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AUTOMATIC SECTION CONTROL FOR PLANTERS AND VARIABLE RATE SEEDING: NEW APPROACHES TO PRECISION PLANTING

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Tese apresentada ao Curso de Pós-Graduação em Engenharia Agrícola, área de concentração em Mecanização Agrícola, da Universidade Federal de Santa Maria, como requisito parcial para a obtenção do grau de **Doutor em Engenharia Agrícola.**

Orientador: Prof. Dr. Telmo Jorge Carneiro Amado

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RESUMO

DESLIGAMENTO AUTOMÁTICO DE SEÇÃO EM SEMEADORAS E TAXA VARIADA DE SEMENTES: NOVAS ABORDAGENS PARA A SEMEADURA PRECISA

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O conceito de semeadura precisa tem ganhado destaque em todo o mundo; no entanto, os benefícios de algumas tecnologias associadas a essa abordagem vêm sendo pouco explorados. Estudos que avaliem os benefícios da tecnologia de desligamento automático de seção em semeadoras, por exemplo, bem como análises relacionadas a taxa ótima de semeadura em soja considerando o ambiente de produtividade - fornecendo diretrizes para adoção de taxa variada de sementes - ainda são incipientes. Assim, o objetivo principal deste estudo foi avaliar duas ferramentas inovadoras relacionadas a agricultura de precisão: a) desligamento automático de seção em semeadoras, e b) taxa variada de sementes na cultura da soja. No primeiro estudo (a) os objetivos específicos foram: quantificar as perdas de produtividade em áreas com sobreposição na semeadura para as culturas de milho e soja; quantificar a área de semeadura necessária para recuperar o investimento da tecnologia e, quantificar o percentual de sobreposição durante a semeadura em áreas agrícolas comerciais. Para o segundo estudo (b), o objetivo principal foi identificar a taxa ótima de sementes na cultura da soja considerando diferentes ambientes de produtividade; fornecendo diretrizes para a taxa variada de sementes. Para tal, modelos estatísticos de inferência Bayesiana foram utilizados como abordagem principal. Os principais resultados para o primeiro estudo (a) foram: i) o uso de desligamento automático de seção em semeadoras aumentou a lucratividade em ambas as culturas, sendo por meio da economia de sementes e pela maior produtividade em milho e apenas pela economia de sementes em soja; ii) para a cultura do milho as perdas de produtividade estiveram associadas à redução no número de grãos por espiga e em menor grau ao peso de mil grãos; iii) a produtividade de soja foi menos sensível a sobreposição, devido a compensação proporcional no número de sementes por unidade de área; iv) quando apenas a cultura do milho foi considerada, o retorno econômico da tecnologia ocorreu com uma menor área semeada; v) a proporção média de sobreposição em áreas comerciais foi de 5,5%; no entanto, a sobreposição aumentou significativamente em talhões irregulares. Para o segundo estudo (b), os resultados evidenciaram que i) a taxa de sementes pode ser otimizada e função do ambiente de produtividade; baseado nele, a taxa ótima de semeadura ideal deverá seguir a tendência: baixo>médio>alto ambiente de produtividade; ii) para o banco de dados avaliado, o número de sementes poderia ser reduzido em 18% em ambientes de alta produtividade em comparação aos de baixa, sem penalizar a produtividade; no entanto, fatores locais e o ajustes para atingir a densidade de plantas finais desejada, considerando os riscos de perda de estande, devem ser considerados.

Palavras-chave: Agricultura de Precisão. Tecnologia. Milho. Soja. Ambiente.

