Precision Agric (2013) 14:450–465
DOI 10.1007/s11119-013-9308-7

Optimization of corn plant population according to management zones in Southern Brazil

T. A. N. Hörbe · T. J. C. Amado · A. O. Ferreira · P. J. Alba

Abstract Precision agriculture relies on site-specific interventions determined by the spatial variability of factors driving plant growth. The main objective of this study was to assess the efficiency of variable-rate seeding of corn (*Zea mays* L.) with delineated management zones. This study involved two experiments carried out in Não-Me-Toque, Rio Grande do Sul, Brazil. For the first experiment, carried out in 2009/2010, management zones were delineated by the farmer's knowledge of the crop field. The field was split into low (LZ), medium (MZ) and high (HZ) crop performance zones. In the second experiment, carried out in 2010/2011, management zones were delineated by overlaying standardized yield data from nine crop seasons (seven of soybean and two of corn). The experiment was carried out with a randomized block design with three management zones and five corn seeding rates ranging from 50 000 to 90 000 seeds per ha^{-1}. The soil was a Rhodic Hapludox with a subtropical climate. Optimization of the corn plant population within the field increased grain yield compared to the reference plant population (70 000 plants ha^{-1}). Yield increases in the LZ, due to corn plant population reduction in relation to the target population, were 1.20 and 1.90 Mg ha^{-1} for first and second experiments, respectively. This resulted in economic gains of 19.8 and 28.7 %, respectively. Yield increases in the HZ were 0.89 and 0.94 Mg ha^{-1}, respectively, and were due to an increase in plant population in relation to the target population. This resulted in economic gains of 5.6 and 6.6 % for the first and second experiments, respectively. In the MZ, the adjustment of the target plant population was not necessary. Optimizing corn population according to management zones is a promising tool for precision agriculture in Southern Brazil.

Keywords Yield map · Variable-rate seeding · *Zea mays* · Site-specific management

---

T. A. N. Hörbe · T. J. C. Amado (✉) · A. O. Ferreira · P. J. Alba
Soil Science Department, Federal University of Santa Maria, Roraima Av., 1000, Santa Maria,
RS 97105-900, Brazil
e-mail: florestatel@hotmail.com

Introduction

Precision agriculture (PA) relies on the concept that variability within the main factors responsible for crop yield can be identified, quantified, and spatially delineated. Site-specific management is a tool that enables famers to achieve optimum crop performance in the whole field (Balastreire et al. 1997). Recently, site-specific management has been largely adopted for fertilizer and lime inputs in Brazil. This trend is associated with low natural soil fertility, which requires high fertilizer and lime inputs (Neto et al. 2011). Variable-rate fertilizer technology makes it possible for producers to achieve more homogeneous crop yields within a field by reducing the areas of poor crop performance and by increasing the areas of high yield when compared to uniform management (Milani et al. 2006; Amado and Santi 2011). Precision agriculture optimizes input and available resource use. As such, it is in line with the principles of sustainable agriculture by avoiding under- and over-fertilization, and thus it decreases environmental risks (Goering and Hans 1993; Portz et al. 2012).

Within-field crop yield variability has been reported even in well-managed fields (Amado et al. 2007). This observation is attributed to zones with different soil types, soil quality differences within the same soil type, past soil erosion, microclimate, input-related factors and the complex interactions between all previous factors (Basnet et al. 2003). Fiorin et al. (1997) reported that the A horizon depth of an Ultisol in central Rio Grande do Sul State was the main driver for non-irrigated corn (*Zea mays* L.) yield variability. In addition, slope length has also been reported as likely to be partly responsible for crop yield variability in the rolling fields that are typical of Southern Brazil (Alba et al. 2011). Homogeneous areas with different crop yield performances have been used to delineate management zones as a consequence of the frequency and intensity of plant growth limiting factors (Basnet et al. 2003; Amado et al. 2009; Neto et al. 2011). In this sense, the use of yield maps of various crops and seasons becomes a key tool for understanding within-field variability (Zhang et al. 2002; Molin 2002; Milani et al. 2006; Amado et al. 2007) and establishing site-specific interventions. Basnet et al. (2003) suggested that low crop performance zones should have priority in soil management.

Management zones can drive several site-specific management strategies, including variable-rate seeding (Molin 1997; Shanahan et al. 2004; Milani et al. 2006; Butzen and Gunzenhauser 2010). Usually several yield maps from different seasons and crops for the same field are required to accurately assess spatial and temporal variability (Blackmore et al. 2003; Basnet et al. 2003). Corn performance is frequently affected by management zones because corn is sensitive to environmental and management factors and is very responsive to inputs (Amado et al. 2007). In addition to yield map data, other tools can be used to define management zones such as: remote sensing (aerial and satellite images), ground-based sensors (soil electrical conductivity and plant reflectance-based data) (Bragachini et al. 2010) and even visual delineation based on the farmer's knowledge of his field.

Corn is the main cereal grown in Brazil with ~13.3 M ha planted annually. The national average yield is 4.2 Mg ha^{-1} (Instituto Brasileiro de Geografia e Estatística: IBGE 2012), although the best Brazilian corn farmers frequently achieve yields of up to 10 Mg ha^{-1}. This crop has high within-field grain yield variability, especially in drought years (Berlato et al. 2005; Amado et al. 2007). This high spatial crop performance variability is attributed to an imbalance of plant-growth factors (Fancelli and Dourado Neto 2000; Basnet et al. 2003), which should be considered in the determination of optimum corn plant population (Vieira Junior 1999; Dourado Neto et al. 2000; Vieira Junior et al. 2006; Molin et al. 2006).

In Argentina, variable-rate seeding of corn has been used successfully for the last five years (Bragachini et al. 2010) although in Brazil it is still incipient.

Uniformity of seeding depth, plant spatial arrangement and plant population are cultural practices that frequently affect corn grain yield (Almeida and Sangoi 1996; Duvick and Cassan 1999; Tollenaar and Wu 1999; Sangoi et al. 2002; Tollenaar and Lee 2002; Pereira et al. 2008). Improvements in corn yield could be obtained by adjusting the plant population to an optimal level, which would be determined by limiting plant-growth factors present within the variability of the field. Vieira Junior et al. (2006) reported that corn yield was also influenced by the spatial distribution of plants within rows. In this case, with populations ranging from 58 000 to 76 000 plants ha^{-1}, the variability of in-row plant spacing (uneven distribution) resulted in a yield reduction of 28.7 %. Therefore, the uniformity of plant spacing within-rows is just as important as the optimization of plant population within-field.

The adoption of variable-rate seeding of corn practices by Brazilian farmers depends on the availability of technical information and regional research support. The objective of this study was to investigate the benefits of optimizing corn plant population according to management zones in two croplands of Rio Grande do Sul, Southern Brazil.

