹. El rendimiento de granos varió entre 8.9 a 15.3 t ha⁻¹ en Lages y 7.4 a 16.4 t ha⁻¹ en Atalanta. No hubo diferencias significativas en el rendimiento de granos ni en la eficiencia agronómica del uso de nitrógeno (EUN) entre los tratamientos con aplicación de la dosis completa de N en los estadios V5 y V10 y aquellos en los que el nutriente se dividió dos o tres veces, independiente de la fecha de siembra. La EUN fue mayor en la siembra realizada al en la fecha preferencial que en la fecha tardía, independientemente del manejo de la aplicación nitrogenada en la superficie. El fraccionamiento de la fertilización nitrogenada en la superficie hasta VT no incrementó el rendimiento de granos ni la EUN del maíz.

Palabras claves: *Zea mays* L., estadio de crecimiento, periodo de siembra, fraccionamiento.

Introduction

Nitrogen is the most unstable element in the soil and also the nutrient that has the largest impact on maize grain yield (Cantarella, 2007). The splitting of nitrogen side-dressing

fertilization at different growth stages is an alternative for enhancing the efficiency of nitrogen fertilizers and to mitigate N losses. This is possible due to the higher N uptake promoted by the synchronization between nitrogen fertilization and maize demand for the nutrient (Silva *et al.*, 2005).

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Several factors are involved in maize response to the splitting of nitrogen side-dressing fertilization: soil type, weather conditions, cropping system, sowing time, hybrid type, N source, growth stage, and the method of nitrogen application (Sangoi *et al.*, 2016). The splitting of nitrogen side-dressing fertilization is usually recommended when high N rates are used on sandy soils and rainy conditions (Fontoura & Bayer, 2009).

Only 5% to 10% of the total nitrogen is taken up by maize until the growth stage V6, according to the scale proposed by Ritchie *et al.* (1993), when the growing point is transformed into a floral primordium (Sangoi *et al.*, 2010). Nearly 75% of the total N absorbed by the plant during its cycle is concentrated between V6 and tasseling (Sangoi *et al.*, 2016). For this reason, the commission of soil chemistry and fertility recommends that N side-dressing fertilization should be performed between the growth stages V4 and V8 in one or two applications, at the beginning of the period of greatest foliar expansion and large increments in plant height (Comissão de Química e Fertilidade do Solo, 2016).

An experiment carried out by DeBruin and Butzen (2014) in the United States of America showed that modern maize hybrids can take up 50% of total nitrogen after flowering. Therefore, late nitrogen fertilizations carried out at tasseling may delay foliar senescence and increase the crop photosynthetic activity during grain filling. These physiological changes may enhance kernel weight and increase grain yield. The results obtained by Kosgey *et al.* (2013) and Ning *et al.* (2014) reinforce this tendency, showing that modern hybrids have the capacity to take up and assimilate great amounts of N after flowering. Therefore, splitting nitrogen side-dressing fertilization up to tasseling may be important to maximize grain yield.

The sowing date is a determinant factor for optimizing maize agronomic performance. The choice of sowing date is specific for each production region. It is affected by environmental conditions, especially temperature, precipitation, and the availability of solar radiation. When there is no water limitation, the most favorable sowing date for maize in southern Brazil is the beginning of spring (September-October) (Serpa *et al.*, 2012). Sowings performed between the middle of September and the middle of October favor the coincidence between flowering and the period of the year with long days, high solar radiation availability, and temperatures ranging from 20 to 30°C. This is the time when maize has maximum leaf area (Sangoi *et al.*, 2010). Despite that, late sowings performed at the end of spring (November-December) and at the beginning of

summer (December-January) are common in southern Brazil, when maize is grown after other crops with higher economic importance, such as tobacco, onion, and garlic (Forsthofer *et al.*, 2004).

The positive effect of splitting N side-dressing fertilization up to maize tasseling may be affected by the sowing date. At late sowings, the soil and air temperatures are high during the early stages of the crop, and this stimulates the plant vegetative growth and development. However, the grain filling period will occur in late summer (February-March) and early autumn (March-April), when the temperature and solar radiation are low and less favorable to N uptake from the soil and transportation of it to the kernels. Thus, the efficiency of side-dressing part of N rate at tasseling as a strategy to increase grain yield may be compromised at late sowing dates.

