Planter Technology to Reduce Double-Planted Area and Improve Corn and Soybean Yields

Geomar M. Corassa,* Telmo J. C. Amado, Thomas Liska, Ajay Sharda,
John Fulton, and Ignacio A. Ciampitti*

ABSTRACT

Double-planted area (DPA) on end rows commonly occurs in corn (*Zea mays* L.) and soybean (*Glycine max* L.) fields. Economic and yield losses from DPA can be reduced by using the automatic section control (ASC) technology on planters. However, the effects of DPA on crop yield within different yield levels (yield potentials) as well as different DPA proportion within Brazilian fields are not yet quantified. Using two datasets, the objectives of this study were: dataset I- (a) quantify yield losses from DPA in corn and soybean; (b) calculate the planting area necessary to recover the investment from ASC for Brazil and U.S. farmers when considering: (i) yield loss, (ii), DPA proportion, (iii) corn/soybean ratio in the rotation, and (iv) planted area; dataset II- (c) estimate DPA proportion at a regional-scale using data from 128 Brazilian fields. The main results were: dataset I- (1) corn yield losses linearly increased due to DPA as yield level decreased; (2) soybean yields were less sensitive to DPA; (3) when only corn was considered, economic returns from using ASC was recovered with a smaller planted area; and dataset II- (4) overall DPA proportion was 5.5% of the total field area, increasing proportionally for irregular shaped fields. Use of ASC technology benefited soybeans via seed savings, while for corn, via both seed savings and superior yields. Future research focused on the ASC benefits should consider potential interactions between crop genotypes, field management, and environments.

Core Ideas

- Corn yield was more proportionally reduced for double-planted area as yield level decreased.
- Soybean yield presented similar behavior for both double-planted area and automatic section control at varying yield levels.
- ROI for the ASC technology is recovered with lower planted area when corn is the main crop.
- Overall DPA% was 5.5%, but for irregular fields double-planted area increased faster as planted area rose.

Published in Agron. J. 110:300–310 (2018)
doi:10.2134/agronj2017.07.0380
Supplemental material available online

5585 Guilford Road, Madison, WI 53711 USA

CORN AND SOYBEAN are among the most important field crops worldwide, representing in combination around 302 million hectares (FAO, 2014). In Brazil, the combined planted area for both crops is around 51 million hectares (CONAB, 2017a), while in the United States is about 72 million hectares (USDA, 2016). Double-planted area on end rows is a common problem in many corn and soybean fields. Plant densities that exceed the optimal rate to maximize yields not only increase seed costs but also can reduce yields. During the last decade, seed costs increased 126% for corn and 83% for soybean (USDA-ERS, 2017), due to the use of genetically modified seeds. Therefore, strategies to reduce DPA should produce seed cost savings while maintaining yield and economic profits for both crops.

For corn, a large proportion of modern hybrids are density dependent (Sangoi et al., 2002; Tokatlidis and Koutroubas, 2004; Fasoula and Tollenaar, 2005; Ciampitti and Vyn, 2011; 2012; Tokatlidis et al., 2011; Assefa et al., 2016). Agronomic optimum plant density can range from 40 to 100 thousand plants ha^{-1} depending on yield levels (i.e., field yield potentials) (Hörbe et al., 2013; Assefa et al., 2016). Plant densities that exceed the optimal can reduce plant growth rate and impact grain components, leading to yield reductions (Tokatlidis and Koutroubas, 2004; Ciampitti and Vyn, 2011; Assefa et al., 2016). Soybean has a compensatory ability that influences the response to plant density variation (Boquet, 1990; Carpenter and Board, 1997; Board, 2000; Norsworthy and Shipe, 2005), with yields that are not affected under a wide range of plant density (Boquet, 1990; Board, 2000; De Bruin and Pedersen, 2008; de Luca and Hungría, 2014). Thus, the use of supra-optimal plant density might result in increasing planting costs without changing yields (Board, 2000; de Luca and Hungría, 2014).

Due to high production costs, farmers are exploring new technologies to fine-tune the use of different inputs. Under

---

G.M. Corassa, Dep. of Agricultural Engineering, Federal Univ. of Santa Maria, Rural Science Center, Santa Maria, RS, Brazil; T.J.C. Amado, T. Liska, Dep. of Soil, Federal Univ. of Santa Maria, Rural Science Center, Santa Maria, RS, Brazil; A. Sharda, Dep. of Biological and Agricultural Engineering, Kansas State Univ., Manhattan, KS 66506; J. Fulton, Dep. of Food, Agricultural and Biological Engineering, Ohio State Univ., Columbus, OH 43210; I.A. Ciampitti, Dep. of Agronomy, Kansas State Univ., 2004 Throckmorton Plant Science Center, Manhattan, KS 66506. Received 11 July 2017. Accepted 4 Nov. 2017. *Corresponding authors (geomarmateus@hotmail.com; ciampitti@ksu.edu).

Abbreviations: ASC, automatic section control; DPA, double-planted area; GNE, grains number per ear; SNP, seed number per plant; TGW, thousand grain weight; TSW, thousand seed weight; ROI, return of investment.

this scenario, ASC technology can be used with different agricultural implements (Larson et al., 2016) such as sprayers and planters, by controlling sections, nozzles, and rows (Luck et al., 2010; Fulton et al., 2011; Sharda et al., 2011; Jernigan, 2012; Shockley et al., 2012a; Luck, 2013; Velandia et al., 2013; Larson et al., 2016). Several studies reported the benefits of ASC with sprayers (Batte and Ehsani, 2006; Luck et al., 2010; Larson et al., 2016), with estimates demonstrating that double application may exceed 10% of the field area (Batte and Ehsani, 2006). Otherwise, the use of ASC for sprayers could reduce overlap from 3% (regular field shape) to 13.5% (irregular field shape) (Larson et al., 2016).

Few studies are published in the scientific literature related to ASC technology for planters (Fulton et al., 2011; Velandia et al., 2013; Larson et al., 2016) with information only available for U.S. farms. From those studies, an average of 4.3% of DPA relative to the planted area was reported in Alabama (Fulton et al., 2011) and an average of 4.6% of DPA in Tennessee (Velandia et al., 2013). For Brazilian fields, research has not been published reporting the average DPA relative to the planted area and the yield response to DPA for field crops. Therefore, based on two different datasets the objectives of this study were to: dataset I (a) quantify the yield losses from DPA in corn and soybean at varying yield levels; (b) quantify the planting area necessary to recover the investment (return of investment, ROI) from ASC technology considering the following variables: (i) yield losses, (ii), DPA, (iii) corn/soybean ratio in the rotation, and (iv) planted area; and dataset II (c) measure the DPA proportion using data collected from a survey 128 Brazilian fields.

MATERIALS AND METHODS

Two datasets were utilized for this study. First, dataset I, based on field experiments, was used to quantify the effects of DPA compared to ASC on corn and soybean yields and to determine the required planted area to recover the investment on the ASC technology when used on planters. Second, dataset II represented geo-referenced planting data collected from 128 farmer fields and was used to quantify the DPA proportion in Brazilian fields.

Dataset I-Field Layout and Crop Yield Measurements

Yield data were collected from 36 corn and 18 soybean field trials during the 2015/2016 and 2016/2017 growing seasons. For corn, experimental trials were performed in 4 site-years, 3 in the state of Rio Grande do Sul (RS) and 1 in the state of Santa Catarina (SC). For soybean, 3 site-years were evaluated, 2 in the state of RS and 1 in the state of SC (Table 1). All studies were conducted using producer planters equipped with ASC technology. For all fields, soil was classified as Oxisol (Soil Survey Staff, 2014). Fields were planted using tractors equipped with global navigation satellite system (GNSS) based auto-steer with real-time differential corrections (Real Time Kinematic-RTK) provided from a reference station installed at each farm. For all site-years, except field 3 for corn (Table 1), producers utilized Evolution RTK from Stara Company (Stara, Não-Me-Toque, RS, Brazil), while for field 3 (Pejuçara/RS), a StarFire RTK from the John Deere Company (Deere & Company, Moline, IL) was used.

At each site-year, two treatments were tested from plots located within the end rows of each field with side-by-side plots: (i) ASC having no overlapped areas through individual row control, and (ii) DPA with over-planting on end rows (Fig. 1). End rows were planted first with planting paths completed with the ASC system; while for the DPA plots, the ASC was turned off (Fig. 1). At site 3 for corn (Pejuçara/RS), a John Deere planter model DB50 equipped with the RowCommand (Deere & Company, Moline, IL) and VacuMeter seed distribution system was used. The rest of the fields were planted with a Stara planter, model Princesa, equipped with Stara row-by-row

Table 1. Location, growing season, rainfall, and hybrid/cultivar data for all corn and soybean studies in southern regions of Brazil (dataset I).