Materials and methods

Two croplands, one with 90 ha (referred to as Experiment 1, carried out in 2009/10) and the other with 124 ha (referred to as Experiment 2, carried out in 2010/11), both of which had been managed under PA with the Aquarius Project (www.ufsm.br/projetoaquarius), were selected for this study. These croplands are located in close proximity to each other, with 28°29′S and 52°51′W for the Experiment 1, 28°48′S and 52°77′W for Experiment 2. Both are located in the municipality of Não-Me-Toque, RS. The soil is classified as Typic Hapludox according to U.S. Soil Taxonomy. The main soil chemical attributes are shown in Table 1.

The climate, according to Köeppen classification, is Cfa—humid subtropical. The warmest month is January, with an average temperature of 24.6 °C, and the coldest is June with an average of 12.9 °C. Rainfall is evenly distributed in all months of the year with annual rainfall ranging from 1 500 to 1 750 mm. Climatic conditions for both years of study were satisfactory for crop performance. However, in Experiment 1 the accumulated rainfall was 21.4 % higher than it was in Experiment 2, with a significant volume of precipitation between the V4 to V12 corn growth stages (Ritchie and Hanway 1993) (Fig. 1).

Croplands in the Aquarius Project are characterized by the adoption of best management practices. In the 2009/10 growing season, the average grain yields were 3.3 and 10.3 Mg ha^{-1} for soybean and corn, respectively. These yields were higher than the Rio Grande do Sul State averages by 32 and 114 %. Both croplands selected for this study have

Table 1 Soil chemical characteristics of the 0–0.15 m soil layer for two croplands in Não-Me-Toque, RS

Sites	Organic (%)	Phosphorus (melich^{-1}) (mg dm^{-3})	Potassium (mmol$_c$ dm^{-3})	pH H_2O (1:1)	Clay (g kg^{-1})
Experiment 1	3.2	22.2	7.21	5.7	601
Experiment 2	3.4	24.1	6.83	5.5	642

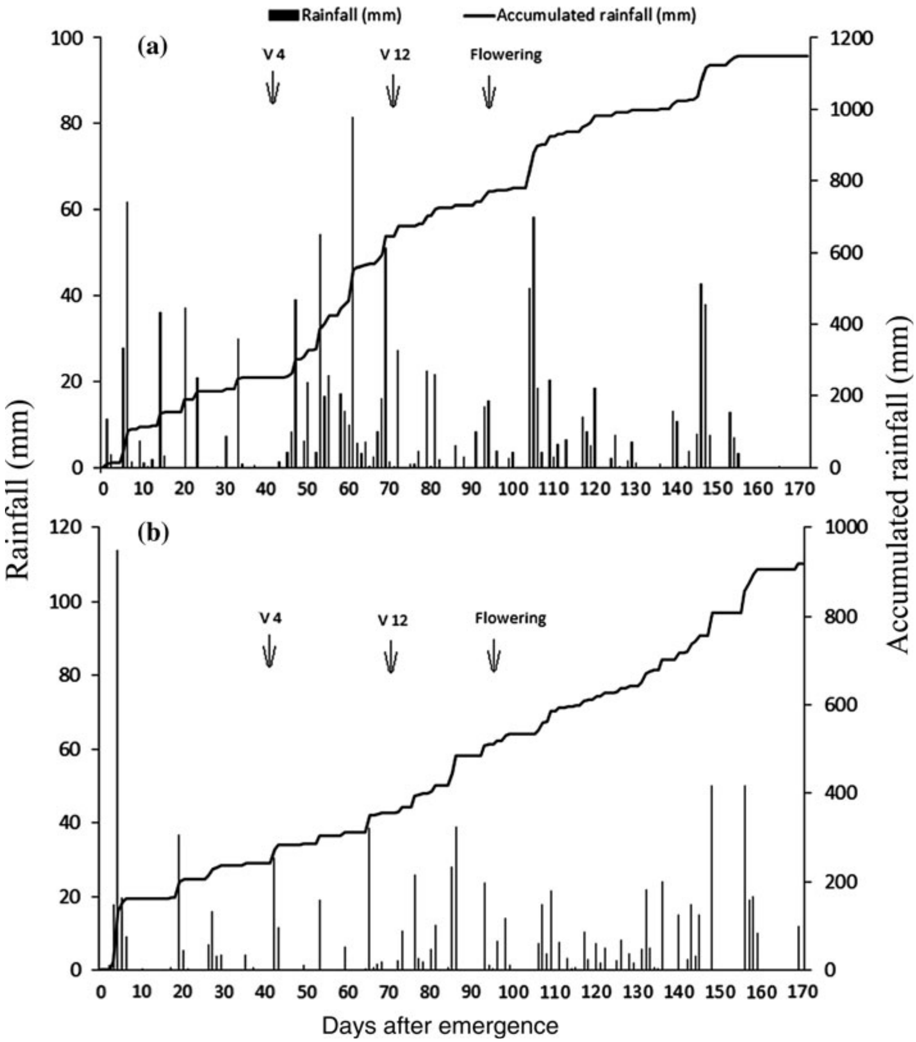

Fig. 1 Daily distribution of rainfall and total rainfall for; **a** Experiment 1 in 2009/10 and **b** Experiment 2 in 2010/11, Não-Me-Toque, RS

been managed under continuous no-till with crop rotation for more than 10 years. The main cash crops grown during the summer are soybean (*Glycine max* (L.) Merr.) and corn, which are grown in a crop rotation program with two or three years of soybean followed by 1 year of corn. In the winter, wheat (*Triticum aestivum* L.) is the main cash crop, and it is annually rotated with black oat (*Avena strigosa* L.) as a single cover crop or intercropped with oil radish (*Raphanus sativus var. oleiferus* Metzg.). Double-cropping systems are used because the precipitation and temperature of the subtropical climate allows plant growth year around.

The corn hybrid used in this study was Pioneer brand 30F53 YieldGard hybrid. This hybrid is one of the most commonly planted by farmers in this area and was seeded in the beginning of September in both seasons. To establish the range of plant population investigated, a planter, Victoria Control (Stara S.A., Não Me Toque, Rio Grande do Sul, Brazil), with an auto-guide system was used. This planter was equipped with a DGPS (Global positioning system with differential signal) receptor, Topper 4500®, which also acts as a controller for variable-rate seeding in accordance with the prescription map. Planter speed was set to 5 km h^{-1} and the variable-rate seeding system was hydraulically driven.

The management zones were used as key parameters for optimizing corn plant population within-field as previously proposed by Butzen and Gunzenhauser (2010). For Experiment 1, the cropland had only 1 year of crop yield data available, which was not enough to delineate the management zones accurately. Therefore, the zones were delineated visually through the farmer's knowledge of his cropland. The field was separated into low (LZ), medium (MZ) and high (HZ) crop performance management zones. For Experiment 2, the cropland had a large set of grain yield data available; so, the delineation of management zones was done as described in the methodology proposed by Molin (2002) and Blackmore et al. (2003). Overlying multiple yield maps (seven of soybean and two of corn) by using averaging techniques and spatial grid cells resulted in a single thematic map. The separation of zones was as follows: the LZ had relative yields <95 % of field average yield, the MZ had relative yields between 95 and 105 %, and the HZ had relative yields >105 % of the field average yield in the respective season (Molin 2002; Amado and Santi 2011). Figure 2 shows the delineation of the management zones based on the farmer's knowledge in Experiment 1 and the delineation based on a nine-year set of yield data in Experiment 2.