This study was based on the hypothesis that the effect of splitting nitrogen side-dressing fertilization as a management strategy to improve grain yield and nitrogen efficiency use is higher when maize is sown at a favorable time, at the beginning of spring. The objective of the experiment was to assess the effect of the sowing date on maize response to the splitting of nitrogen side-dressing fertilization at different growth stages.

Materials and methods

Two field experiments were set in Lages (2015/2016) and Atalanta (2016/2017) in the State of Santa Catarina, southern Brazil. The experimental site of Lages is located at 27°50'35" S, 50°02'45" W and 849 m a.s.l. and the experimental site of Atalanta is located at 27°26'03" S, 49°42'06" W at 586 m a.s.l. The soils were classified as Distrofic red Nitossol (Lages) and Distrofic Haplic Cambisol (Atalanta) (Santos *et al.*, 2018). The results of soil analysis performed at the plowable layer (0 to 20 cm) in August of each growing season are shown in Table 1. Maize was sown after black oat (*Avena strigosa*) desiccation at both experimental sites. Winter coverage was killed with an application of glyphosate (1200 g a.i.) 45 d before each sowing date.

A randomized block design was used with treatments arranged in split plots and 4 repetitions. Two sowing times were tested in the main plots: preferential (beginning of spring) and late (end of spring). The preferential sowing dates were 10/15/2015 (Lages) and 09/20/2016 (Atalanta). The late sowing dates were 12/5/2015 (Lages) and 12/5/2016 (Atalanta). Six nitrogen side-dressing management treatments were assessed in the split plots: control (without N);

TABLE 1. Soil properties in the 0 to 20 cm layer of the experimental areas during the 2015/16 (Lages) and 2016/17 (Atalanta) growing seasons.

Locality	Clay g kg ⁻¹	pH		OM g kg ⁻¹	P ---mg dm ⁻³ ---	K -----cmolc dm ⁻³ -----	Ca ²⁺	Mg ²⁺	Al ³⁺
		H ₂ O	SMP						
Lages	530	5.1	5.2	46.0	13.0	195.0	7.01	2.45	0.30
Atalanta	452	5.7	6.2	22.5	80.1	22.5	7.55	2.07	0.00

SMP - Shoemaker-McLean-Pratt; OM - organic matter; P and K were extracted with Mehlich-1; Ca²⁺, Mg²⁺, and Al³⁺ were extracted with KCl 1 mol L⁻¹.

complete N rate applied at V5 (vegetative grown stage - fifth leaf collar); complete N rate applied at V10; ½ N rate applied at V5 and ½ N rate applied at V10; ⅓ N rate applied at V5, ⅓ N rate applied at V10; and ⅓ N rate applied at VT (tasseling); and complete N rate applied at VT, according to a scale proposed by Ritchie *et al.* (1993) (Tab. 2). Each split plot comprised four rows, with 0.7 m row spacing, 0.19 m plant spacing and 6.0 m length. All data were collected in the two central rows of each split plot, except for 0.5 m at the end of each line, in an area of 7.0 m².

The experimental areas were fertilized with a mixture of phosphorus, potassium, and nitrogen on each sowing date, based on the results of soil analyses carried out yearly and in accordance with the recommendations of the commission

TABLE 2. Characterization of the fertilization on each sowing date and N side-dressing managements. Lages (2015/2016) and Atalanta (2016/2017).

Treatments	Fertilization on each sowing date (kg ha ⁻¹)			N side-dressing managements (N kg ha ⁻¹)		
	K ₂ O	P ₂ O ₅	N	V5	V10	VT
Control	200	300	30	-	-	-
V5	200	300	30	300	-	-
V10	200	300	30	-	300	-
VT	200	300	30	-	-	300
V5+V10	200	300	30	150	150	-
V5+V10+VT	200	300	30	100	100	100

Growth stages according to the scale proposed by Ritchie *et al.* (1993): V5 (vegetative growth stage - fifth leaf collar); V10 (vegetative growth stage - tenth leaf collar); VT (tasseling).