ABSTRACT

AUTOMATIC SECTION CONTROL FOR PLANTERS AND VARIABLE RATE SEEDING: NEW APPROACHES TO PRECISION PLANTING

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Precision planting has been an emerging concept worldwide; however, the benefits of some technologies associated to this approach are still a knowledge gap. Studies evaluating the benefits of automatic section control technology for planters as well as a comprehensive analysis on soybean seeding rate prescription by yield environment, providing guidelines to variable rate seeding adoption were not yet assessed. Thus, the main goal of this study was to provide scientific knowledge about two new precision agriculture tools: a) automatic section control for planters and b) variable rate seeding for soybean. For the first study (a), the specific goals were to quantify the yield losses from double-planted areas in corn and soybean; quantity the planting area necessary to recover the investment from automatic section control technology; and measure the double-planted area proportion in Brazilian fields. For the second study (b), the main goal was to identify the optimum soybean seeding rate at varying yield environments, providing guidelines to variable rate seeding. Bayesian statistical inference models was used as the main approach. The main outcomes for the first study (a) were to: i) the use of automatic section control for planters increased profitability in both corn and soybean crops, by both seed savings and higher yields for corn and primarily by seed savings for soybean; ii) corn yield losses were primarily related to reduction in grain number per ear than the thousand grain weight component; iii) soybean yields were less sensitive to double-planted area due to a similar number of seeds per unit area and thousand seed weight; iv) when only corn was considered, economic return for the automatic section control was recovered with a smaller planted area; v) the average double-planted area proportion within fields was 5.5% of the total area; however, it increased linearly as planted area raised and for irregular field shapes. Finally, for the second study (b) we documented that i) seeding rate prescription can be optimized when yield environment is considered; the most probable optimum seeding rate should follow the trend from high to low yielding environment: low>medium>high; ii) seeding rate could be reduced by 18% at high relative to low environments, without penalizing yields; however, local factors and adjustments in seeding rates to achieve desired final stand densities with stand loss risks should also be considered.

Keywords: Precision agriculture. Technology. Corn. Soybean. Environment.

SUMÁRIO

1. INTRODUÇÃO GERAL

Globalmente, o conceito de Agricultura de Precisão (AP) tem sido amplamente difundido nas últimas décadas (AMADO; SANTI, 2011; GEBBERS; ADAMCHUK, 2010; GRIFFIN et al., 2017; KHOSLA et al., 2008; KOCH; KHOSLA, 2003; SHANAHAN et al., 2004). A partir do uso de novas ferramentas e de estratégias agronômicas, a AP tem permitido o gerenciamento da variabilidade espacial e temporal das culturas, visando melhorar a eficiência no uso de insumos e o retorno econômico (GEBBERS; ADAMCHUK, 2010; GRIFFIN et al., 2017). Em teoria, a ideia intuitiva por trás da AP é buscar otimizar a quantidade de insumos adicionada ao ambiente, uma vez que suas ferramentas oferecem a possibilidade de adotar a prática de manejo certa, no lugar certo, no momento certo e da maneira certa (PIERCE; NOWAK, 1999). De modo geral, a principal estratégia é substituir informações e conhecimento em decisões práticas (BONGIOVANNI; LOWENBERG-DEBOER, 2004). Nos países em que a AP está comercialmente disponível, a adoção pelos produtores tem crescido constantemente (ANTOLINI; SCARE; DIAS, 2015; GRIFFIN et al., 2017; PIERPAOLI et al., 2013; ZHANG; WANG; WANG, 2002); no entanto, a aceitação de novas tecnologias na agricultura raramente é imediata (PIERPAOLI et al., 2013).