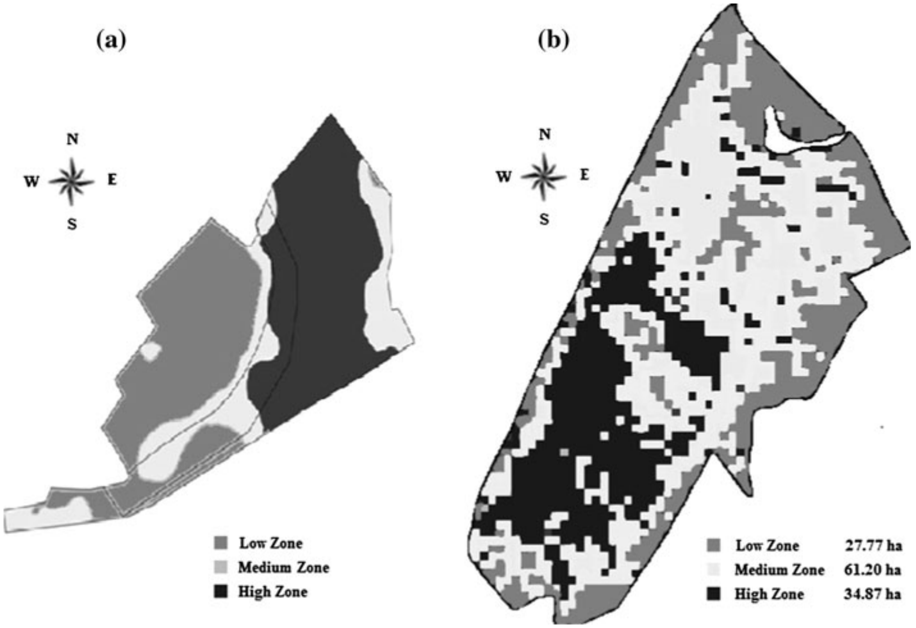

Fig. 2 Spatial distribution of management zones for two croplands; **a** based on farmer's knowledge in Experiment 1 and **b** based on a nine-year set of yield data in Experiment 2, Não-Me-Toque, RS

For the cropland in Experiment 2, corn and soybean yields from 2002 to 2010 were mapped with a MF 34 combine equipped with a yield impact sensor. The sensor was re-calibrated at least five times per day based on weighted scale data. The details of this procedure can be obtained in Amado et al. (2007). The data were processed using Microsoft Office Excel® 2007 and CR—Campeiro 7 software (Federal University of Santa Maria, Santa Maria, RS, Brazil). Filtration eliminated the main sources of error such as positioning errors and unlikely yield values (outliers). Filtration was performed as proposed by Menegatti and Molin (2004) and Amado and Santi (2011). The yield results were then adjusted to 13 % moisture for both corn and soybean.

The experiment was carried out with a random block design, with five treatments and five replications. The blocks were set based on management zones (LZ, MZ and HZ). Each plot was 50 m long by 5.50 m wide. The planter had 11 lines (rows) that were 0.50 m apart. The treatments consisted of five seeding rates: 50 000, 60 000, 70 000, 80 000 and 90 000 seeds ha^{-1}.

The minimum purity and average germination percentages of seed lots were 97 and 98 % for Experiments 1 and 2, respectively. Mineral fertilization rates were based on a yield goal of 10 Mg ha^{-1}. Fertilizer amounts used were 72 kg ha^{-1} of P_2O_5 and 27 kg N ha^{-1} in row at seeding followed by 60 kg ha^{-1} of K_2O broadcast on the soil surface. Additional N fertilization was applied as a topdress and was split between stages V4 and V8, with 75 kg ha^{-1} for each growth stage, resulting in a total N application rate of 177 kg ha^{-1}.

The corn plant population was evaluated at the V6 stage using four central rows with a length of 30 m. The evaluation area was 60 m^2 and the results were extrapolated out to an area of 10 000 m^2. In Experiment 2, additional evaluations were performed including the distribution of plants in-row using the following classification: acceptable, flawed, or double, according to the methodology described by Vieira Junior et al. (2006). The efficiency of plant distribution in-row was evaluated by the following classification: optimum performance, in the range of 90–100 % of the target plant spacing; acceptable performance, in the range of 75–90 %; regular performance, in the range of 50–75 %; and unsatisfactory performance, in the range of < 50 % of target spacing as suggested by Torino and Klingensteiner (1983). Thus, for the seeding rates of 50 000, 60 000, 70 000, 80 000 and 90 000 seeds ha^{-1} the target plant in-row spaces were 0.40, 0.33, 0.29, 0.25 and 0.22 m, respectively. The corn plant in-row spacing was evaluated at the V6 stage using three central rows with a length of 30 m.

The corn yield data from both experiments for the 2010/11 season were obtained with a MF 9790 combine equipped with a yield sensor. The combine head was selected to have the same width as the planter (5.50 m). For economic analysis, corn selling prices of US\$0.12 and US\$0.20 kg^{-1} and seed costs of US\$190 and US\$210 per bag with 60 000 seeds were used for Experiments 1 and 2, respectively, based on regional market prices for each year. As the cost of seeds was different between years, the same seeding rate had a different cost. In this study, the reference plant population for hybrid Pioneer brand 30F53 was 70 000 plants ha^{-1} following the technical recommendation.

The results were submitted to ANOVA using SISVAR 5.0 (Ferreira 2010) software and mean values were compared by the Tukey test ($p < 0.05$). Linear regression equations were used to evaluate the relationship between corn plant population and management zone. The regression analyzes were performed by the program, JMP IN, version 3.2.1 (Sall et al. 2005), using the F test ($p < 0.05$).

Results and discussion

Variable-rate seeding of corn

Optimization of corn plant population in PA relies on, among other factors, the efficiency of the planter to accurately follow the variable-rate seeding prescription map. Uniformity of seed spacing in rows influences final plant population and yield (Dourado Neto et al. 2001; Vieira Junior et al. 2004; Liu et al. 2004). The adjustment between variable-rate seeding and corn plant population achieved was distinct between the experiments (Fig. 3). No adjustment is seeding rate was made considering the high purity and germination value of the hybrid used. In Experiment 1, as expected, the average difference between seeding rate and corn plant population was 1.3 %, ranging from 0.7 to 2.9 %, while in Experiment 2 it was 9.4 %, ranging from 7.1 to 12.4 % (Table 2). The greater difference between seeding-rate and corn plant population in Experiment 2 was attributed to climatic conditions that were prevalent just after seeding. There was a large-precipitation event exceeding 100 mm within a 24 hour period which hampered plant emergence (Fig. 1b). Therefore, in this study, the variable-rate seeding of corn was affected by the interaction of planter performance, seed quality, environmental factors (precipitation and temperature), soil attributes (moisture, compaction and aeration) and insect and disease pressure, all of which affected the achieved plant population in the field.