Crop	Site	Location	Coordinates	Rainfall†	Growing season	Hybrid/Cultivar
				mm		
Corn	1	Não-Me-Toque/RS	28°22′48.45″ S 52°52′42.41″ W	1013	2015/2016	Agroceres 9025 PRO3‡
	2	Palmeira das Missões/RS	27°57′18.68″ S 53°29′2.33″ W	1136	2016/2017	Agroeste 1666 VTPROIII‡
	3	Pejuçara/RS	28°28′48.86″ S 53°33′32.94″ W	953	2016/2017	Pioneer 1630H§
	4	Xanxerê/SC	26°50′27.18″ S 52°30′55.41″ W	911	2016/2017	Dekalb 230 VTPROIII‡
Soybean	5	Condor/RS	28° 2′57.01″ S 53°28′35.85″ W	1249	2015/2016	Brasmax Desafio¶
	6	Condor/RS	28° 1′21.97″ S 53°29′53.67″ W	891	2016/2017	Brasmax Raio¶
	7	Xanxerê/SC	26°51′57.85″ S 52°28′20.31″ W	811	2016/2017	TMG 7062 IPRO#

† Obtained during the growing season.

‡ Trademark of Monsanto Technology LLC Monsanto Technology LLC, St. Louis, MO.

§ Trademark of DuPont, Pioneer, Johnston, Iowa.

¶ Trademark of GDM Seeds, Cambé, Paraná, Brazil.

Trademark of Tropical Melhoramento & Genética, Rondonópolis, MT, Brazil.

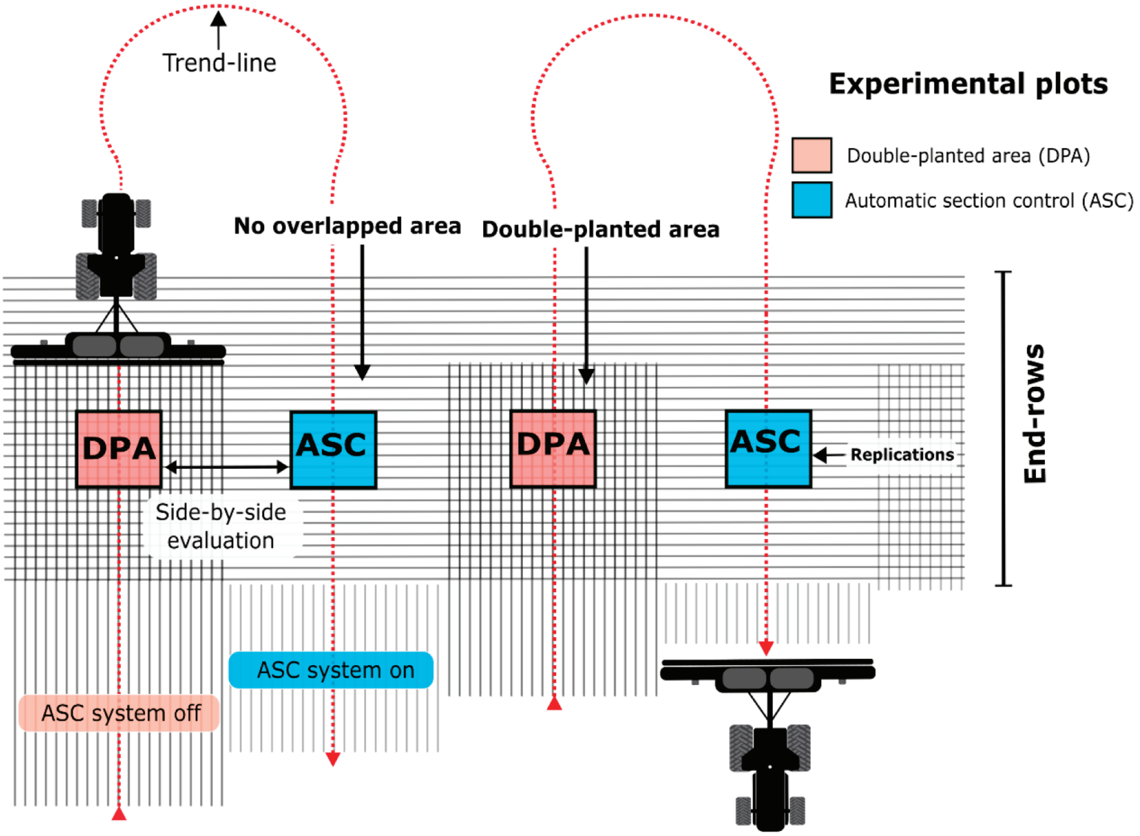

Fig. 1. Experimental plot layout and location in double-planted area (DPA) and without over-planting by utilization of automatic section control (ASC) controlled row-by-row for both corn and soybean crops during 2015/2016 and 2016/2017 growing seasons, Brazil (dataset I).

control (Stara, Não-Me-Toque, RS, Brazil) and vSet seed distribution system (Precision Planting, Tremont, IL). Passes were planted at 90° angle relative to the end rows (Fig. 1). Lastly, 6 (field 1) and 10 (fields 2, 3, and 4) planter passes were replicated for each treatment (e.g., ASC and DPA), establishing 36 side-by-side evaluations for corn, while six planter passes (Fig. 1) were replicated for soybean (field 5, 6, and 7), creating 18 side-by-side evaluations. Both ASC systems were previously row-by-row tested and calibrated to automatically turn-off 0.25 m before and turn-on 0.25 m as the planter exited the end rows. Row spacing for both crops was 0.5 m.

All primary crop management practices and hybrid/cultivar selections were made by each producer. After crop emergence, experimental plots were delineated within the end rows and based on the centerline of the planter pass (Fig. 1). Plots were 3.5-m long by 3.5-m wide for corn, and 3.0-m long by 3.0-m wide for soybean. Plant density was determined at V4 (fourth-leaf) stage for corn (Abendroth et al., 2011) and V3 (third-trifoliolate) for soybean (Fehr et al., 1971) in five central rows of the plots (Fig. 1). At the end of the season, all corn and soybean plots were manually harvested. Grain and seed moisture content were determined for each plot and adjusted to 130 g kg^{-1} for both corn and soybean, since this is the most common approach utilized in Brazil. In addition, 10 plants per plot were individually harvested to determine yield components: grain number per ear (GNE) and the thousand-grain weight (TGW, g) in corn, and the seed number per plant (SNP), total pods and pods with one, two, three, and four seeds were manually counted, and thousand-seed weight (TSW, g) in soybean.

Dataset I-Corn and Soybean Yield Losses from Double-Planted Areas

To estimate yield losses, the yield from a DPA relative to ASC ratio ($\text{Yield}_{\text{DPA}}/\text{Yield}_{\text{ASC}}$) (Mg ha^{-1}) was calculated for both corn and soybean. Based on this approach, the cumulative frequency distribution (from 0–1) of yield loss/gain was calculated. Additionally, relative yield loss (Mg ha^{-1}) related to the DPA proportion was calculated presenting four scenarios of DPA proportion: 1, 5, 10, and 15% of the field. The range of scenarios presented is in agreement with Velandia et al. (2013), reporting a range from 0.15 to close to 16% of DPA when 52 fields were evaluated in Tennessee. Farmer fields evaluated by Velandia et al. (2013) presented similar characteristics as related to the shape relative to southern Brazilian fields (Supplemental Fig. S1). For all DPA scenarios, economic losses were quantified. The yield loss was multiplied by market price for each crop: US\$0.15 kg^{-1} for corn and \$0.30 kg^{-1} for soybean, both based on current Brazilian market (CONAB, 2017b), while, the seed cost, \$307 ha^{-1} for corn and \$60 ha^{-1} for soybean (CONAB, 2017b), was calculate as a function of DPA.

Dataset I-Return of Investment from the Automatic Section Control for Planters in Corn and Soybean

A second approach was implemented to estimate the ROI (i.e., the planting area necessary to recover the investment from the ASC technology). In this approach, a change in net revenue (ΔREV) was calculated using Eq. [1] proposed by Velandia et al. (2013), as following:

$$\Delta \mathrm{REV}_j = a_j(p_j\Delta y_j + \Delta sc_j)\sum_{k=3}^{3}\omega_k\mu_k \qquad [1]$$

where ΔREV*j* is the change in net revenue ($ ha^{-1}) for crop *j* (*j* = corn, soybean or both), a_j is the planted area (ha) in crop *j*, p_j is the market price for each *j* crop ($ kg^{-1}), Δy_j is yield gain (kg ha^{-1}) due to the reduction in DPA, Δsc_j is the reduction in seed cost ($ ha^{-1}) due to reduction in the DPA, ω_k is percentage ($0 \le \omega_k \le 1$) of fields in DPA category *k* [*k* = 1 (low DPA fields, <2% of total), *k* = 2 (moderate DPA fields, 2–5% of total planted area), and *k* = 3 (high DPA fields, >5% of total planted area)], μ_k is percentage ($0 \le \mu_k \le 1$) of DPA for overlap category *k* (Velandia et al., 2013).

The Eq. [1] was used to test the scenarios for field classification categories (i.e., ω_k for each category *k*) separately. Thus, in each scenario $\omega_k = 1$ (i.e., all the fields in the same category) was considered.