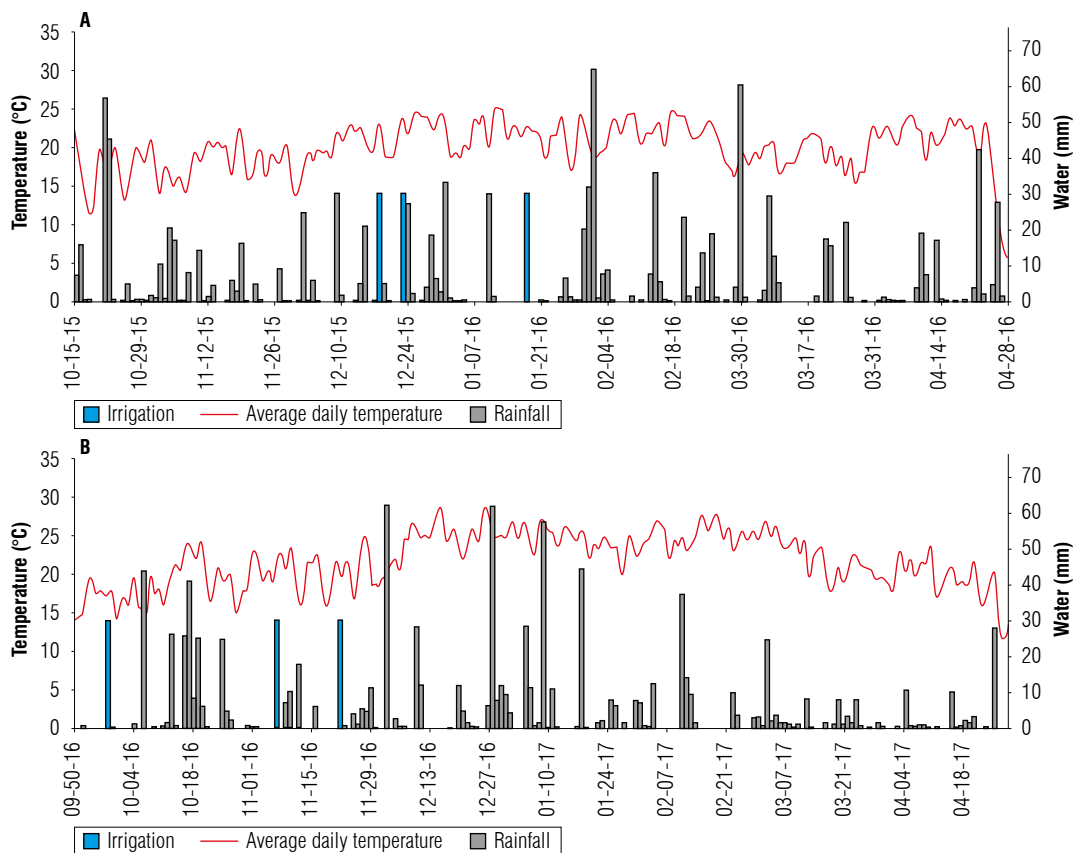


FIGURE 1. Average daily temperature, daily rainfall and irrigation of maize cycles from seedling to harvest during A) 2015/2016 (Lages-SC) and B) 2016/2017 (Atalanta-SC) growing seasons.

of soil chemistry and fertility (Comissão de Química e Fertilidade do Solo, 2016) to achieve a grain yield of 21 t ha⁻¹. The sources used to supply N, P, and K were urea (45% N), triple superphosphate (46% P₂O₅), and potassium chloride (60% K₂O), respectively. The rates applied at sowing were equivalent to 30 kg ha⁻¹ N, 300 kg ha⁻¹ P₂O₅, and 200 kg ha⁻¹ K₂O (Tab. 2). Fertilizers were distributed on the soil surface close to the plant rows. Nitrogen was side-dressing at a rate of 300 kg N ha⁻¹, according to the growth stages defined for each treatment (Tab. 2). The experiment was planted by hand in a no-tillage system, with manual seeders and marked strings for a plant population of 75000 plants ha⁻¹. The hybrid tested was P30F53YH. The experiments were irrigated to maintain soil moisture close to the field capacity (Fig. 1).

Weed control was carried out with two herbicide applications. The first one was performed at preemergence immediately after sowing and with a combination of atrazine (1259 g a.i. ha⁻¹) and metolachlor (1250 g a.i. ha⁻¹). The second application was performed after maize emergence, when plants were at V4 with tembotriona (100 g a.i. ha⁻¹). Insects and diseases were controlled whenever necessary so that they did not to interfere with the crop development.