The planter efficiency in delivery of the correct seeding rate was evaluated indirectly through the final corn plant population achieved in the field. In Experiment 2, the in-row plant spacing was also evaluated and was classified following Torino and Klingensteiner (1983). It was classified as being optimum for the 50, 60, 70 and 80 thousand seeds ha^{-1}

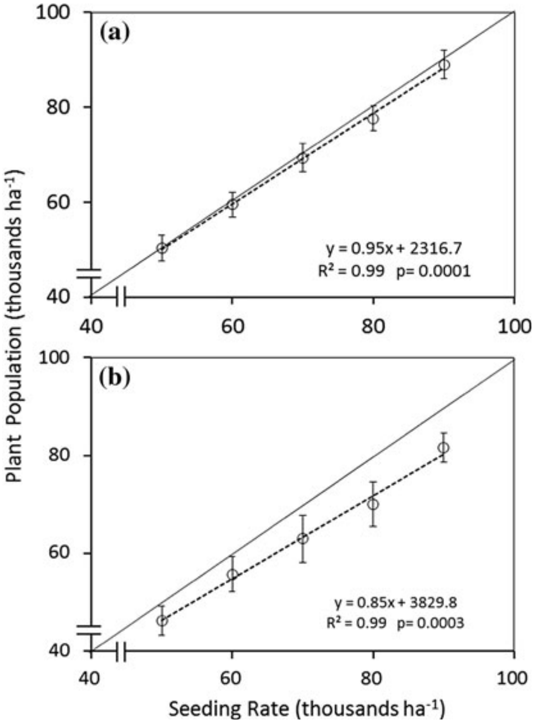

Fig. 3 Relationship between the prescribed seeding rates and achieved field corn plant populations in; **a** Experiment 1 and **b** Experiment 2, Não-Me-Toque, RS

Table 2 Target and achieved seeding rates for Experiments 1 and 2 and uniformity in plant spacing for three qualitative categories for Experiment 2, Não-Me-Toque, RS

Variable-seeding rate	Corn plant population		Spacing among plants			CV
			Experiment 2			
(seeds ha^{-1})	Experiment 1 (plants ha^{-1})	Experiment 2 (plants ha^{-1})	Acceptable (%)	Flawed (%)	Double (%)	
50 000	49 816	46 242	94.14	5.11	0.75	11.25
60 000	59 500	55 753	93.63	5.89	0.48	11.87
70 000	69 333	63 018	92.50	6.68	0.82	14.50
80 000	77 666	70 096	90.68	8.18	1.14	16.63
90 000	87 816	81 576	89.16	9.48	1.36	16.75

CV coefficient of variation

Table 3 Analysis of variance for corn grain yield and partial net economic return for variable-rate seeding according to management zones

Causes of variation	d.f.	Corn yield		Partial net economic return	
		Experiment 1	Experiment 2	Experiment 1	Experiment 2
MZ	2	**	**	**	**
PP	4	ns	ns	ns	**
CV[a] (%)		9.62	12.17	11.46	13.56
PP × MZ	8	**	**	**	**
CV[b] (%)		4.19	3.37	4.99	3.75

ns non-significant, *MZ* management zone, *PP* corn plant population, *d.f.* degrees of freedom

** Significant $p < 0.01$

[a] coefficient of variation

[b] CV of the interaction of PP × MZ

rates and good for the 90 000 seeds ha^{-1} rate (Table 2). The coefficient of variation (CV) for in-row plant spacing ranged from 11.3 to 16.8 % with an average of 14.2 % for the five seeding rates investigated (Table 2). This characteristic is dependent on planter features and the vigor and germination percentage of crop seed (Thomison et al. 2004). Vieira Junior et al. (2006) reported that a CV > 20 % in the uniformity of plant spacing will reduce corn yields. In this work the CV values were always below that limit.

Plant population, corn yield and economic analysis by management zones

The ANOVA and the partial net economic analysis showed that the interaction between plant population and management zone was significant for both experiments (Table 3). Regardless of the experiment and method used to delineate management zones, there was an optimum plant population for each management zone (Bragachini et al. 2010; Butzen and Gunzenhauser 2010). Fulton et al. (2010) previously reported that the optimum corn plant population varied among management zones and that variable-rate seeding resulted in an increased economic return. In the same way, Shanahan et al. (2004) observed that adjusting for the optimum plant population based on yield map data was an effective strategy for increasing grain yield in corn croplands.

Optimizing corn plant population by management zone provided an increase in grain yield when compared to the flat reference plant population (70 000 plants ha^{-1}) within the experimental field. Thus, for each management zone there was a distinct optimum corn plant population. In the LZ, as the corn plant population increased, there was a linear decrease in grain yield in both experiments (Fig. 4). For the LZ in particular, the lowest seeding rate (50 000 seeds ha^{-1}) had resulting corn populations of 49 816 (Fig. 4a) and 46 242 (Fig. 4b) plants ha^{-1} in Experiments 1 and 2, respectively. This seeding rate resulted in increased grain yields of 1.2 and 1.9 Mg ha^{-1}, respectively, in relation to the flat reference plant population. The variable-rate seeding strategy provided a seed-cost saving of US\$63 and US\$105 ha^{-1}, in Experiments 1 and 2, respectively, in relation to the seed cost needed to achieve the reference plant population (70 000 and 80 000 seeds ha^{-1} in Experiments 1 and 2, respectively) (Table 4).

Although, both growing seasons were favorable to corn-crop performance in non-irrigated fields, the LZ was not able to support any increase beyond the lowest corn plant population achieved without grain yield reduction. Management zones classified as LZ are usually associated with lower soil quality in relation to other field zones' and are likely to have reduced crop growth (Cassman 1999). The increase in corn plant population in the LZ resulted in inter-specific competition for available resources such as water and nutrients. In both experiments, and regardless of management zones, soil fertility was not restrictive to corn productivity. Therefore, lower soil water storage capacity and lower soil organic matter content in the LZ compared to the HZ could be an explanation for our results as verified in previous studies under PA in South Brazil (Amado et al. 2009; Girardello et al. 2011; Santi et al. 2012). Since improvement in soil quality may require long-term and