Many of the fields in southern region of Brazil are often-irregular shaped (Supplemental Fig. S1); therefore, two scenarios were tested based on the DPA proportion: 5% ($\mu_k = 0.05$) and 10% ($\mu_k = 0.1$). In the former (5%) and latter scenario (10%), we considered *k* = 2 (which represents moderate DPA fields, 2–5% of total planted area) and *k = 3* (high DPA fields, >5% of planted area), respectively, as proposed by Velandia et al. (2013). The Δ*scj* (the reduction in seed cost) was based on the seed cost of $307 ha^{-1} for corn and $60 ha^{-1} for soybean, while market price for each crop (p_j in the equation) was $0.15 kg^{-1} for corn and $0.30 kg^{-1} for soybean (CONAB, 2017b). In this approach, simulations were also tested for the U.S. price scenario of seed price of $260 ha^{-1} for corn and $120 ha^{-1} for soybean, while market price was $0.11 kg^{-1} for corn and $0.31 kg^{-1} for soybean (USDA-NASS, 2017).

To represent the Δy_j (yield gain from ASC), two values of yield loss were assumed for corn and soybean. Both values were based on the empirical cumulative frequency analysis based on field experiments: (1) YL_{50} = based on yield loss from 50% (0.5) of probability and (2) YL_{20} = based on yield loss with 20% (0.2) of probability. In addition, three cropping scenarios were considered to represent the a_j (planted area) in each *j* (crop): (a) 100% of the planted area with soybean (S_{100}), (b) 50% of the planted area with soybean and 50% with corn ($\mathrm{S}_{50}\mathrm{C}_{50}$), and (c) 100% of the planted area with corn (C_{100}). These estimates were performed for a farm size ranging from 1 to 1000 ha.

To determine ROI to ASC, the economic threshold was assumed as the cost of the ASC technology for Brazil and the United States, based on information obtained from private industry. Training or maintenance costs were not considered. Planter size was assumed to be 14 rows with the total cost of ASC as $10,500 ($750 per row) in Brazil and $7000 ($500 per row) in the United States. It was assumed that other components required (GPS, auto-steer) were available at the farm and not considered in this analysis.

Dataset II-Planting Data Analysis and Estimation of Double-Planted Areas

An additional analysis was implemented utilizing the dataset II from geo-referenced farmer planting data for estimating the DPA proportion in Brazilian fields. The dataset was composed by 128 fields from the states of Mato Grosso (31 fields), São Paulo (25 fields), and Rio Grande do Sul (72 fields), totaling 5725 ha. Planting data (shapefiles) were collected using planters without the ASC technology (121 fields), but all equipped with real-time differential corrections. A monitor Topper 5500 VT (Stara, Não-Me-Toque, RS, Brazil) was used for data collection storage. At planting, the operations (path orientation, headland turns, etc.) were conducted using a normal planting plan defined by the producer. At the end rows, a sensor identified when the planters were lowered or raised, and this data was collected and saved as shapefiles. Since DPA is influenced by planter size, only fields planted with similar number of rows were selected for the analysis, usually between 12 and 16 rows, which is the most frequent planter size in this region. Data were provided by producers and customers of Stara Company (STARA, Não-Me-Toque, RS, Brazil). In addition, with the goal of eliminating coverage errors of GPS in the DPA estimation, seven fields were planted using the ASC technology for a 14-row planter. It was hypothesized that if the planting shapefiles from the ASC indicated some percentage of DPA, this overall value must be discounted from the DPA data to obtain a more precise estimation of the DPA proportion. Errors could be a result of field topography or loss of GPS signal.

Planting data were analyzed using the geo-referenced polygons shapefiles (Fig. 2), and planted area was calculated with the geometry function in QGis Software (QGIS Development Team, 2015). Area of individual polygons (including overlapped polygons) was used to calculate the total planted area. The field area was determined based on field boundary, using the outermost planter boundary. Since there is some degree of overlap during the planting procedure, the planted area will be larger than the boundary area. For each field evaluated, the DPA was determined by calculating planted area/boundary area ratio (Fig. 2).

Statistical Analysis

For dataset I, descriptive statistics such as mean, minimum, maximum, standard deviation (SD), coefficient of variation (CV), 25% percentile (1Q), and 75% percentile (3Q) were obtained for plant density, yield, and its components for both corn and soybean using R program (R Development Core

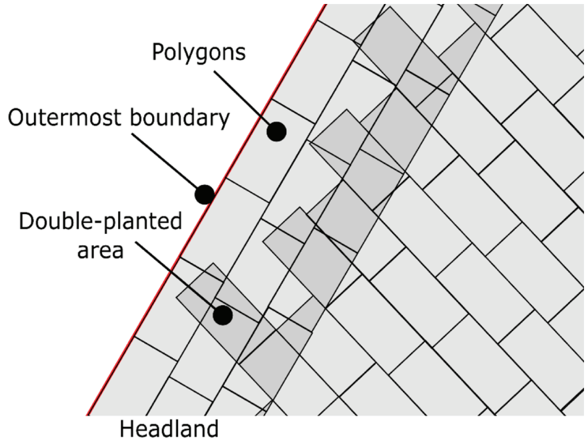

Fig. 2. Shapefile information from dataset II used to calculate the planted area (total polygons area), field area (boundary area), double-planted area (DPA) (total polygons area minus field area), and DPA proportion (total polygons area/field area ratio) in each field evaluated.

Team, 2013) (Table 2). The multi-site ANOVA of the yield and yield components (i.e., GNE and TGW in corn, and SNP and TSW in soybean) between the ASC and DPA treatments for both corn and soybean was conducted on NLME procedure (R Development Core Team, 2013) with plant density, replication and site treated as random variables. Linear regressions were used to characterize the relationship between $\text{Yield}_{\text{DPA}}$/$\text{Yield}_{\text{ASC}}$ ratio and $\text{Yield}_{\text{ASC}}$ (Fig. 3) as well as plant density$_{\text{DPA}}$/plant density$_{\text{ASC}}$ ratio and plant density$_{\text{ASC}}$ (Fig. 4) using the LME procedure (R Development Core Team, 2013). An allometric analysis (log-log scale) was conducted to compare the slopes of the plant density$_{\text{DPA}}$/plant density $_{\text{ASC}}$ ratio and plant density$_{\text{ASC}}$ association for both crops using Past program (Hammer et al., 2001). For dataset II, the DPA in southern Brazil was based on the average of the DPA proportion, calculated from 121 fields planted without the ASC (82 with soybean and 39 with corn) and seven planted with the ASC technology (four with soybean and three with corn). Linear models between planted area (ha) and DPA (ha and %) were also tested using the R program.

RESULTS

For corn, plant density was 78% greater in the DPA relative to the ASC treatment (Table 2). Similarly, soybean had 71% more plants in the DPA relative to the ASC treatment. However, greater plant density for soybean did not change the yield (Table 2). For corn, the overall yield loss for the DPA treatment was 1.3 Mg ha^{-1}, or 8.5% lower ($p < 0.001$) than the

Table 2. Summary statistics of plant density (PD), yield, and yield components for the automatic section control (ASC) and double planted area (DPA) for both corn and soybean during 2015/2016 and 2016/2017 growing seasons (dataset I).

Crop	Treatment†	Parameter‡	Mean		Min.	Max.	SD§	CV	1Q	3Q
Corn	ASC	PD ha^{-1} (× 1000)	84	***	71	93	6.5	8.0	79	89
		Yield, Mg ha^{-1}	15.4	***	9.4	19.7	3.2	21.0	12.9	18.4
		Grains ear^{-1}	531	***	309	726	111	20.9	431	631
		TGW, g	395	*	294	461	47.3	11.9	372	431
	DPA	PD ha^{-1} (× 1000)	149		117	163	12	8.0	144	156
		Yield, Mg ha^{-1}	14.1		6.8	19.3	3.7	25.9	11.4	17.7
		Grains ear $^{-1}$	344		163	544	96	27.9	284	423
		TGW, g	342		267	462	40	11.9	314	375
Soybean	ASC	PD ha^{-1} (× 1000)	268	***	207	311	31	12.0	237	289
		Yield, Mg ha^{-1}	4.9	ns¶	4.0	6.3	0.8	15.7	4.2	5.6
		Seeds plant^{-1}	160	***	117	216	31	20.0	134	187
		TSW, g	203	ns	167	241	24	12.0	181	225
	DPA	PD ha^{-1} (× 1000)	460		400	533	45	10.0	415	494
		Yield, Mg ha^{-1}	4.8		3.9	6.6	0.8	16.3	4.2	5.2
		Seeds plant^{-1}	101		75	155	20	20	85	108
		TSW, g	204		175	240	23.7	11.6	182	228

* Significant by *t* test between ASC and DPA for each crop at the 5% level.

*** Significant by *t* test between ASC and DPA for each crop at the 0.1% level.

† ASC = Automatic section control; DPA = Double-planted area.

‡ TGW = Thousand grain weight; TSW = Thousand seed weight.