Green leaves were measured when maize reached the R1 growth stage (silking), to determine the leaf area and leaf area index (LAI). These determinations were repeated periodically every 14 d, up to 70 d after silking, when the kernels were physiologically ripened. Leaf area per plant (LA) was calculated using the following expression according to the method described by Borrás *et al.* (2003):

$$LA = L \times W \times 0.75 \quad (1)$$

where L is the length of the leaf, W is the width of the leaf, and 0.75 is the correlation coefficient.

The ears were manually harvested on 04/02/2016 and 05/02/2016 in the first year, and 03/02/2017 and 04/28/2017 in the second year. The ears were mechanically threshed. The kernels were oven dried at 60°C until they had constant weight using a drying oven with circulation/air exchange (MA035/1152, Marconi, Piracicaba, SP, Brazil). Afterwards, grain yield and its components were determined and expressed at the standard moisture of 13%.

Agronomic efficiency of nitrogen use (AE) expressed in kg kg⁻¹ was determined according to Fageria and Baligar (2005), using the following formula:

$$AE = (GYf - GYu)/Na \quad (2)$$

where AE is the agronomic efficiency, GYf is the fertilized grain yield, GYu is the unfertilized grain yield, and Na is the application rate of side-dressing N.

The data were examined by analysis of variance using the F test with the software ASSISTAT 7.7 (E Silva & de Azevedo, 2016). The F values were considered significant at the error probability level of 5%. When the treatment differences were significant, the means were compared by the Tukey's test. The LAI variations during grain filling were assessed by polynomial regression analysis, testing the linear and quadratic models. Average comparisons were carried out at the significance level of 5%.

Results and discussion

The leaf area index (LAI) was affected by the interaction between sowing date, nitrogen side-dressing fertilization treatment, and days after silking (Tab. 3). There was a reduction of LAI from silking to kernel physiological maturity in all six nitrogen side-dressing management treatments due to the gradual leaf senescence occurred during grain filling (Fig. 2). The LAI values at each sampling time and their rate of decrease during the sampling period of treatments with the entire N fertilization at V5 and V10 or split into two and three times were similar at both experimental sites, regardless of the sowing date. Such behavior shows that dividing side-dressing into two or three growth stages neither delayed leaf senescence nor increased the crop LAI at the end of grain filling. The control without N showed a higher decrease of LAI values whereas the treatment with all nitrogen side-dressing fertilization at VT showed the lowest decrease of this variable along the 70-day sampling period. These differences are related to the important role of nitrogen on chlorophyll formation and its effect on keeping leaves photosynthetically active for a longer period (Sangoi *et al.*, 2016).

Grain yield ranged from 8.9 to 15.3 t ha⁻¹ in Lages and from 7.4 to 16.4 t ha⁻¹ in Atalanta (Tab. 4). It was affected by the interaction between sowing date and nitrogen side-dressing fertilization in Lages (Tab. 3). When maize was sown at the preferential time, the control and the treatment with complete N fertilization at VT showed lower yields than the other treatments. At the late sowing date, there were no differences between grain yield of the treatments with nitrogen side-dressing fertilization and the control. This behavior shows that grain yield response to nitrogen fertilization was higher when maize was sown at the beginning of spring (September/October). The highlands of the State of Santa Catarina, where the experimental site of Lages is located, have a long and cold winter.

TABLE 3. F-values and significances according to the analysis of variance for grain yield, weight of 1000 grains, grains per ear and agronomic efficiency of N use as a function of the main effect of sowing date and nitrogen side-dressing management and agronomic efficiency of N use as a function of the main effect of sowing date, nitrogen side-dressing management and days after silking.