Atualmente, a adoção de novas ferramentas de AP está associada à quantidade de habilidades adicionais necessárias para implementar a respectiva tecnologia (GRIFFIN et al., 2017). Conceitualmente, as ferramentas chamadas de “conhecimento incorporado”, onde não são necessárias habilidades adicionais para perceber o valor da tecnologia (por exemplo, uso de piloto automático e controle de seção), são mais prontamente adotadas do que ferramentas de “informação intensa”; estas últimas fornecem dados que devem ser analisados e interpretados para serem totalmente úteis (por exemplo, a taxa variada de fertilizantes e a taxa variada de sementes) (GRIFFIN et al., 2017). Por fim, outro fator importante para a adoção integral de uma tecnologia também está relacionado a quantidade de informações disponíveis sobre a mesma e quais os seus reais benefícios. Nesse contexto, o processo de semeadura precisa tem sido um conceito emergente (HÖRBE et al., 2016; SHANAHAN et al., 2004); entretanto, os benefícios de algumas tecnologias associadas a este conceito, como: a) o desligamento automático de seção em semeadoras e b) a taxa variada de sementes na cultura da soja ainda são uma lacuna de conhecimento na literatura científica. A primeira tecnologia (desligamento automático de seção em semeadoras) visa reduzir a sobreposição nas “cabeceiras” (isto é, evitar áreas semeadas duplamente) (FULTON et al., 2011; VELANDIA et al., 2013), bem como evitar perdas de produtividade causadas pelo excesso de plantas. Por outro lado, a segunda tecnologia (taxa variada de sementes) visa otimizar a taxa de sementes dentro de um mesmo talhão enquanto maximiza a produtividade. Diversos estudos foram conduzidos utilizando desligamento automático de seção em pulverizadores (BATTE; EHSANI, 2006; LARSON et al., 2016; LUCK et al., 2010), demonstrando que a área com sobreposição pode exceder 10% (BATTE; EHSANI , 2006); no entanto, pouco se sabe sobre os benefícios dessa tecnologia em semeadoras (FULTON et al., 2011; VELANDIA et al., 2013). Essa lacuna de conhecimento inclui os efeitos da sobreposição sobre a produtividade das culturas, bem como a proporção da área sobreposta em áreas comerciais. Para campos brasileiros, ambos ainda não foram quantificados.

De modo similar, o baixo número de informações é também uma barreira para a adoção em larga escala da taxa variada de sementes na cultura da soja. O número de sementes por unidade de área é um dos principais fatores controlados pelos produtores que buscam altas produtividade na cultura da soja (COX; CHERNEY, 2011; EGLI, 1988; LEE; EGLI; TEKRONY, 2008; MUELLER; REEG; KYVERYGA, 2014; THOMPSON et al., 2015 WALKER et al., 2010); entretanto, modelos de taxa de semeadura x produtividade considerando ambientes de produtividade estão disponíveis atualmente apenas para as culturas de milho (ASSEFA et al., 2016; HÖRBE et al., 2013; SCHWALBERT et al., 2018) e canola (ASSEFA et al., 2017). Diretrizes para a taxa variada de sementes na cultura da soja poderiam aumentar a adoção dessa tecnologia ao longo do tempo.

Assim, o objetivo deste estudo foi fornecer conhecimento técnico/científico sobre dois tópicos relacionados ao conceito de semeadura precisa: (a) desligamento automático de seção em semeadoras e (b) taxa variada de sementes na cultura da soja. No primeiro artigo (I), foram utilizados dois conjuntos de dados e os objetivos específicos foram: conjunto de dados 1 - (A) quantificar as perdas de produtividade em áreas com semeadura sobreposta para as culturas de milho e soja; (B) quantificar a área de cultivo necessária para recuperar o investimento (retorno do investimento) da tecnologia considerando as seguintes variáveis: a) perdas de produtividade em virtude da sobreposição, b), proporção de área com sobreposição, c) relação de área milho:soja no sistema de rotação, e d) área semeada; conjunto de dados 2 (C) quantificar o percentual de sobreposição na semeadura, utilizando dados coletados em 128 campos comerciais de produção de grãos. Para o segundo artigo (II), um grande conjunto de dados (109 experimentos de campo) foi utilizado e o objetivo principal foi identificar a taxa ótima de sementes em diferentes ambientes de produtividade, fornecendo diretrizes para a taxa variada de sementes na cultura da soja. Modelos de inferência Bayesiana foram utilizados como abordagem estatística principal, visando quantificar a probabilidade de alterar taxa de sementes em função dos ambientes produtivos, sem penalizar a produtividade.