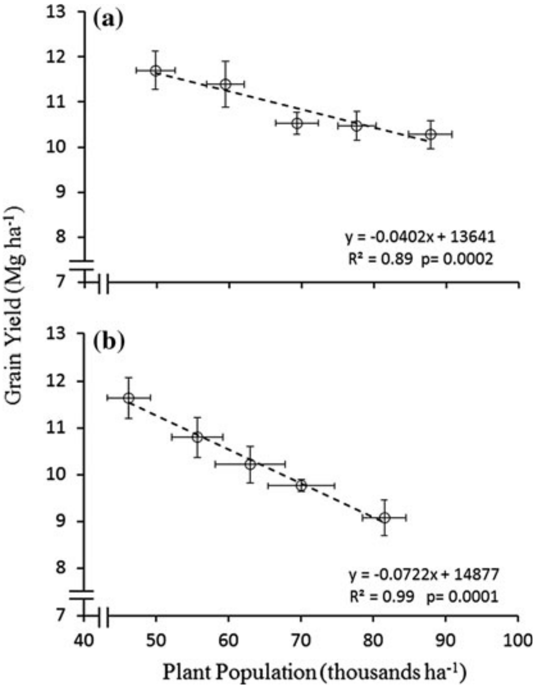

Fig. 4 Relationship between corn plant population and grain yield in the low management zone for; **a** Experiment 1 and **b** Experiment 2, Não-Me-Toque, RS

Table 4 Partial net economic return attributed to corn plant population for two experiments with three management zones

Experiment	MZ	PP (plants ha^{-1})	Yield (Mg ha^{-1})	Gross income (US$ ha^{-1})	Seed cost (US$ ha^{-1})	Net income (US$ ha^{-1})
1	Low	49 816	11.704	1 404.48	158.30	1 246.18
		59 500	11.395	1 367.40	190.00	1 177.40
		69 333	10.533	1 263.96	221.70	1 042.26
		77 666	10.472	1 256.64	253.30	1 003.34
		87 816	10.280	1 233.60	285.00	948.00
	Medium	49 816	10.740	1 288.80	158.30	1 130.50
		59 500	11.231	1 347.72	190.00	1 157.72
		69 333	12.120	1 454.40	221.70	1 232.70
		77 666	11.655	1 398.60	253.30	1 145.30
		87 816	11.499	1 379.88	285.00	1 094.88
	High	49 816	12.183	1 461.96	158.30	1 303.66
		59 500	12.232	1 467.84	190.00	1 277.84
		69 333	12.843	1 541.16	221.70	1 319.46
		77 666	13.724	1 646.88	253.30	1 393.58
		87 816	13.113	1 573.56	285.00	1 288.56
2	Low	46 242	11.647	2 329.40	175.00	2 154.40
		55 753	10.803	2 160.60	210.00	1 950.60
		63 018	10.224	2 044.80	245.00	1 799.80
		70 096	9.767	1 953.40	280.00	1 673.40
		81 576	9.086	1 817.20	315.00	1 502.20
	Medium	46 242	9.937	1 987.40	175.00	1 812.40
		55 753	10.560	2 112.00	210.00	1 902.00
		63 018	11.644	2 328.80	245.00	2 083.80
		70 096	11.959	2 391.80	280.00	2 111.80
		81 576	10.169	2 033.80	315.00	1 718.00
	High	46 242	12.066	2 413.20	175.00	2 238.20
		55 753	12.381	2 476.20	210.00	2 266.20
		63 018	12.432	2 486.40	245.00	2 241.40
		70 096	12.950	2 590.00	280.00	2 310.00
		81 576	13.889	2 777.80	315.00	2 462.80

MZ management zone, *PP* corn plant population

expensive soil management practices, adjustment of corn plant population in low crop performance zones is an efficient strategy to decrease inter-specific competition (Dourado Neto et al. 2001; Maddoni et al. 2001) and save seed costs in relation to a flat seeding-rate.

Studies in the United States from 2004 to 2008 showed corn plant populations ranging from 40 000 to 45 000 plants ha^{-1} were considered optimum in zones with lower productivity potential (Butzen and Gunzenhauser 2010). They also observed a linear decrease in net economic return with higher plant populations in this specific yield zone. In studies in Brazil, Duarte and Paterniani (2000) and Fancelli and Dourado Neto (2000) reported that in areas subject to recurrent drought during the growing season, corn plant population around 55 000 plants ha^{-1} should be recommended. In the same way, a region in western

Kansas with frequent water deficiency reported that the corn population should not be more than 45 000 plants ha^{-1} (Norwood 2001). Similarly, within-field zones with poor soil physical-hydraulic quality may require a lower corn plant population.

In the MZ, the optimum corn plant population ranged between 74 138 and 65 689 plants ha^{-1} in Experiments 1 and 2, respectively (Fig. 5). Even though corn yield increased up to a point, seed cost for each plant population continued to rise resulting in lower economic returns at the highest populations (Table 4). These results corroborate with those previously reported by Butzen and Gunzenhauser (2010) for the MZ. In summary, the optimum population in the MZ was similar to the reference plant population (70 000 plants ha^{-1}) recommended for the hybrid used. Therefore, in this zone no plant population adjustment was necessary.

In the HZ for both experiments, the corn grain yield was improved following the increase in plant population (Fig. 6). Results suggest that this specific zone was able to support a higher population than the reference plant population, probably because of superior soil quality and better environmental resources available to plant growth (Cassman 1999). The increase in crop production costs due to an increase in seeding rate that achieved plant populations of 77 666 (Fig. 6a) and 81 576 (Fig. 6b) plants ha^{-1} was offset by yield increments of 0.88 and 0.94 Mg ha^{-1}, respectively, in relation to the reference plant population (Table 4). In favorable environments for plant growth, such as irrigated and well fertilized croplands, the increase in plant population up to 80 000 plants ha^{-1} generally improves corn yields (Merotto et al. 1997; Sangoi et al. 2002; Peake et al. 2008; Abendroth and Elmore 2007; Paszkiewicz and Butzen 2007; Butzen and Gunzenhauser 2010).

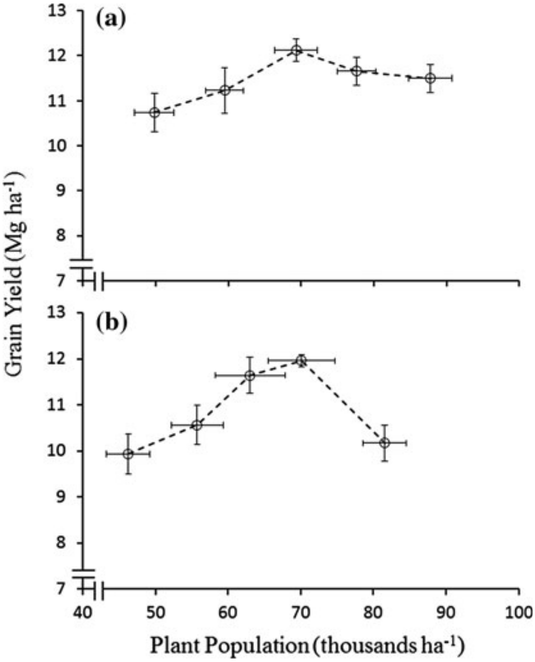

Fig. 5 Relationship between corn plant population and grain yield in the medium management zone for; **a** Experiment 1 and **b** Experiment 2, Não-Me-Toque, RS