§ SD = Standard deviation; CV = Coefficient of variation; 1Q = 1th quartile; 3Q = 3th quartile; Min. = minimum; Max. = maximum.

¶ ns, not significant.

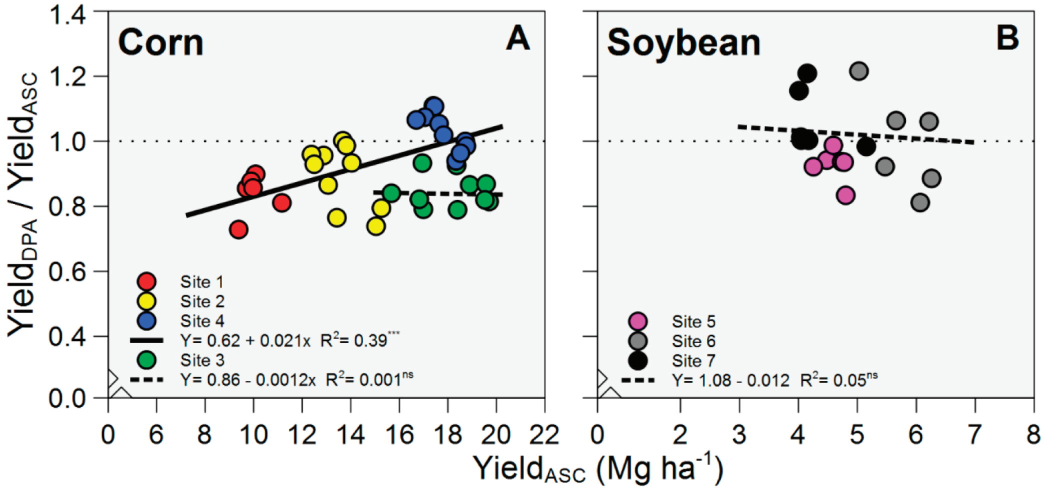

Fig. 3. Relationship between relative yield ($\text{Yield}_{\text{DPA}}$/$\text{Yield}_{\text{ASC}}$) calculated as the $\text{Yield}_{\text{DPA}}$/$\text{Yield}_{\text{ASC}}$ ratio, and the $\text{Yield}_{\text{ASC}}$ for (A) corn and (B) soybean crops. Each observation represents a side-by-side yield evaluation for corn (36 total, four sites) and for soybean (18 total, three sites). Relative $\text{Yield}_{\text{DPA}}$/$\text{Yield}_{\text{ASC}}$ below one indicates that DPA were lower than yields for the ASC treatment.

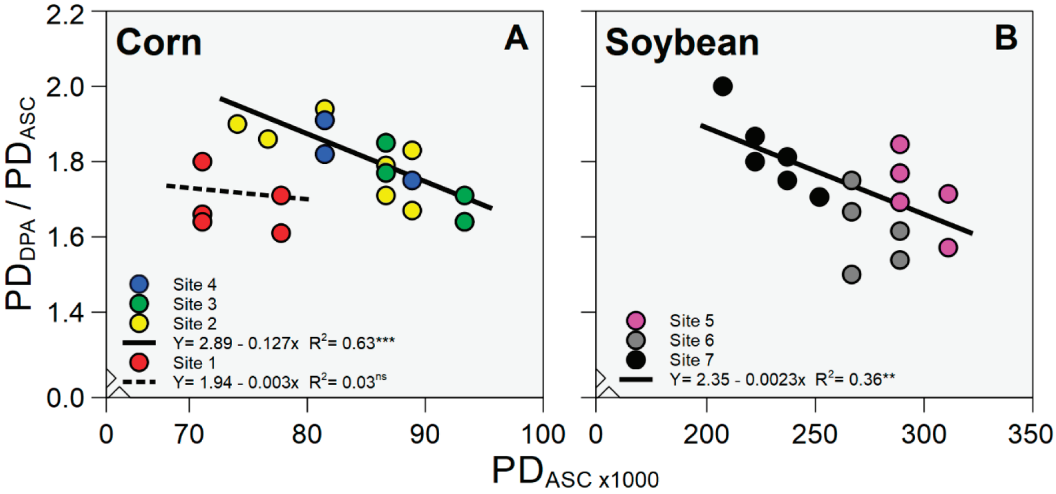

Fig. 4. Relationship between relative plant density calculated as the plant density$_{DPA}$/plant density$_{ASC}$ ratio (PD_{DPA}/PD_{ASC}), and the plant density$_{ASC}$ for (A) corn and (B) soybean crops. Each observation represents a side-by-side yield evaluation for corn (36 total, four sites) and for soybean (18 total, three sites). Relative plant density$_{DPA}$/ plant density$_{ASC}$ above one indicates that DPA were higher than plant density for the ASC treatment.

yields in the ASC areas; while for soybean, mean yield loss for the DPA was 2%, or 0.1 Mg ha^{-1} lower ($p = 0.70$) relative to the yields in the ASC areas (Table 2).

Corn and Soybean Yield Response to Automatic Section Control and Double-Planted Areas

Yield results for the DPA was calculated as a ratio between Yield$_{DPA}$ to Yield$_{ASC}$ across all corn (sites 1, 2, 3, and 4) and soybean (sites 5, 6, and 7) fields. To estimate yield losses at varying yield levels, the relationship between relative yield (Yield$_{DPA}$/Yield$_{ASC}$) and the Yield$_{ASC}$ was calculated (Fig. 3). A linear model fit ($R^2 = 0.39, p < 0.001$) was adjusted between the Yield$_{DPA}$/Yield$_{ASC}$ to Yield$_{ASC}$ for sites 1, 2, and 4, presenting an overall negative yield for the DPA treatment as the yield level was reduced (Fig. 3A). In 81% of the side-by-side evaluations ($n = 29$), lower yields were obtained for the DPA relative to the ASC treatment for corn. At site 3, the ratio between Yield$_{DPA}$ to Yield$_{ASC}$ was flat (and not-significant) for the yield range investigated (from 14 to 20 Mg ha^{-1}) and a model was not adjusted. The latter could be partially explained as a result of planting a less density-dependent hybrid for this site (Fig. 3A).

Relative yield (Yield$_{DPA}$/Yield$_{ASC}$) above one, representing yields for DPA greater than for the ASC areas-were obtained at site 4 ($n = 6$) (Fig. 3A). This site also showed the greatest overall yield across sites (Fig. 3A). It is worth noticing that this is a high-yielding level (18 Mg ha^{-1}), which is not common for southern Brazil region. Frequent yields for this growing area are usually below 12 Mg ha^{-1}. For corn sites 1 and 2, Yield$_{DPA}$ were 16 and 11% lower, respectively, than the Yield$_{ASC}$ (Table 2). Yields above 14 Mg ha^{-1} (site 3) presented an overall corn yield loss of 15% or 2.8 Mg ha^{-1} (Fig. 3A). In summary, except for site 4, corn sites showed an overall yield reduction of 14% for the DPA relative to the ASC areas. The maximum yield penalty for the DPA to the ASC was 27%, documented in one of the lowest yielding level (<10 Mg ha^{-1}) (Fig. 3A).

Regression models did differ when corn and soybeans were compared for the Yield$_{DPA}$/Yield$_{ASC}$ ratio and the Yield$_{ASC}$ (Fig. 3A, 3B). For soybean, the response model was flat, with 45% of the side-by-side evaluations ($n = 8$) showing superior yields for DPA, but with the opposite trend in 55% of the cases ($n = 10$) (Fig. 3B). In summary, the Yield$_{DPA}$/Yield$_{ASC}$ ratios were not related for soybean yields; while for corn, Yield$_{DPA}$/Yield$_{ASC}$ ratio increase with higher yields (Fig. 3).

The final plant density for each treatment was recorded and the difference between the plant density in the DPA and the ASC treatment was calculated (plant density$_{DPA}$/plant density$_{ASC}$ ratio). For corn, the majority of the DPA treatments had 60% more plants relative to the ASC areas (Fig. 4A). For sites 2, 3, and 4, a negative trend in plant density$_{DPA}$/plant density$_{ASC}$ ratio was documented from 2 to 1.6 units ($R^2 = 0.63, p < 0.001$) when plant density increased from 70 to more than 90 thousand plants ha^{-1} (Fig. 4A). This trend reflects a superior double-planted number at lower plant density. For site 1 (Table 1), the plant density$_{DPA}$/plant density$_{ASC}$ ratio did not correlate with plant density$_{ASC}$ (Fig. 4A). For soybean, a negative trend was common for all the sites (sites 5, 6, and 7) (Fig. 4B), with lower plant density$_{DPA}$/plant density$_{ASC}$ ratio as plant density$_{ASC}$ increased ($R^2 = 0.36, p < 0.01$). Using a log-log analysis, slopes of linear models for corn (sites 2, 3, and 4) and soybean (sites 5, 6, and 7) were tested, presenting comparable ($p = 0.11$) reductions of plant density$_{DPA}$ to plant density$_{ASC}$ as the plant density$_{ASC}$ increased (Fig. 4).