2. ARTIGO I

PLANTER TECHNOLOGY TO REDUCE DOUBLE-PLANTED AREA AND IMPROVE CORN AND SOYBEAN YIELDS

Corassa, G. M., Amado, T. J. C., Liska, T., Sharda, A., Fulton, J. and Ciampitti, I. A. 2018. Planter Technology to Reduce Double-Planted Area and Improve Corn and Soybean Yields. Agronomy Journal, v. 110, p. 300-310. doi:10.2134/agronj2017.07.038. Disponível em: https://dl.sciencesocieties.org/publications/aj/abstracts/110/1/300

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 for 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 the 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-to-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) soybeans 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.

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

INTRODUCTION

Corn (*Zea mays* L.) and soybean (*Glycine max* L.) are among the most important field crops worldwide, representing in combination around 302 million ha (FAO, 2014). In Brazil, the combined planted area for both crops is around 51 million ha (CONAB, 2017a), while in U.S. is about 72 million ha (USDA, 2016). Double-planted area (DPA) 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, the 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 maintain 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 this scenario, automatic section control (ASC) technology can be use 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., 2012; 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 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 2015/16 and 2016/17 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, USA) was used.

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

Crop	Site	Location	Coordinates	Rainfall (mm)†	Growing season	Hybrid/Cultivar
Corn	1	Não-Me-Toque/RS	28°22'48.45"S 52°52'42.41"W	1,013	2015/16	Agroceres 9025 PRO3‡
	2	Palmeira das Missões/RS	27°57'18.68"S 53°29'2.33"W	1,136	2016/17	Agroeste 1666 VTPROIII‡
	3	Pejuçara/RS	28°28'48.86"S 53°33'32.94"W	953	2016/17	Pioneer 1630H§
	4	Xanxerê/SC	26°50'27.18"S 52°30'55.41"W	911	2016/17	Dekalb 230 VTPROIII‡
Soybean	5	Condor/RS	28° 2'57.01"S 53°28'35.85"W	1,249	2015/16	Brasmax Desafio RR¶
	6	Condor/RS	28° 1'21.97"S 53°29'53.67"W	891	2016/17	Brasmax Raio IPRO¶
	7	Xanxerê/SC	26°51'57.85"S 52°28'20.31"W	811	2016/17	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

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, USA) 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 control™ (Stara, Não-Me-Toque, RS, Brazil) and vSet® seed distribution system (Precision Planting, Tremont, IL, USA). 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 6 planter passes (Fig. 1) were replicated for soybeans (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.