SV	SD	NSDM	SDxNSDM	DAS	SDxDAS	NSDMxDAS	SDxNSDMxDAS
DF	1	5	5	5	5	25	25
2015/2016 (Lages-SC)							
GY	11.2273 ^{ns}	15.5383 ^{**}	6.5588 ^{**}	-	-	-	-
GW	4.6708 ^{ns}	10.9596 ^{**}	0.7836 ^{ns}	-	-	-	-
GE	27.9211 [*]	5.7070 ^{**}	2.3709 ^{ns}	-	-	-	-
AE	25.2284 [*]	3.4486 [*]	2.5536 ^{ns}	-	-	-	-
LAI	31.4945 [*]	4.4587 ^{**}	1.4498 ^{ns}	492.0726 ^{**}	6.0787 ^{**}	5.6660 ^{**}	3.2579 ^{**}
2016/2017 (Atalanta-SC)							
GY	8.1533 [*]	51.8202 ^{**}	1.4450 ^{ns}	-	-	-	-
GW	12.9454 [*]	45.7972 ^{**}	2.1787 ^{ns}	-	-	-	-
GE	3.8681 ^{ns}	34.7024 ^{**}	0.4869 ^{ns}	-	-	-	-
AE	6.5999 ^{ns}	7.8824 ^{**}	0.8398 ^{ns}	-	-	-	-
LAI	0.5239 ^{ns}	35.4390 ^{**}	1.2505 ^{ns}	610.9370 ^{**}	10.4832 ^{**}	9.9511 ^{**}	2.4922 ^{**}

F-test. ^{**} significant at 1% probability level ($P < 0.01$); ^{*} significant at 5% probability level ($0.01 < P < 0.05$); ^{ns} - not significant ($P > 0.05$). SV - source of variation; SD - sowing date; NSDM - nitrogen side-dressing management; DAS - days after silking; DF - degree of freedom. GY - grain yield; GW - weight of 1000 grains; GE - grains per ear; AE - agronomic efficiency of N use. LAI - leaf area index.