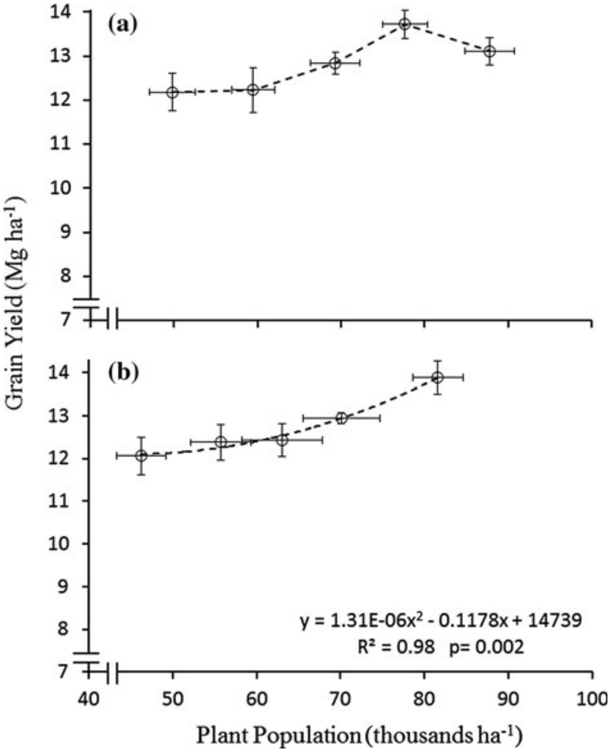

Fig. 6 Relationship between corn plant population and grain yield in the high management zone for; **a** Experiment 1 and **b** Experiment 2, Não-Me-Toque, RS

Partial economic analysis of corn plant adjustment according to management zones

Economic analysis, in both experiments, indicates the feasibility of optimizing corn plant population in management zones when compared with the flat reference population for a whole field (Fig. 7; Table 4). Thus, the highest partial economic return for each management zone was achieved with a distinct corn plant population. Bullock et al. (1998), in a large study carried out in the U.S. Corn Belt region, also reported that the economic-optimum plant population varied as a function of the crop yield zone.

The adjustment of corn plant population according to management zones resulted in higher partial net economic returns of 19.80 and 28.72 % and 5.56 and 6.61 % (Table 4), for the LZ and HZ, respectively, in Experiments 1 and 2 in relation to the reference plant population. These increases in the partial economic return resulted in lower differences in economic return among management zones. As such, the profitability of the LZ was closer to the HZ under variable-rate seeding (Fig. 7). The partial economic return in the LZ and MZ with optimization of plant population was equivalent: US$1 207.00 and US$1 217.95, respectively, in Experiment 1 (Fig. 7a) and US$2 154.32 and US$2 111.73, respectively, in Experiment 2 (Fig. 7c). On the other hand, the partial economic return of these two management zones (LZ and MZ) with flat reference plant population was US$1 007 and US$1 218, respectively, in Experiment 1 (Fig. 7b) and US$1 673.59 and US$2 111.73, respectively in Experiment 2 (Fig. 7d).

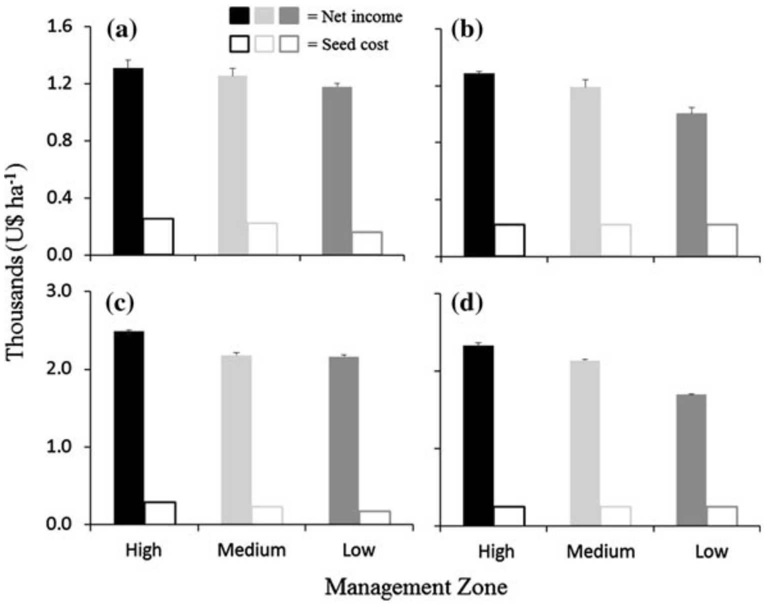

Fig. 7 Partial economic return and seed cost by management zone (high, medium and low) for Experiment 1 with **a** optimized seeding rate and **b** flat-rate seeding and for Experiment 2 with **c** optimized seeding rate and **d** flat-rate seeding, Não-Me-Toque, RS

The results for Experiment 2 were scaled up to 124 ha of cropland in order to estimate the economic impact. The relative spatial distribution of yield zones was 22.3, 49.3 and 28.1 % for the LZ, MZ and HZ, respectively (Fig. 2b). In this case, if the corn plant population had been 46 242, 70 096 and 81 576 plants ha^{-1} in the LZ, MZ and HZ (Table 4), respectively, the partial net economic return by adopting variable-rate seeding for the whole cropland would be US$18 674. Based on this figure, it would take approximately 4 years to recuperate the investment required to purchase the variable-rate planter. Note that 71.5 % of this economic gain projected was obtained in the LZ despite the fact this zone was smaller than the others. The adjusted seeding rate in the LZ was a win–win strategy because it allows for a higher grain yield with a lower seed cost. Lowenberg-DeBoer (1998) reported that the investments necessary for adopting variable-rate corn seeding would be economically justifiable if at least 10 % of the cropland was classified as LZ. On the other hand, in this study the HZ was responsible for 28.5 % of the estimated positive economic return from the whole field.

Conclusions

Management zones based on previous yields were an effective parameter for adjusting corn seeding rates. Seeding technologies that allowed for adjustment of corn plant population according to management zones resulted in increased yields and partial net economic returns in relation to the flat reference plant population. Averaged across the experiments, reducing the recommended plant population by 31 % in the low management zone resulted in a yield increase of 1.5 Mg ha^{-1} and induced an increase of US$342.46 ha^{-1} in partial net economic return. Increasing the recommended plant population by 13 % in the high management zone resulted in an increase of 0.91 Mg ha^{-1} in grain yield and induced an increase of \$113.46 ha^{-1} in partial net economic return. This study demonstrates that variable-rate seeding of corn can be an efficient tool for improving yields and profitability in Brazilian agriculture.

Acknowledgments To Roberto Stapelbroek and Marcos Van Riel farmers' that provides experimental areas to this study. To STARA, Massey Ferguson, COTRIJAL and YARA for technical and financial support. To CNPq and CAPES for financial support to this research.

References

Abendroth, L., & Elmore, R. (2007). Corn seeding rates and variable-rate seeding. *Integrated Crop Management, 9*, 110–111.