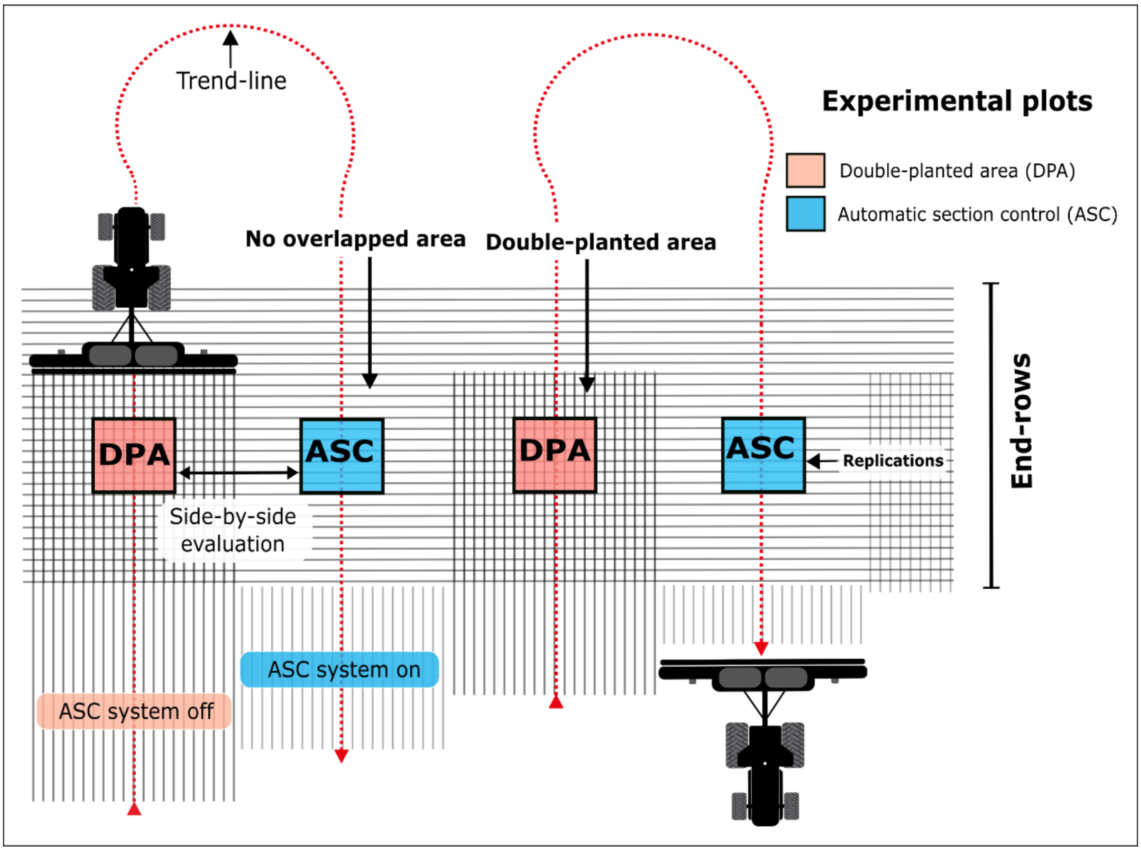

Figure 1. Experimental layout and plot location in double-planted area (DPA) and without over-planting by utilization of automatic section control (ASC) controlled row-by-row for both corn and soybean crops during 2015/16 and 2016/17 growing seasons, Brazil (dataset I). Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

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 soybeans. Plant density was quantified at V4 (fourth-leaf) stage for corn (Abendroth et al., 2011) and V3 (third-trifoliolate) for soybeans (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 soybeans, 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 1, 2, 3 and 4 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 DPA relative to ASC ratio ($Yield_{DPA}/Yield_{ASC}$) (Mg ha^{-1}) was calculated for both corn and soybean. Based on this approach, the cumulative frequency distribution (from 0 to 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 (U.S.). Farmer fields evaluated by Velandia et al. (2013) presented similar characteristics as related to the shape relative to southern Brazilian fields (see 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 US$ 0.30 kg^{-1} for soybean, both based on current Brazilian market (CONAB, 2017b), while, the seed cost, US$ 307 ha^{-1} for corn and US$ 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 the Eq. [1] propose by Velandia et al. (2013), as following:

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

where $\Delta REVj$ is the change in net revenue (US\$ ha^{-1}) for crop *j* (*j* = corn, soybean or both), *aj* is the planted area (ha) in crop *j*, *pj* is the market price for each *j* crop (US\$ kg^{-1}), *Δyj* is yield gain (kg ha^{-1}) due to the reduction in DPA, *Δscj* is the reduction in seed cost (US\$ ha^{-1}) due to reduction in the DPA, *ωk* is percentage (0≤ *ωk* ≤ 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)], *µk* is percentage (0≤ *µk* ≤ 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. *ωk* for each category *k*) separately. Thus, in each scenario *ωk=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 (see Supplemental Fig. S1); therefore, two scenarios were tested based on the DPA proportion: 5% (*µk*=0.05) and 10% (*µk*=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 *Δscj* (the reduction in seed cost) was based on the seed cost of US$ 307 ha^{-1} for corn and US$ 60 ha^{-1} for soybeans, while market price for each crop (*pj* in the equation) was US$ 0.15 kg^{-1} for corn and US$ 0.30 kg^{-1} for soybean (CONAB, 2017b). In this approach, simulations were also tested for the US price scenario of seed price of US$ 260 ha^{-1} for corn and US$ 120 ha^{-1} for soybean, while market price was US$ 0.11 kg^{-1} for corn and US$ 0.31 kg^{-1} for soybean (USDA-NASS, 2017).