Dissecting Corn and Soybean Yield Components

To understand the effect of the DPA on yield, an analysis at plant scale was done to measure how the main yield components affected yield responses. For corn, both GNE and TGW decreased as the plant density increased for the DPA treatment. A yield distribution for GNE shows a 54% yield reduction for the DPA compared to the ASC treatment (Fig. 5A). The median (50%IQR) showed that GNE ranged from 431 to 631 for the ASC and from 284 to 423 for the DPA (Table 2; Fig. 5A). For the TGW, overall value was 16% greater for the ASC relative to the DPA; the 50%IQR ranged from 372 to 431 g for the ASC technology and from 314 to 375 g for the DPA treatment (Table 2, Fig. 5B).

For soybean, yields were not affected by DPA likely due to compensation between the SNP and number of plants per unit area (Table 2). Mean SNP was reduced by 60% while plant density increased by 71% for the DPA treatment relative to the ASC (Table 2, Fig. 5C), but in overall TSW was not affected (Table 2, Fig. 5D). In summary, greatest yield response was documented for corn relative to soybean for the ASC system.

Yield and Economic Loss to Double-Planted Areas

Based on the cumulative frequency analysis, a probability of yield loss from DPA was estimated as 81% for corn and 59% for soybean (Fig. 6). In addition, the absolute yield value at which the yield loss probability was zero occurred at 15.4 Mg ha^{-1} for corn and at 4.9 Mg ha^{-1} for soybean. For corn, yield loss in 20% of the cases (YL_{20}) portrayed economic losses of $60, 30, 15, and 5 ha^{-1} for 15, 10, 5, and 1% for the DPA scenarios, respectively (Fig. 6A). At the same cumulative yield frequency level (e.g., 20%), soybean presented economic losses of $18, 10, 5, and 2 ha^{-1} for 15, 10, 5, and 1% for the DPA scenarios, respectively (Fig. 6B). Considering the seed cost, economic losses ($ ha^{-1}) reached 95 and 98% of cumulative frequency in corn for 5 and 10% DPA scenario, respectively (Fig. 6A). Economic losses were three times greater in corn than soybean (Fig. 6).

Considering yield losses in 50% of the cases (YL_{50}), a larger planted area is required to reach the economic threshold when only soybean is the planted crop (S_{100}) (Fig. 7A, 7D). For the S_{100} scenario, the United States presented superior ROI than Brazil (due to higher seed cost in the United States than Brazil), recovering this investment with 700 ha at 10% of DPA (Fig. 7A, 7D). In a farm with 50% of the area planted with corn and 50% with soybean ($S_{50}C_{50}$), around 670 ha are required with 10% of DPA to fully recovered the cost of the ASC technology in Brazil and 540 ha in the United States (Fig. 7B, 7E). On the other hand, when corn is the main crop (C_{100}), in a scenario of 5 and 10% of DPA close to 880 and 440 ha, respectively, will be required to pay the technology in Brazil and 830 and 420 in the United States (Fig. 7C, 7F). In synthesis, for scenario of YL_{20}, ASC could be covered in 350, 250, and

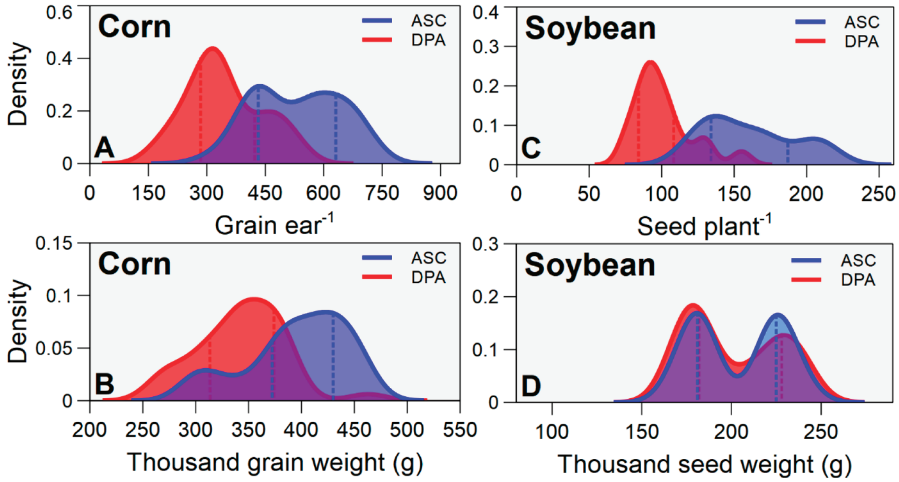

Fig. 5. Kernel density of (A) grains per ear and (B) thousand grain weight for corn, and (C) final seed number per plant and (D) thousand seed weight for the automatic section control (ASC) and double-planted area (DPA) treatments. Dotted lines represent 25 and 75% of interquartile, respectively.

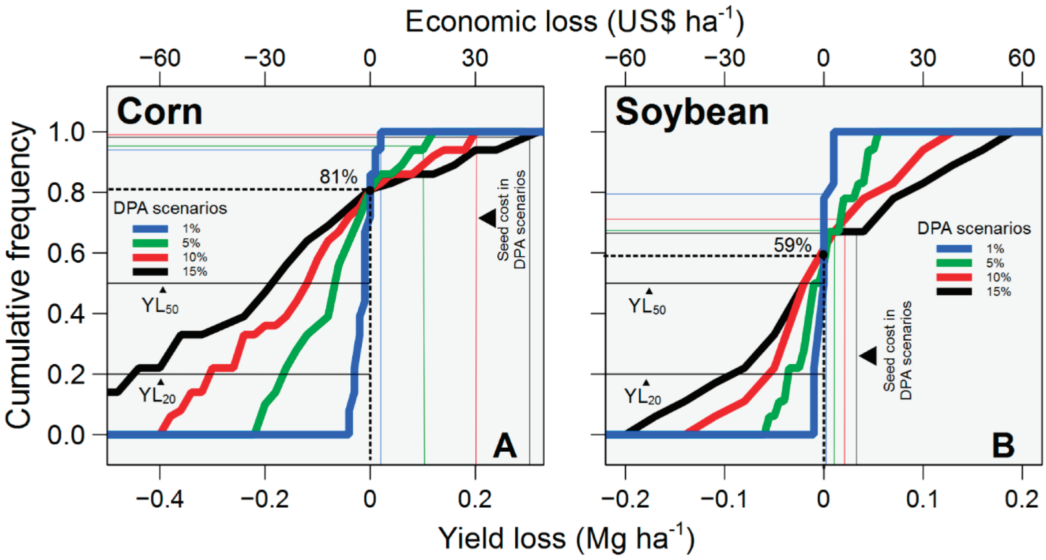

Fig. 6. Cumulative frequency distribution of yield and economic loss for double-planted area (DPA) minus automatic section control (ASC) technology ($Yield_{DPA} – Yield_{ASC}$) for (A) corn and (B) soybean considering the scenarios of 1, 5, 10 and 15% of DPA. Results based on data from 36 side-by-side evaluations in corn and 18 in soybean. YL_{50} and YL_{20} represent the yield loss with 50 and 20% of probability, respectively.