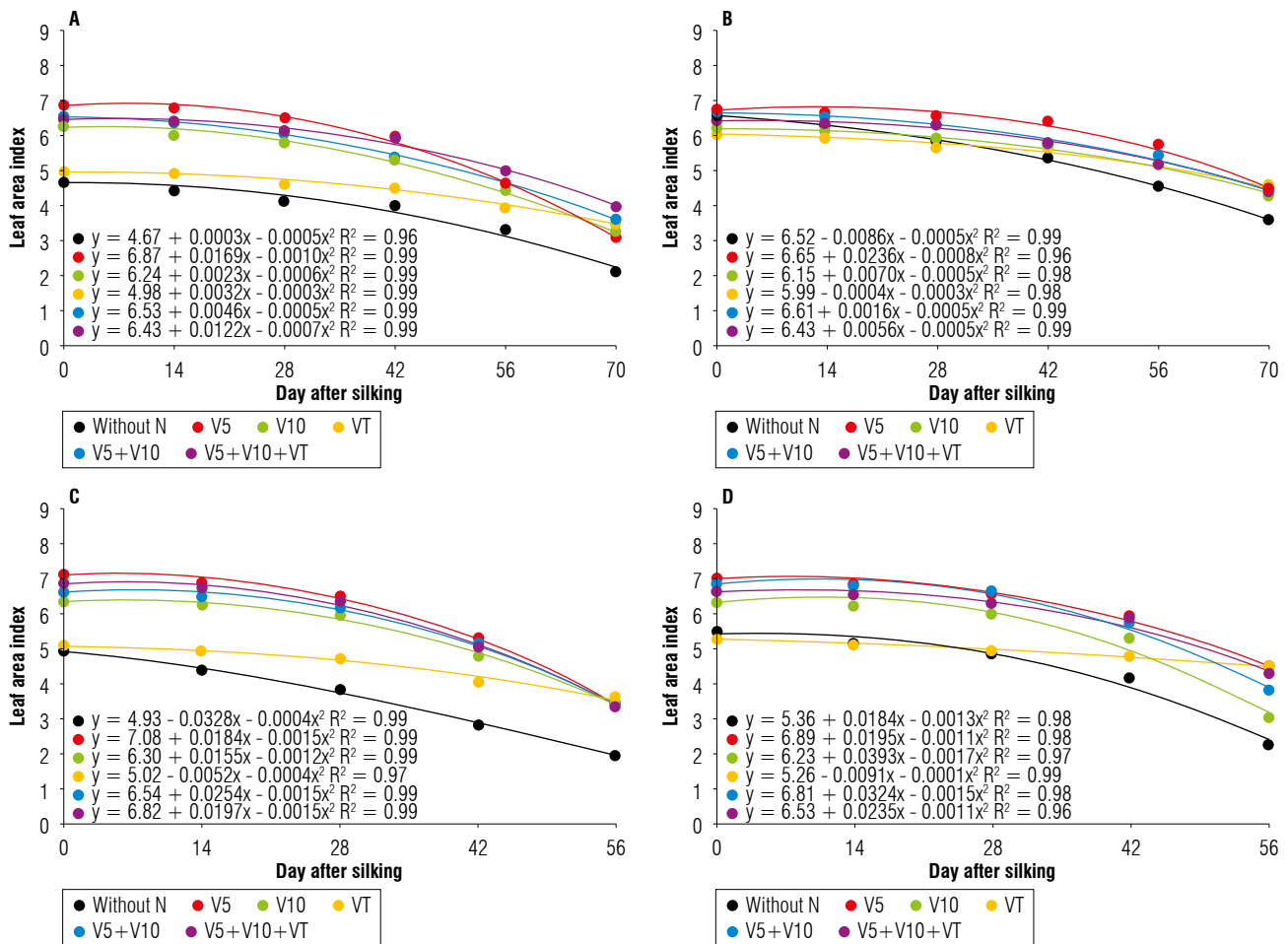


FIGURE 2. Leaf area index (LAI) during maize grain filling as affected by sowing date and nitrogen side-dressing fertilization in Lages A) 10/15/2015; B) 12/05/2015), and Atalanta C) 09/20/2016; D) 12/05/2016).

When maize is grown in early spring, the soil temperature is still low. The low temperature values delay soil organic matter mineralization and decrease the speed of *Avena strigosa* straw decomposition (Fontoura & Bayer, 2009). Both factors reduce N availability to the crop, enhancing its response to N side-dress fertilization.

In the 2015/2016 experiment, grain yield was greater at the preferential sowing date than at the late sowing date when nitrogen side-dressing fertilization was applied at V5 and V10 at one or more growth stages (Tab. 3). An opposite trend was observed in the control without N fertilization which obtained higher productivity when maize was sown in December rather than in October. At both sowing dates, there were no significant differences among treatments with the entire nitrogen rate applied in V5 or V10 and treatments where N side-dressing was split into two (V5+V10) or three (V5+V10+VT) times.

Grain yield was affected by the main effects of the sowing date and nitrogen side-dressing management system in Atalanta (Tab. 3). The treatments with N fertilization in V5, V10, V5+V10 and V5+V10+VT did not show significant differences and were more productive than the treatments without N and with complete fertilization in VT, on the average of two sowing dates (Tab. 4). Grain yield was higher when maize was sown in September than in December, on the average of six nitrogen side-dressing fertilization treatments.

The main hypothesis of this work was based on the results of experiments conducted in the northern hemisphere by DeBruin and Butzen (2014), Kosgey *et al.* (2013) and Ning *et al.* (2014). According to this hypothesis, splitting N side-dressing fertilization in order to supply part of the N rate at crop tasseling is an effective strategy to potentialize grain yield when maize is sown at the preferential time at the beginning of spring. The data gathered in Lages and Atalanta did not confirm this hypothesis. Trials carried out by Cardoso *et al.* (2011), Cruz *et al.* (2008) and Panison *et al.* (2019) in different production regions of Brazil also did not detect increments of maize grain yield with the fractioning on N side-dressing fertilization.

The division of N side-dressing rates at different growth stages with the application of some amount of N fertilizer at VT has a large potential to increase maize grain yield when farmers grow hyper-early hybrids and achieve high kernel productivities (DeBruin & Butzen, 2014). Although the N rate (300 kg ha⁻¹) was defined as aiming to reach yield levels of 21 t ha⁻¹, the maximum grain productivity

recorded in the experiment was 16.4 t ha⁻¹. Furthermore, the hybrid P30F53YH does not have a hyper-early cycle and shows great production stability at different environments. It is possible that these two characteristics have mitigated the positive effect of splitting N side-dressing fertilization on grain yield in this research. A third factor that may have contributed to the grain yield behaviour is the soil type where the experiments were carried out. At both experimental sites, the soils contain more than 400 g kg⁻¹ of clay (Tab. 1). The chance of having a positive kernel yield response to the splitting of N side-dressing is greater in sandy soils, where N losses by leaching are more pronounced (Cantarella, 2007).