To represent the *Δyj* (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 *aj* (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 ($S_{50}C_{50}$) 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 US, 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 US$ 10,500 (US$ 750 per row) in Brazil and US$ 7,000 (US$ 500 per row) in US. 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 frequently 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, 7 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 quantified based on field boundary, using the outermost planter boundary. Since there is some degree of overlapped 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 to boundary area ratio (Fig. 2).

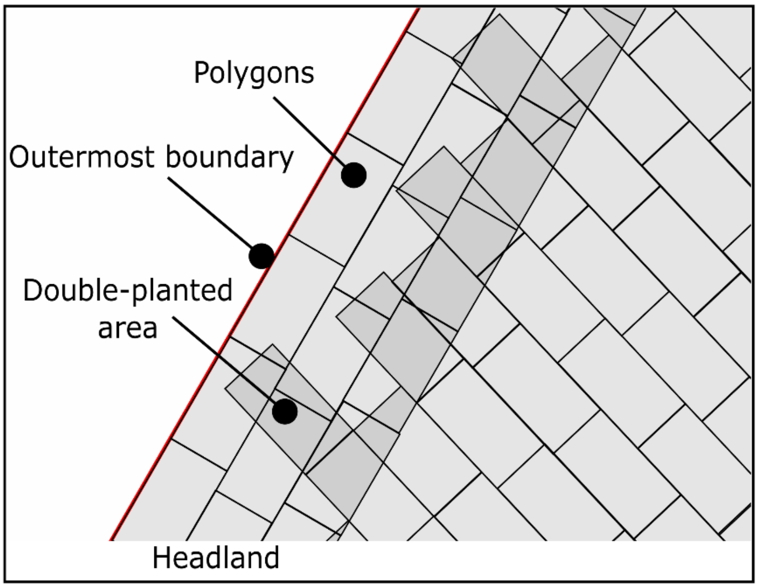

Figure 2. Shapefile information from dataset II used to calculate the planted area (total polygons area), field area (boundary area), DPA (total polygons area minus field area) and DPA proportion (total polygons area to field area ratio) in each field evaluated**.**

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 Team, 2013). 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 $Yield_{DPA}$ to $Yield_{ASC}$ ratio and $Yield_{ASC}$ as well as plant $density_{DPA}$ to plant $density_{ASC}$ ratio and plant $density_{ASC}$ using the LME procedure (R Development Core Team, 2013). An allometric analysis (log-log scale) was conducted to compare the slopes of the plant $density_{DPA}$ to the plant density $_{ASC}$ ratio and plant $density_{ASC}$ 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 7 planted with the ASC technology (4 with soybean and 3 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, soybeans had 71% more plants in the DPA relative to the ASC treatment. However, greater plant density for soybeans did not changes 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 yields in the ASC areas; while for soybeans, 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).

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 2015/16 and 2016/17 growing seasons (dataset I).

Crop	Treatment†	Parameter‡	Mean		Min	Max	SD§	CV	1Q	3Q
Corn	ASC	PD ha^{-1} (x 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} (x 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} (x 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} (x 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

†ASC= Automatic Session Control; DPA= Double-planted area
‡TGW= Thousand grain weight; TSW= Thousand seed weight
§ SD= Standard deviation; CV= Coefficient of variation; 1Q= 1^{th} quartile; 3Q= 3^{th} quartile
***, * - Significant by t-test between ASC and DPA for each crop at 0.1 and 5% level, respectively; ^{ns} non-significant

Corn and soybean yield response to ASC 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).