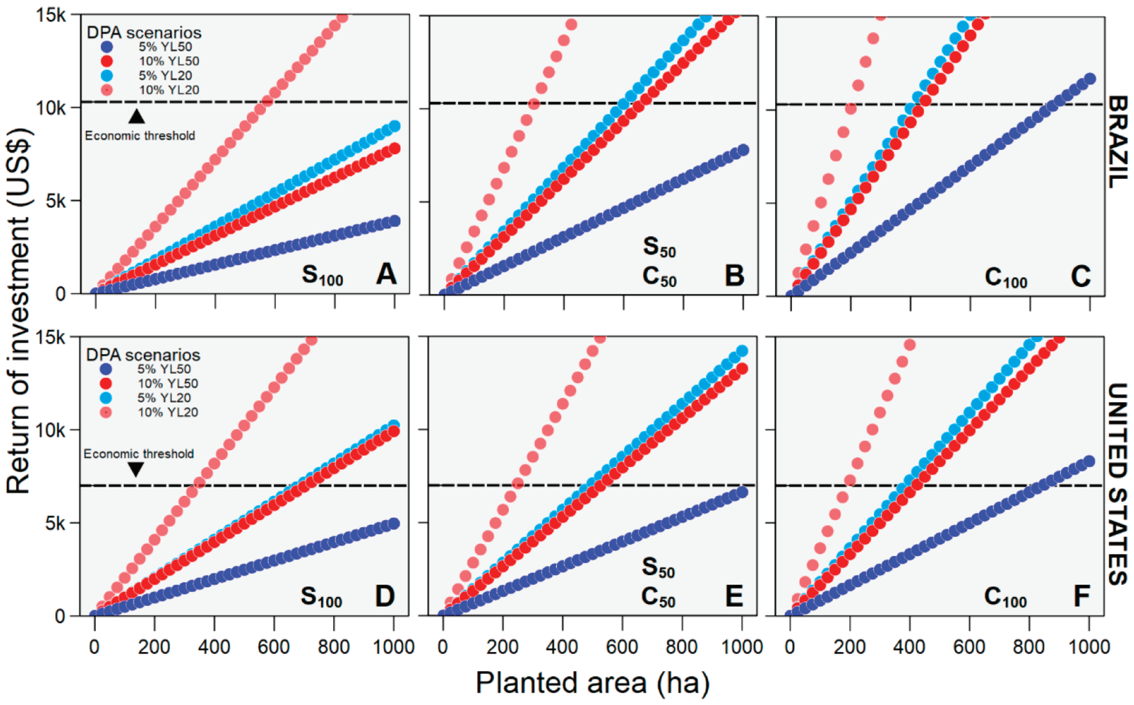

Fig. 7. Return of investment (ROI) relative to planted area (ha) to recover the cost of the automatic section control (ASC) technology considering the following farming scenarios: (S_{100}) 100% of the area planted with soybean, ($S_{50}C_{50}$) 50% with soybean and 50% with corn and (C_{100}) 100% of the area with corn, and two proportion of double-planted area (DPA) scenarios: 5 and 10%. DPA scenarios were tested considering yield losses from 50% of cumulative frequency (YL_{50}) (dark colors) and 20% of cumulative frequency (YL_{20}) (light colors), as previously documented in the Fig. 6. A, B, and C are the scenarios S_{100}, $S_{50}C_{50}$, and C_{100} for Brazil, respectively, while D, E, and F are the scenarios S_{100}, $S_{50}C_{50}$ and C_{100} for the United States, respectively. The ASC technology cost was considered to be US\$10,500 for Brazil and 7,000 for the United States as the economic threshold based on the price of the technology for a 14-row planter in the current market.

190 ha with 10% of the DPA at S_{100}, $C_{50}S_{50}$, and C_{100}, respectively, for the United States (Fig. 7D, 7E, 7F); while for Brazil those values were 570, 300, and 205 ha (Fig. 7A, 7B, 7C).

DISCUSSION

Corn and Soybean Yields and Response to Double-Planted Areas

This study provides a new insight about the ASC technology on planters, and suggests an opportunity to fine-tune optimum plant density for improving yields and reducing operational costs. Field research studies revealed that the DPA resulted in higher yield reduction in corn than in soybean. The latter observation could be due to greater effect of plant density on corn yield (Assefa et al., 2016). Genotypic characteristics could also play a role in corn hybrids that are density dependent (Tokatlidis et al., 2005, 2011). Plant density above the agronomic optimum level, similar as to the DPA treatment, caused yield reduction as previously documented by several studies (Sangoi et al., 2002; Hörbe et al., 2013; Assefa et al., 2016). Overall, yield loss increased when over-planted at low yielding levels with hybrids presenting a lower optimum than plant density relative to the high-yielding levels (Tokatlidis and Koutroubas, 2004; Hörbe et al., 2013; Assefa et al., 2016).

Similarly, to the main outcomes summarized in a recent synthesis analysis by Assefa et al. (2016), the response to DPA showed a trend related to yield levels (Fig. 3A). Yield increase for DPA at a high-yielding level was related to a specific hybrid response, with a more density-dependent hybrid (e.g., DKB230 hybrid with lower penalty in ear size). The higher yield penalty for site 3 compared to site 4 was likely due to hybrid response, with Pioneer 1630H less density-dependent hybrid as reported by Mendes et al. (2013). Final ear size is related to potential GNE, and these yield components are main factors for increasing yield potential (Ciampitti and Vyn, 2012; Egli, 2015; Assefa et al., 2016). Yield decrease in the DPA treatment was primarily explained by reductions in both GNE and TGW, connected to the level of intraspecific competition exacerbated in resource-limited environments (Maddonni and Otegui, 2004; Pagano and Maddonni, 2007). Thus, utilization of the ASC systems could pay at a faster pace under lower yielding levels due to both benefits in yield gain and seed savings. Similar is true for more rain-limited environments, the high plant-to-plant competition in those resource-limited environments resulted in superior yield reduction as related to high-yielding levels (Hörbe et al., 2013; Assefa et al., 2016).

Soybean compensatory ability influences the response to plant density, with small or no response to plant density changes documented from a wide range of seeding rates, from 80 to 900 thousand seeds ha^{-1} (Lehman and Lambert, 1960; Reiss and Sherwood, 1965; Costa et al., 1980; Beuerlein, 1988; Ablett et al., 1991; Adams and Weaver, 1998; Board, 2000; Kratochvil et al., 2004; Conley et al., 2008; De Bruin and Pedersen, 2008; Epler and Staggenborg, 2008; de Luca and Hungría, 2014). Following this rationale, the low probability of yield loss ("flat trend") was predicted even when evaluated at different yield levels (4–6 Mg ha^{-1}). Similarly, in Brazil Ferreira et al. (2016) recently documented the lack of yield response to plant density, with changes in yield response when plant density was lower than 235 thousand plants ha^{-1} and below 3.5 Mg ha^{-1}. For the United States (Kansas), positive yield responses to plant density were documented when plant density was below 200 thousand plants ha^{-1} (Epler and Staggenborg, 2008). In summary, the lack of yield response to DPA in soybean can be explained by the narrow yield variation and plant density range (ranging from 200,000–300,000 plants ha^{-1}) explored (Fig. 3B, 4B); although, the plant density range evaluated is the most used by both Brazilian and American farmers.

As related to ASC technology, economic benefit for soybean production is primarily related to improved profits via seed savings. Thereby, no or small potential for yield gain using ASC system is expected for soybean production which aligns with findings by Velandia et al. (2013). This research study supports this statement by understanding the modifications in SNP and TSW–with similar TSW but counterbalancing the reduction in SNP by the number of plants in the DPA areas (Fig. 5C, 5D). Several researchers reported that the main compensation mechanism in soybean plants was related to the number of pods and seeds per plant (Lehman and Lambert, 1960; Weber et al., 1966; Board et al., 1990; Boquet, 1990; Ball et al., 2000; Norsworthy and Shipe, 2005). At low plant densities, more dry mass is partitioned to branches, improving number of pods per plant (Kasperbauer, 1987; Carpenter and Board, 1997; Board, 2000). This response is activated by red/far red light ratios within the canopy during early stages, with higher ratio inducing dry mass partitioning to branches (Kasperbauer, 1987; Carpenter and Board, 1997; Board, 2000). Thus, at low plant density, more seeds per plant compensate for fewer plants, with the opposite occurring at high plant density, resulting in similar yields in both cases.

In summary, for corn, the percentage of yield loss for DPA should be evaluated under various yield levels; while for soybean, a zero-yield loss could be assumed if yields are ranging from 4 to 6 Mg ha^{-1} and plant density ranging from 200,000 to 300,000 plants ha^{-1}. For corn, yield losses in DPA can be assumed to be 15% with yields below 10 Mg ha^{-1}, 10% below 13 Mg ha^{-1}, 5% below 16 Mg ha^{-1} and 0% above 16 Mg ha^{-1} for density-dependent hybrids. Based on similar corn yield response to plant density recently reported by Schwalbert et al. (2018) between the United States and Brazil, comparable yield losses for DPA should be expected to occur in the United States.

Table 3. Summary of parameters evaluated using planting geo-referenced shapefiles from dataset II to calculate the planted area, field area, and double-planted area (DPA) in absolute (ha) and relative terms (%) for 128 fields in Brazil.

	Traditional system†			ASC technology‡		
Field characteristics	Min.§	Mean	Max.	Min.	Mean	Max.
Area, ha	2.2	46.8	228	4.0	23.7	50.9
Planted area, ha	2.3	49.5	235	4.0	23.9	51.2
DPA, ha	0.2	2.7	15.8	0.03	0.2	0.4
DPA proportion, %	1.8	6.3	18.0	0.2	0.8	1.1

† Based on 121 fields evaluated.

‡ Based on seven reference fields planted with automatic section control (ASC) (row-by-row) in the planter.

§ Min. = minimum; Max. = maximum.

Economic Analysis from Automatic Section Control Technology for Planters

Savings were related to the seed cost and yield gain for corn, but only related to seed cost for soybean (Fig. 6). Field size and shape were also identified as main factors affecting ASC, with smaller field size and more irregular shapes presenting more benefits for the use of this technology (Luck et al., 2010; Shockley et al., 2012b; Velandia et al., 2013; Larson et al., 2016). The survey of 128 fields in Brazil (dataset II) showed an average DPA of 5.5% (6.3% from traditional systems minus 0.8% from ASC technology) (Table 3). This DPA value is greater than those reported for Alabama and Tennessee, with overall average ranging from 4.3 to 4.6% (Fulton et al., 2011; Velandia et al., 2013).