Grain yield was higher at the preferential sowing date than at the late sowing date when nitrogen was side-dressing to the crop. This behaviour is related to the more favorable climatic conditions for reaching high yields, verified when maize is sown at the beginning of spring in southern Brazil (Sangoi *et al.*, 2010). Late sowings decrease maize potential yield due to the low temperatures and less solar radiation available during grain filling (Mundstock & Silva, 2005).

In Lages, the control without N showed higher kernel productivity when the sowing was performed in December rather than in October. Such response emphasizes the effect of the sowing date on nitrogen availability derived from soil organic matter content and *Avena strigosa* straw decomposition. This effect is accentuated in the highlands of the State of Santa Catarina, which show low soil temperatures at the end of winter (August-September). The higher soil temperatures registered at the end of spring stimulate organic matter mineralization and *Avena strigosa* straw decay, enhancing N availability for maize development at late sowing dates (Fontoura & Bayer, 2009).

There was a significant increment on maize productivity with the entire N fertilization at VT compared to the control (Tab. 3). Numerically, the yield increase was equivalent to 3.4 and 4.7 t ha⁻¹ at the preferential sowing time, for the growing seasons of 2015/2016 and 2016/2017, respectively (Tab. 4). These data corroborate the statements of DeBruin and Butzen (2014) and Ning *et al.* (2014), showing that modern hybrids have great capacity to uptake nitrogen during grain filling.

At both growing seasons, control plants produced less kernel weight than the other treatments with N fertilization (Tab. 4). Nitrogen supply is directly related to the crop leaf area index. Maize LAI decreased more drastically during grain filling when N

TABLE 4. Grain yield, weight of 1000 grains, grains per ear and agronomic efficiency (AE) of N use of maize in two sowing dates and six nitrogen side-dressing management treatments.

Sowing date	Growth stage of N side-dressing fertilization						Mean	C.V. (%)
	Control	V5	V10	VT	V5+V10	V5+V10+VT		
Grain yield (t ha⁻¹)								
2015/2016 (Lages-SC)								
10/15	8.9 bC	15.3 aA	14.8 aAB	12.2 aB	15.2 aA	15.0 aA	13.6	6.3
12/05	11.5 aA	13.0 bA	12.0 bA	12.9 aA	13.9 bA	12.8 bA	12.7	
Mean	10.2	14.2	13.4	12.5	14.6	13.9		
C.V. (%)							7.6	
2016/2017 (Atalanta-SC)								
09/20	8.3	15.2	15.2	13.0	15.7	16.4	14.0 a	12.3
12/05	7.4	13.5	12.6	10.4	12.7	13.0	11.6 b	
Mean	7.9 C	14.3 A	13.9 A	11.7 B	14.2 A	14.7 A		
C.V. (%)							8.1	
Weight of 1000 grains (g)								
2015/2016 (Lages-SC)								
10/15	348	397	404	404	400	419	395 NS	3.4
12/05	356	389	390	391	393	396	386	
Mean	352 B	393 A	397 A	397 A	396 A	407 A		
C.V. (%)							3.7	
2016/2017 (Atalanta-SC)								
09/20	277	336	340	336	344	345	329 a	2.9
12/05	276	333	317	337	324	331	320 b	
Mean	277 B	334 A	328 A	337 A	334 A	338 A		
C.V. (%)							3.1	
Grains per ear (n°)								
2015/2016 (Lages-SC)								
10/15	382	512	504	446	521	468	472 b	1.9
12/05	475	517	480	480	504	474	488 a	
Mean	428 B	515 A	492 A	463 AB	513 A	471 AB		
C.V. (%)							7.1	
2016/2017 (Atalanta-SC)								
09/20	352	523	517	444	616	537	481 NS	19.6
12/05	327	471	474	380	465	467	431	
Mean	340 C	497 A	496 A	412 B	419 A	502 A		
C.V. (%)							7.0	
AE (kg kg⁻¹)								
2015/2016 (Lages-SC)								
10/15	-	21.6	19.7	11.2	21.2	20.5	18.9 a	64.3
12/05	-	5.1	1.9	4.6	8.1	4.5	4.9 b	
Mean	-	13.4 AB	10.8 AB	7.9 B	14.7 A	12.5 AB		
C.V. (%)							29.0	
2016/2017 (Atalanta-SC)								
09/20	-	22.8	23.0	9.8	24.5	26.8	21.4 a	29.1
12/05	-	20.2	17.4	10.1	17.7	18.8	16.9 b	
Mean	-	21.5 A	20.2 A	10.0 B	21.1 A	22.8 A		
C.V. (%)							27.41	