Alba, P. J., Amado, T. J. C., Giotto, E., Schossler, D., & Fiorin, J. E. (2011). Precision farming: Yield maps and soil atributes investigated in third dimension (Agricultura de precisão: Mapas de rendimento e de atributos de solo analisados em três dimensões). *Enciclopédia Biosfera-Goiânia, 7*, 29–41.

Almeida, M. L., & Sangoi, L. (1996). Increase in corn plant population in short-growth season regions (Aumento da densidade de plantas de milho para regiões de curta estação estival de crescimento). *Pesquisa Agropecuária Gaúcha, 2*, 179–183.

Amado, T. J. C., Pes, L. C., Lemainski, C. L., & Schenato, R. B. (2009). Physical and chemical Oxisol attributes and its relationship with irrigate corn and black bean yield (Atributos químicos e físicos de latossolos e sua relação com o rendimento de milho e feijão irrigado). *Revista Brasileira de Ciência do Solo, 33*, 831–843. doi:10.1590/S0100-06832009000400008.

Amado, T. J. C., Pontelli, C. B., Santi, A. L., Viana, J. H. M., & Sulzbach, L. A. S. (2007). Spatial and temporal grain crop yield variability under no-tillage system (Variabilidade espacial e temporal da produtividade de culturas sob sistema plantio direto). *Pesquisa Agropecuária Brasileira, 42*, 1101–1110.

Amado, T. J. C., & Santi, A. L. (2011). Using precision farming to overcome yield-limiting factors in Southern Brazil Oxisols: a case study. In D. Clay, J. Shanahan & J. Francis Pierce (Eds.), *GIS Applications in Agriculture—Nutrient Management for Improved Energy Efficiency* (3rd ed., pp. 31–60). CRC: Boca Raton. doi:10.1201/b10600-4.

Balastreire, L. A., Elias, A. I., & Amaral, J. R. (1997). Precision farming: Corn crop yield map (Agricultura de Precisão: Mapeamento da produtividade da cultura do milho). *Revista Engenharia Rural, 8*, 97–111.

Basnet, B., Apan, A., Kelly, R., Jensen, T., Strong, W., & Butler, D. (2003). Delineation of management zones using multiple crop yield data. *Proceedings of the 16th Triennial Congress of the International Soil Tillage Research Organization (ISTRO), July* (pp. 13–18). Brisbane, Australia: University Of Queensland.

Berlato, M. A., Farenzena, H., & Fontana, D. C. (2005). Relationship between El Nino and corn yield in Rio Grande do Sul State (Associação entre El Nino Oscilação Sul e a produtividade do milho no Estado do Rio Grande do Sul). *Pesquisa Agropecuária Brasileira, 39*, 423–432. doi:10.1590/S0100-204X2005000500001.

Blackmore, S., Godwin, R. J., & Fountas, S. (2003). The analysis of spatial and temporal trends in yield map data over six years. *Biosystems Engineering, 84*, 455–466. doi:10.1016/S1537-5110(03)00038-2.

Bragachini, M., Mendez, A., Scaramuzza, F., Velez, J. P., & Vilarroel, D. (2010). Dosificacion variable de insumos. In *9no Curso Internacional de Agricultura de Precisión y 4ta Expo de Máquinas Precisas,* Córdoba-Argentina.

Bullock, D. G., Bullock, D. S., Nafziger, E. D., Doerge, T. A., Paszkiewicz, S. R., Carter, P. R., et al. (1998). Does variable rate seeding of corn pay? *Agronomy Journal, 90*, 830–836.

Butzen, S., & Gunzenhauser, B. (2010). Putting variable-rate seeding to work on your farm. *Crop Insights, 19*, No 15. Pioneer Hi-Bred, Johnston, IA.

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of National Academy of Sciences USA, 96*, 5952–5959. doi:10.1073/pnas.96.11.5952.

Dourado Neto, D., Fancelli, A. L., & Lopes, P. P. (2001). Corn: plant population and plant arragment (Milho: população e distribuição de plantas). In A. L. Fancelli & D. Dourado Neto (Eds.), *Corn:*

technology to high productivity (Milho: tecnologia da produtividade) (pp. 120–125). Piracicaba, Brazil: Esalq.

Duarte, A. P., & Paterniani, M. E. A. G. Z. (2000). *Biotic and abiotic factors effect in corn cultivars and environmental conditions (Fatores bióticos e abióticos em cultivares de milho e estratificação ambiental: Avaliação IAC/CATI/Empresas-1999/2000)*. Campinas, Brazil: Instituto Agronômico de Campinas.

Duvick, D. N., & Cassan, K. G. (1999). Post-green revolution trends in yield potential of temperate maize in the North-Central United States. *Crop Science, 39*, 1622–1630.

Fancelli, A. L., & Dourado Neto, D. (2000). *Corn Growth (Produção de milho)*. Guaíba: Agropecuária, Brazil.

Ferreira, D. F. (2010) Sisvar versão 5.3-Sistemas de análises de variância para dados balanceados: programa de análises estatísticas e planejamento de experimentos. Lavras, MG. Universidade Federal de Lavras.

Fiorin, J. E., Reinert, D. J., & Albuquerque, J. A. (1997). Soil water storage and corn growth and productivity (Armazenamento de água no solo e crescimento e produção de milho). *Revista Brasileira Ciência do Solo, 21*, 249–255.

Fulton, J. P., Winstead, A., Shaw, J. N., Rodekhor, D., & Brodbeck, C. J. (2010). A case study for variable-rate seeding of corn and cotton in the Tennessee valley of Alabama. In *10th International Conference on Precision Agriculture*.

Girardello, V. C., Amado, T. J. C., Nicoloso, R. S., Hörbe, T. A. N., Ferreira, A. O., Tabaldi, F. M., et al. (2011). Soil physic attributes change in Red Oxisol under no-till affected by different chisel and soybean yield (Alterações nos atributos físicos de um latossolo vermelho sob plantio direto induzidas por diferentes tipos de escarificadores e o rendimento da soja). *Revista Brasileira Ciência do Solo, 35*, 2115–2126. doi:10.1590/S0100-06832011000600026.

Goering, C. E., & Hans, S. (1993). A field information system for SSCM. In International Off-highway and Powerplant Congress and Exposition, 1993, Milwaukee. Warrendale: SAE, 11 p. (SAE Technical Paper Series n. 932422). doi:10.4271/932422.

Instituto Brasileiro de Geografia e Estatística: IBGE (2012). Agricultural production data (Dados de produção agrícola). http://www.ibge.gov.br. Accessed 19 June 2012.

Liu, W., Tollenaar, M., Stewart, G., & Deen, W. (2004). Response of corn grain yield to spatial and temporal variability in emergence. *Crop Science, 44*, 847–854. doi:10.2135/cropsci2004.8470.

Lowenberg-DeBoer, J. M. (1998). Economics of variable rate planting for corn. In P. C. Robert, R. H. Rust, & W. E. Larson (Eds.), *Proceedings of 4th International Conference on Precision Agriculture* (pp. 1643–1651). Saint Paul: Purdue University.