After dividing the 121 fields (with DPA) in two categories, regular [perimeter (m)/area (ha), P/A ratio < 0.02] and irregular [P/A ratio ≥ 0.02], representing low/moderate (regular) to high (irregular) DPA, respectively (Velandia et al., 2013), only 15% of all fields were classified as "regular" (P/A ratio < 0.02), while 85% presented P/A ratio ≥ 0.02, then classified as irregular (Fig. 8). The latter might help to explain the greater DPA

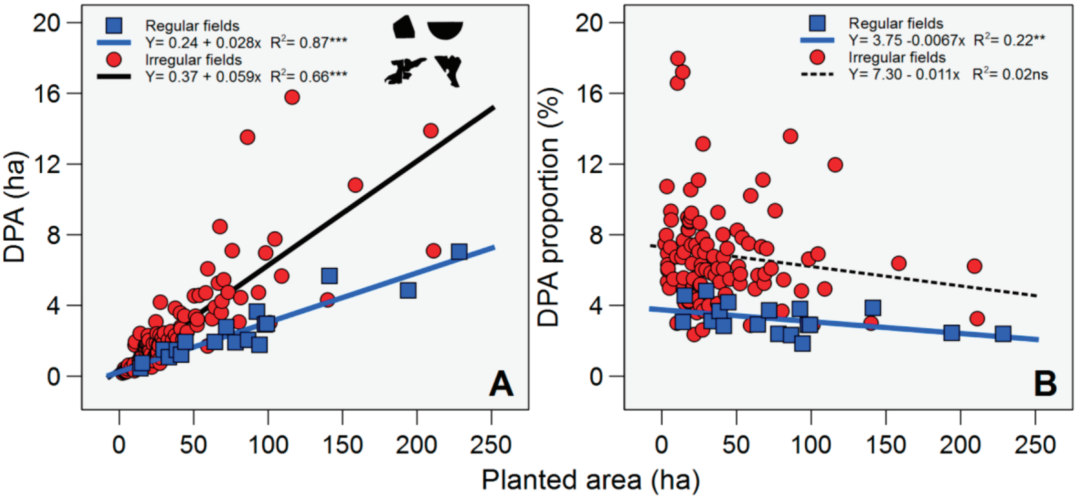

Fig. 8. (A) Relationship between planted area (ha) and double-planted area (DPA, ha) for regular (*n* = 18) and irregular (*n* = 103) fields; and (B) between planted area (ha) and DPA proportion for regular and irregular fields. The perimeter/area ratio (P/A ratio) was used to classify the fields (Luck et al., 2013). We considered as regular fields with P/A <0.02 and irregular when P/A ≥0.02. Examples of regular and irregular fields are shown in the top of A, after their respective legends.

value reported in this study relative to the aforementioned U.S. studies (Fulton et al., 2011; Velandia et al., 2013). Irregular fields presented more than two-fold greater DPA (6.8%) than regular ones (3.2%). In addition, when the planted area (ha) increased, irregular fields presented a more than proportional ($p < 0.001$) increase of the DPA (slope = $0.059X$) compared with regular fields (slope = $0.028X$) (Fig. 8A). Furthermore, in regular fields the proportion of the DPA is reduced with the increase of the field area ($R^2 = 0.22, p < 0.05$), while for the irregular fields a model was not adjusted–without presenting a clear trend (Fig. 8B). In agreement with the previous studies, field shape and size largely influenced DPA areas (Batte and Ehsani, 2006; Luck et al., 2010; Fulton et al., 2011; Sharda et al., 2012; Velandia et al., 2013; Larson et al., 2016), reinforcing the benefits of the ASC for planters for the southern Brazil region.

Overall, the findings from this study support the adoption of ASC technology for planters. These outcomes highlight the benefits of using this technology, in agreement with previously published studies (Fulton et al., 2011; Jernigan, 2012; Shockley et al., 2012b; Smith et al., 2013; Velandia et al., 2013). For a corn–soybean rotation, economic benefits considering seed savings and/or avoiding yield losses in the headland areas due to DPA should be considered in the decision-making process. Finally, these results reinforce that considering an actual farm scenario (planted area, DPA, and crop), the number of years to pay for ASC is relatively short. Currently, the ASC is becoming a standard technology for new planters worldwide, with the projected cost decreasing as the adoption rate is increasing.

CONCLUSIONS

The use of ASC for planters increased profitability in both crops, by both seed savings and higher yields for corn and primarily by seed savings for soybean. The main results were: dataset I- (1) corn yield losses linearly increased for the DPA as yield level decreased, with yield losses primarily related to reduction in GNE than the TGW component; (2) soybean yields were less sensitive to DPA due to a similar number of seeds per unit area and TSW; (3) when only corn was considered, economic return for the ASC was recovered with a smaller planted area; and dataset II- (4) the average DPA proportion within fields was 5.5% of the total area; it increased linearly as planted area raised and for irregular field shapes, increasing the savings for ASC on planters.

Future research should be conducted with different crops under diverse crop rotations to quantify the overall benefits at the cropping system level, potentially improving farming profitability while reducing the technology cost.

ACKNOWLEDGMENTS

The authors wish to thank to CNPq (process nos. 140508/2015-5, 140275/2016-9, and 141144/2017-3), CAPES (process no. 88881.132762/2016-01) and Aquarius project for funding this research. Thanks to Stara company for providing planters and other equipment/tools essentials for this research as well as to Willian Lima and Willian Wagner for collaboration and technical support. Additional thanks to Sementes Van Ass, Alan Cherobin, Lucas Macagnan, Diones Carmo Jr., and Fernando Trennepohl producers to lend the fields and for all technical support. This is contribution no. 18-008-J from the Kansas Agricultural Experiment Station.

SUPPLEMENTAL MATERIAL

Fig. S1. Google earth aerial image from fields in the county of Não-Me-Toque, state of Rio Grande do Sul, Brazil. The image shown the frequency of irregular fields and represents the main field scenario in the southern Brazil region.

REFERENCES

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. PMR 1009. Iowa State Univ. Ext., Ames.

Ablett, G.R., W.D. Beversdorf, and V.A. Dirks. 1991. Row width and seeding rate performance of indeterminate, semideterminate, and determinate soybean. J. Prod. Agric. 4:391–395. doi:10.2134/jpa1991.0391

Adams, P.D., and D.B. Weaver. 1998. Brachytic stem trait, row spacing, and plant population effects on soybean yield. Crop Sci. 38:750–755. doi:10.2135/cropsci1998.0011183X003800030022x

Assefa, Y., P.V. Vara Prasad, P. Carter, M. Hinds, G. Bhalla, R. Schon et al. 2016. Yield responses to planting density for US modern corn hybrids: A synthesis-analysis. Crop Sci. 56:2802–2817. doi:10.2135/cropsci2016.04.0215

Ball, R.A., L.C. Purcell, and E.D. Vories. 2000. Optimizing soybean plant population for a short-season production system in the southern USA. Crop Sci. 40:757–764. doi:10.2135/cropsci2000.403757x

Batte, M.T., and M.R. Ehsani. 2006. The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. Comput. Electron. Agric. 53:28–44. doi:10.1016/j.compag.2006.03.004

Beuerlein, J.E. 1988. Yield of indeterminate and determinate semidwarf soybean for several planting dates, row spacings, and seeding rates. J. Prod. Agric. 1:300–303. doi:10.2134/jpa1988.0300

Board, J. 2000. Light interception efficiency and light quality affect yield compensation of soybean at low plant populations. Crop Sci. 40:1285–1294. doi:10.2135/cropsci2000.4051285x

Board, J.E., B.G. Harville, and A.M. Saxton. 1990. Narrow-row seed-yield enhancement in determinate soybean. Agron. J. 82(1):64–68. doi:10.2134/agronj1990.00021962008200010014x

Boquet, D.J. 1990. Plant population density and row spacing effects on soybean at post-optimal planting dates. Agron. J. 82:59–64. doi:10.2134/agronj1990.00021962008200010013x

Carpenter, A.C., and J.E. Board. 1997. Branch yield components controlling soybean yield stability across plant populations. Crop Sci. 37:885–891. doi:10.2135/cropsci1997.0011183X003700030031x

Ciampitti, I.A., and T.J. Vyn. 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crop. Res. 121:2–18. doi:10.1016/j.fcr.2010.10.009

Ciampitti, I.A., and T.J. Vyn. 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crop. Res. 133:48–67. doi:10.1016/j.fcr.2012.03.008

CONAB. 2017a. Acompanhamento da safra brasileira de grãos (Nono levantamento- junho 2017). Monit. Agrícola 4: 161. Companhia Nacional de Abastecimento/Ministério da Agric., Pecuária e Abastecimento. http://www.conab.gov.br/OlalaCMS/uploads/arquivos/17_06_08_09_02_48_boletim_graos_junho_2017.pdf (accessed 15 June 2017).

CONAB. 2017b. Preços Agropecuários- preços médio semanais. Milho. Companhia Nacional de Abastecimento/Ministério da Agric., Pecuária e Abastecimento. http://sisdep.conab.gov.br/precosiagroweb/ (accessed 4 Apr. 2017).