V5 - five expanded leaves; V10 - ten expanded leaves; VT - tasseling, according to the growth stage scale proposed by Ritchie *et al.* (1993); preferential sowing date - early spring (10/15/2015 and 09/20/2016); Late sowing date - end of spring (12/05/2015 and 12/05/2015); means followed by the same lowercase letter in the column and uppercase letter in the row do not differ significantly by the Tukey test at the significance level of 5% ($P < 0.05$); NS - not significant ($P \geq 0.05$). C.V. - coefficient of variation.

side-dressing was not performed (Fig. 2) which contributed to a decrease of the 1000 grain mass in the control. Such a tendency was also reported by Cruz *et al.* (2008) and Cardoso *et al.* (2011). The splitting of N fertilization, combined with the application of $\frac{1}{3}$ of the N rate at tasseling was expected to delay leaf senescence, increase grain filling duration, and enhance kernel mass, especially at the preferential sowing date. The hypothesis was not confirmed because there were no significant differences for LAI and 1000 grain mass among treatments with N side-dressing carried out at growth stages one (V5 or V10), two (V5+V10) or three (V5+V10+VT).

In 2015/2016, the control obtained ears with a lower number of kernels than the treatment with N fertilization at V5 and V10 (Tab. 4). The ears produced fewer grains when maize was sown in October rather than in December, on the average of N side-dressing fertilization treatments. In the growing season of 2016/2017, the control and the treatment with complete N side-dressing fertilization in VT obtained ears with a lower kernel number than the other treatments that contributed to the lower yields of these two treatments. This behavior confirms the observations of Bortolini *et al.* (2000) and Forsthofer *et al.* (2006), showing that the kernel number per ear is the yield component that affects maize productivity the most.

The agronomic efficiency of nitrogen use (AE) was affected by the main effects of sowing date and nitrogen side-dressing fertilization (Tab. 3). This variable was higher at the preferential sowing date rather than at the late sowing date at both experimental sites, regardless of the nitrogen side-dressing fertilization treatment (Tab. 4). At both experimental sites, the lowest AE values were recorded in the treatment with complete N fertilization in VT. The supply of the complete N rate at maize tasseling can recover partially the damages caused by nitrogen deficiency during the crop vegetative stages. This was confirmed by the weight of 1000 grains behaviour, which did not show statistical differences among the treatments with N fertilization at V5, V10 or VT (Tab. 4). However, the application of the complete N rate at VT could not totally compensate the negative effects of the lack of nitrogen between V5 and VT when the number of ears per plant and the number of potential kernels per ear were defined (Sangoi *et al.*, 2010). Therefore, nitrogen deficiency up to maize flowering reduced grain yield and AE when the whole side-dressing fertilization was performed at VT.

At both growing seasons, the AE values were lower than 25 kg of side-dressing N per kg of kernel (Tab. 4). Mota *et al.* (2015) and Sangoi *et al.* (2015) obtained AE values between

30 and 60 under similar experimental conditions, depending on the N rate and source. The lower yield than that planned for the nitrogen rate used (21 t ha^{-1}) in the trials contributed to reduce AE. The low nitrogen efficiency to enhance grain production probably contributed to the differences in the absence of productivity among treatments with complete N fertilization at V5 or V10 and treatments where the side-dressing operation was split into two or three times.

Conclusions

The splitting of N side-dressing fertilization into two (V5+V10) or three (V5+V10+VT) growth stages does not increase maize grain yield or AE, compared to the complete N application at V5 or V10, regardless of the sowing date.

The AE is higher when maize is sown at the beginning of spring, regardless of the nitrogen side-dressing fertilization system.

The complete nitrogen side-dressing fertilization at VT can help to recover partial damages to grain yield caused by no nitrogen application during maize vegetative development.

Author's contributions

HFK formulated the research goals and aims, applied the statistical techniques to analyze the study data, and wrote the original draft of the manuscript; LS formulated the research goals and aims and reviewed the manuscript; AEC and LSL reviewed the manuscript and performed the experiments; MCMJ, VLO, and RLS developed the methodology, performed the experiments and collected the data, and all authors revised and agreed to the published version of the manuscript.

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