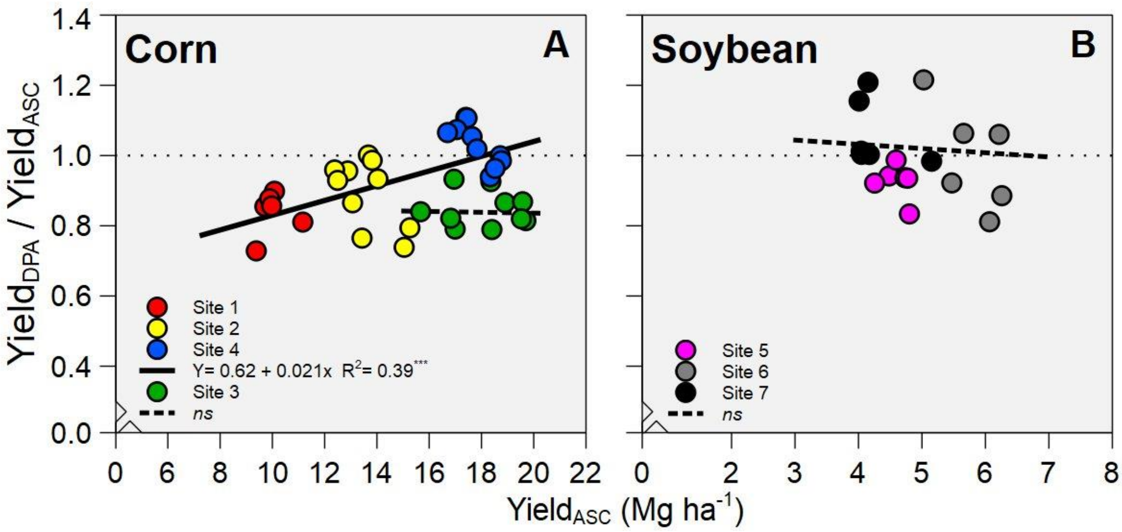

Figure 3. Relationship between relative yield ($Yield_{DPA}/Yield_{ASC}$) calculated as the $Yield_{DPA}$ to $Yield_{ASC}$ ratio, and the $Yield_{ASC}$ for corn (panel A) and soybean (panel B) crops. Each observation represents a side-by-side yield evaluation for corn (36 total, 4 sites) and for soybean (18 total, 3 sites). Relative $Yield_{DPA}/Yield_{ASC}$ below one indicates that DPA were lower than yields for the ASC treatment. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

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 it 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 $Yield_{DPA}$ to $Yield_{ASC}$ ratio and the $Yield_{ASC}$ (Fig. 3A, B). For soybeans, 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 $density_{DPA}$ to 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 $density_{DPA}$ to 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 relationship between plant $density_{DPA}$ to plant $density_{ASC}$ ratio and plant $density_{ASC}$ was not significant (Fig. 4A). For soybean, a negative trend was common for all the sites (site 5, 6 and 7) (Fig. 4B), with lower plant $density_{DPA}$ to 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 (site 2, 3 and 4) and soybeans (site 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).