Conley, S.P., L. Abendroth, R. Elmore, E.P. Christmas, and M. Zarnstorff. 2008. Soybean seed yield and composition response to stand reduction at vegetative and reproductive stages. Agron. J. 100(6):1666–1669. doi:10.2134/agronj2008.0082

Costa, J.A., E.S. Oplinger, and J.W. Pendleton. 1980. Response of soybean cultivars to planting patterns. Agron. J. 72:153–156. doi:10.2134/agronj1980.00021962007200010029x

De Bruin, J.L., and P. Pedersen. 2008. Soybean seed yield response to planting date and seeding rate in the upper Midwest. Agron. J. 100:696–703. doi:10.2134/agronj2007.0115

de Luca, M.J., and M. Hungría. 2014. Plant densities and modulation of symbiotic nitrogen fixation in soybean. Sci. Agric. 71:181–187. doi:10.1590/S0103-90162014000300002

Egli, D.B. 2015. Is there a role for sink size in understanding maize population-yield relationships? Crop Sci. 55:2453–2462. doi:10.2135/cropsci2015.04.0227

Epler, M., and S. Staggenborg. 2008. Soybean yield and yield component response to plant density in narrow row systems. www.plantmanagementnetwork.org/cm/. Crop Manage. p. 1–13.

FAO. 2014. FAO Statistics. FAO. United Nations. http://www.fao.org/faostat/en/#data/QC (accessed 15 June 2017).

Fasoula, V.A., and M. Tollenaar. 2005. The impact of plant population density on crop yield and response to selection in maize. Maydica 50:39–48.

Fehr, W.R., E.C. Caviness, D.T. Burmood, and J.S. Pennington. 1971. Stage of development descriptions for soybeans, *Glycine max* (L.). Merrill. Crop Sci. 11:929–931. doi:10.2135/cropsci1971.0011183X001100060051x

Ferreira, A.S., A. Antonio, B. Junior, F. Werner, C. Zucareli, J.C. Franchini, and H. Debiasi. 2016. Plant density and mineral nitrogen fertilization influencing yield, yield components and concentration of oil and protein in soybean grains. Bragantia 75:362–370. doi:10.1590/1678-4499.479

Fulton, J., D. Mullenix, B. Brooke, A. Winstead, and B. Ortiz. 2011. Automatic section control (ASC) technology for planters. Precis. Agric. Ser. Timely Info. September: p. 1–4.

Hammer, O., D.A.T. Harper, and P.D. Ryan. 2001. PAST: Paleontological statistics software package for education and data analysis. Palaeontol. Electronica 4:1–9.

Hörbe, T.A.N., T.J.C. Amado, A.O. Ferreira, and P.J. Alba. 2013. Optimization of corn plant population according to management zones in Southern Brazil. Precis. Agric. 14:450–465. doi:10.1007/s11119-013-9308-7

Jernigan, B.M. 2012. Defining and modeling parameters associated with double-planted areas in row crop production fields. Master's thesis. Univ. of Tennessee, Knoxville.

Kasperbauer, M.J. 1987. Far-red light reflection from green leaves and effects on phytochrome-mediated assimilate partitioning under field conditions. Plant Physiol. 85:350–354. doi:10.1104/pp.85.2.350

Kratochvil, R.J., J.T. Pearce, and M.R. Harrison. 2004. Row-spacing and seeding rate effects on glyphosate-resistant soybean for Mid-Atlantic production systems. Agron. J. 96:1029–1038. doi:10.2134/agronj2004.1029

Larson, J.A., M.M. Velandia, M.J. Buschermohle, and S.M. Westlund. 2016. Effect of field geometry on profitability of automatic section control for chemical application equipment. Precis. Agric. 17(1):18–35. doi:10.1007/s11119-015-9404-y

Lehman, W.F., and J.W. Lambert. 1960. Effects of spacing of soybean plants between and within rows on yield and its components. Agron. J. 52:84–86. doi:10.2134/agronj1960.00021962005200020008x

Luck, J.D. 2013. Agricultural sprayer automatic section control (ASC) systems. Univ. of Nebraska–Lincoln Ext. p. 1–6.

Luck, J.D., S. Pitla, S.A. Shearer, T. Mueller, C. Dillon, J. Fulton, and S.F. Higgins. 2010. Potential for pesticide and nutrient savings via map-based automatic boom section control of spray nozzles. Comput. Electron. Agric. 70:19–26. doi:10.1016/j.compag.2009.08.003

Maddonni, G.A., and M.E. Otegui. 2004. Intra-specific competition in maize: Early establishment of hierarchies among plants affects final kernel set. Field Crop. Res. 85:1–13. doi:10.1016/S0378-4290(03)00104-7

Mendes, M.C., P.H. Matchula, E.S. Rossi, B.R. de Oliveira, C.A. da Silva, and C.R. Sékula. 2013. Adubação nitrogenada em cobertura associada com densidades populacionais de híbridos de milho em espaçamento reduzido. Rev. Bras. Milho e Sorgo 12:92–101. doi:10.18512/1980-6477/rbms.v12n2p92-101

Norsworthy, J.K., and E.R. Shipe. 2005. Effect of row spacing and soybean genotype on mainstem and branch yield. Agron. J. 97:919–923. doi:10.2134/agronj2004.0271

Pagano, E., and G.A. Maddonni. 2007. Intra-specific competition in maize: Early established hierarchies differ in plant growth and biomass partitioning to the ear around silking. Field Crop. Res. 101:306–320. doi:10.1016/j.fcr.2006.12.007

QGIS Development Team. 2015. QGIS Geographic Information System. Open Source Geospatial Foundation Project. QGIS. http://www.qgis.org/ (accessed 11 Dec. 2016).

R Development Core Team. 2013. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/ (accessed 20 May 2017).

Reiss, W.D., and L.V. Sherwood. 1965. Effect of row spacing, seeding rate, and potassium and calcium hydroxide additions on soybean yields on soils of southern Illinois. Agron. J. 57:431–433. doi:10.2134/agronj1965.00021962005700050006x

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

Schwalbert, R., T.J.C. Amado, T.A.N. Horbe, L.O. Stefanello, Y. Assefa, P.V.V. Prasad et al. 2018. Corn yield response to plant density and nitrogen: Spatial models and yield distribution. Agron. J. (in review).

Sharda, A., J.P. Fulton, T.P. McDonald, and C.J. Brodbeck. 2011. Real-time nozzle flow uniformity when using automatic section control on agricultural sprayers. Comput. Electron. Agric. 79:169–179. doi:10.1016/j.compag.2011.09.006

Sharda, A., J.D. Luck, J.P. Fulton, T.P. McDonald, and S.A. Shearer. 2012. Field application uniformity and accuracy of two rate control systems with automatic section capabilities on agricultural sprayers. Precis. Agric. 14:307–322. doi:10.1007/s11119-012-9296-z

Shockley, J., C.R. Dillon, T. Stombaugh, and S. Shearer. 2012a. Whole farm analysis of automatic section control for agricultural machinery. Precis. Agric. 13:411–420. doi:10.1007/s11119-011-9256-z

Shockley, J., C. Dillon, T. Stombaugh, and S. Shearer. 2012b. Whole farm analysis of automatic section control for agricultural machinery. Precis. Agric. 13:411–420. doi:10.1007/s11119-011-9256-z

Smith, B.C.M., K.C. Dhuyvetter, T.L. Kastens, L. Dietrich, and L.M. Smith. 2013. Economics of Precision Agricultural Technologies Across the Great Plains. ASFMRA 76:185–206.

Soil Survey Staff. 2014. Keys to soil taxonomy.

Tokatlidis, I.S., V. Has, V. Melidis, I. Has, I. Mylonas, G. Evgenidis et al. 2011. Maize hybrids less dependent on high plant densities improve resource-use efficiency in rainfed and irrigated conditions. Field Crop. Res. 120:345–351. doi:10.1016/j.fcr.2010.11.006

Tokatlidis, I.S., and S.D. Koutroubas. 2004. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. Field Crop. Res. 88:103–114. doi:10.1016/j.fcr.2003.11.013

Tokatlidis, I.S., M. Koutsika-Sotiriou, and E. Tamoutsidis. 2005. Benefits from using maize density-independent hybrids. Maydica 50:9–17.

USDA. 2016. Crop production 2015 Summary. January 2016. U.S. Dep. of Agric., Natl. Agric. Stat. Serv., Washington, DC. p. 1–100.

USDA-ERS. 2017. Commodity costs and returns. U.S. Dep. of Agric.-Econ. Res. Serv. https://www.ers.usda.gov/data-products/commodity-costs-and-returns/ (accessed 15 June 2017).

USDA-NASS. 2017. Agricultural prices (May 2017). USDA, Natl. Agric. Stat. Serv., Washington, DC. p. 45.

Velandia, M., M. Buschermohle, J.A. Larson, N.M. Thompson, and B.M. Jernigan. 2013. The economics of automatic section control technology for planters: A case study of middle and west Tennessee farms. Comput. Electron. Agric. 95:1–10. doi:10.1016/j.compag.2013.03.006

Weber, C.R., R.M. Shibles, and D.E. Byth. 1966. Effect of plant population and row spacing on soybean development and production. Agron. J. 58:99–102. doi:10.2134/agronj1966.00021962005800010034x