Maddoni, G. A., Otegui, M. E., & Cirilo, A. G. (2001). Plant population density, row spacing and hybrid effects on maize canopy architecture and light attenuation. *Field Crops Research, 71*, 183–193. doi:10.1016/S0378-4290(01)00158-7.

Menegatti, L. A. A., & Molin, J. P. (2004). Errors elimination in crop yield map through raw data filter operation (Remoção de erros em mapas de produtividade via filtragem de dados brutos). *Revista Brasileira de Engenharia Agrícola e Ambiental, 8*, 126–134. doi:10.1590/S1415-43662004000100019.

Merotto, J. R., Almeida, M. L., & Fucks, O. (1997). Corn yield increase trough corn plant population increase (Aumento do rendimento de grãos de milho através do aumento da população de plantas). *Ciência Rural, 27*, 549–554. doi:10.1590/S0103-84781997000400004.

Milani, L., Souza, E. G., Uribe-Opazp, M. A., Gabriel Filho, A., Johann, J. A., & Pereira, J. O. (2006). Management zones delineate by crop yield data (Unidades de manejo a partir de dados de produtividade). *Acta Scientiarum Agronomy, 28*, 591–598. doi:10.4025/actasciagron.v28i4.937.

Molin, J. P. (1997). Precision farming, study I; art-state in remote sensors (Agricultura de precisão, parte I: o que é e estado da arte em sensoriamento remoto). *Engenharia Agrícola*, *22*, 83-02.

Molin, J. P. (2002). Delineate management zones using crop yield data (Definição de unidades de manejo a partir de mapas de produtividade). *Engenharia Agrícola, 22*, 83–92.

Molin, J. P., Mascarin, L. S., & Vieira Junior, P. A. (2006). Assess site-specific fertilizer and corn plant population (Avaliação de intervenções em unidades de aplicação localizada de fertilizantes e de populações de milho). *Engenharia Agricola, 26*, 528–536.

Neto, F. N., Roloff, G., Dieckow, J., & Motta, A. C. V. (2011). Spatial soil and plant attributes relationship with corn crop yield (Atributos de solo e cultura espacialmente distribuídos relacionados ao rendimento do milho). *Revista Brasileira Ciencia do Solo, 35*, 1025–1036. doi:10.1590/S0100-06832011000300036.

Norwood, C. A. (2001). Dryland corn in Western Kansas: Effects of hybrid maturity, planting, date and plant population. *Agronomy Journal, 93*, 540–547.

Paszkiewicz, S., & Butzen, S. (2007). Corn hybrids response to plant population. *Crop Insights*, 17, No 16. Pioneer Hi-Bred, Johnston, IA.

Peake, A., Robertson, M. J., & Bidstrup, R. (2008). Optimising maize plant population and irrigation strategies on the Darling Downs using the APSIM crop simulation model. *Australian Journal of Experimental Agriculture, 48*, 313–325. doi:10.1071/EA06108.

Pereira, F. R. S., Cruz, S. C. S., Albuquerque, A. W., Santos, J. R., & Silva, E. T. (2008). Arranjo espacial de plantas de milho em sistema plantio direto. *Revista Brasileira Engenharia Agricola Ambiental, 12*, 69–74.

Portz, G., Molin, J. P., & Jasper, J. (2012). Active crop sensor to detect variability of nitrogen supply and biomass on sugarcane fields. *Precision Agriculture, 13*, 33–44. doi:10.1007/s11119-011-9243-4.

Ritchie, S. W., & Hanway, J. J. (1993). *How a corn plant develops? Special Report 48*. Ames: Iowa State University of Science and Technology Cooperative Extension Service.

Sall, J., Creighton, L., & Lehman, A. (2005). *JMP start statistics: A guide to statistics and data analysis using JMP and JMP IN software. 3ed*. Cary: Duxbury Press.

Sangoi, L., Gracietti, M. A., Rampazzo, C., & Bianchetti, P. (2002). Response of Brazilian maize hybrids from different eras to changes in plant densities. *Field Crops Research, 79*, 39–51. doi: 10.1016/S0378-4290(02)00124-7.

Santi, A. L., Amado, T. J. C., Da Silva, V. R., Basso, C. J., Della Flora, L. P., Cherubin, M. R., et al. (2012). Infiltração de água no solo, determinada por diferentes métodos, como indicador do potencial produtivo em dois Latossolos manejados com agricultura de precisão. *Interciencia, 3*, 1–5.

Shanahan, J., Doerge, T. A., Johnson, J. J., & Vigil, M. F. (2004). Feasibility of site-specific management of corn hybrids and plant densities in the Great Plains. *Precision Agriculture, 5*, 207–225. doi: 10.1023/B:PRAG.0000032762.72510.10.

Thomison, P., Lipps, P., Hammond, R., Mullen, R., & Eisley B. (2004). Corn Production, Bulletin 472-05, Ohio State University. http://ohioline.osu.edu/b472/0005.html. Accessed 19 June 2012.

Tollenaar, M., & Lee, E. (2002). Yield potential, yield stability and stress tolerance in maize. *Field Crops Research, 75*, 161–169. doi:10.1016/S0378-4290(02)00024-2.

Tollenaar, M., & Wu, J. (1999). Yield improvement in temperate maize is attributable to greater stress tolerance. *Crop Science, 39*, 1597–1604.

Torino, M. C., & Klingensteiner, P. (1983). *Congresso Brasileiro de Engenharia Agrícola* (pp. 103–116)., Evaluation of planters (Ensaio e avaliação de semeadoras-adubadoras) Brazil: UFRJ-Rio de Janeiro.

Vieira Junior, P. A. (1999). Milho. In P. R. C. Castro & R. A. Kluge (Eds.), *Annual crops ecophysiology (Ecofisiologia dos cultivos anuais)* (pp. 41–72). São Paulo, Brazil: Nobel.

Vieira Junior, P. A., Molin, J. P., Dourado Neto, D., Manfron, P., Mascarin, L. S., Faulin, G. C., et al. (2004). *Relationship between plant population, arrangement, soil attributes and corn grain yields (Relação entre população, distribuição espacial de plantas, atributos do solo e rendimento de grãos de milho)*. Brazil: Congresso Brasileiro de Agricultura de Precisão, Piracicaba- Escola Superior de agricultura "Luiz de Queiroz", Universidade de São Paulo.

Vieira Junior, P. A., Molin, J. P., Dourado Neto, D., Manfron, P. A., Mascarin, L. S., Faulin, G. D. C., et al. (2006). Plant population and soil attributes that drives corn grain yield (População de plantas e alguns atributos do solo relacionados ao rendimento de grãos de milho). *Acta Scientiarum Agronomy, 28*, 483–492.

Zhang, N., Wang, M., & Wang, N. (2002). Precision agriculture: A worldwide overview. *Computers and Electronics in Agriculture., 36*, 113–132. doi:10.1016/S0168-1699(02)00096-0.