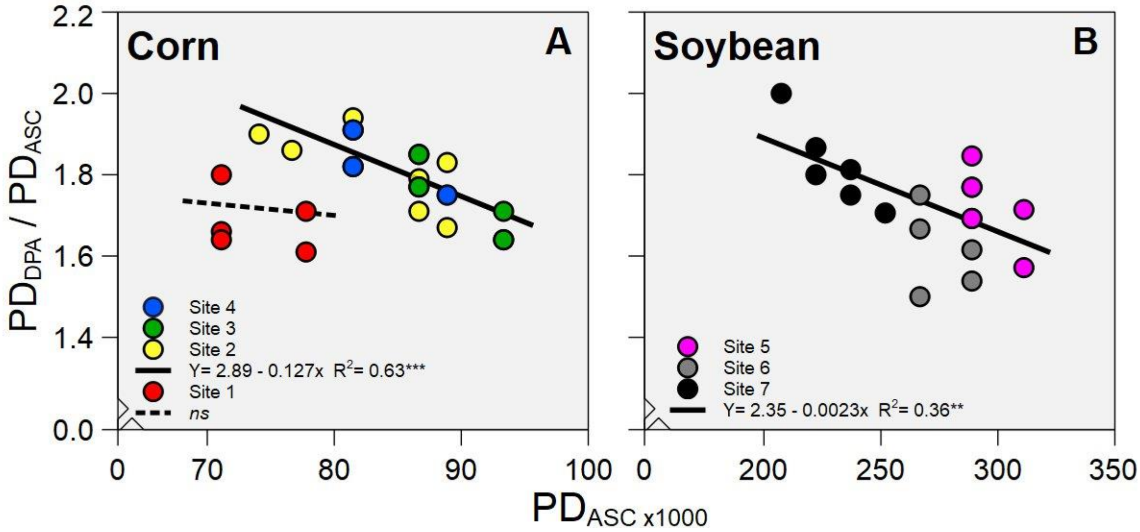

Figure 4. Relationship between relative plant density (PD_{DPA}/PD_{ASC}) calculated as the plant density$_{DPA}$ to plant density$_{ASC}$ ratio, and the plant density$_{ASC}$ for corn (panel A) and soybean (panel B) crops. Each observation represents a side-by-side yield evaluation for corn (36 total, 4 sites) and for soybean (18 total, 3 sites). Relative plant density$_{DPA}$/ plant density$_{ASC}$ above one indicates that DPA were higher than plant density for the ASC treatment. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

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.

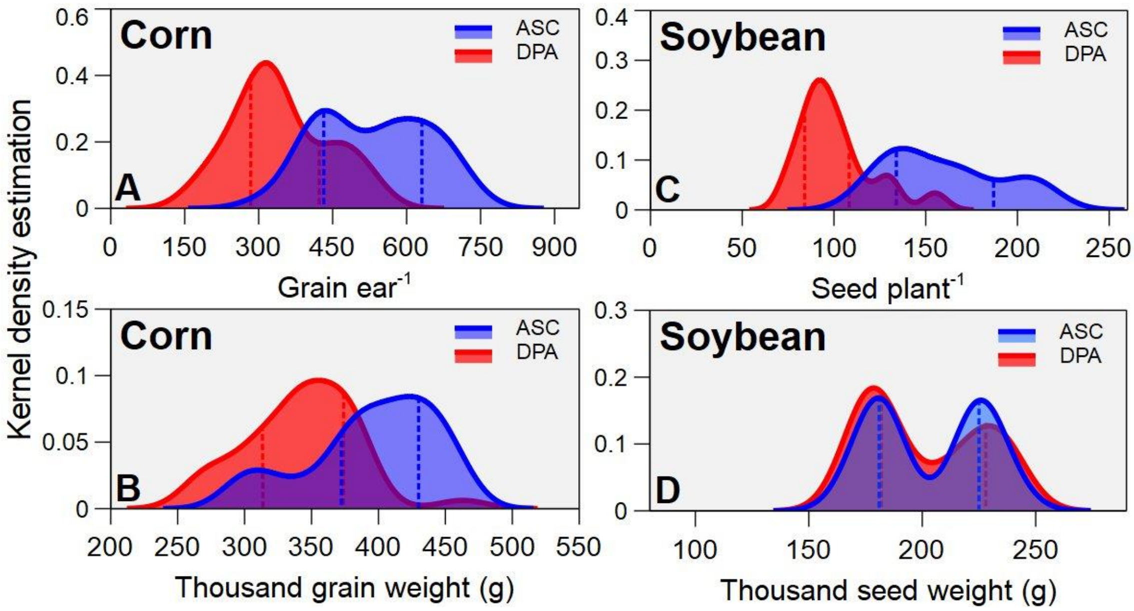

Figure 5. Kernel density estimation of grains per ear (panel A) and thousand grain weight (panel B) for corn, and final seed number per plant (panel C) and thousand seed weight (panel D) for the automatic section control (ASC) and double-planted area (DPA) treatments. Dotted lines represent 25 and 50% of interquartile, respectively. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

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 US$ 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 US$ 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 (US$ ha^{-1}) reached 95% and 98% of cumulative frequency in corn for 5 and 10% DPA scenario, respectively (Fig. 6A). Economic losses were 3 times greater in corn than soybean (Fig. 6).

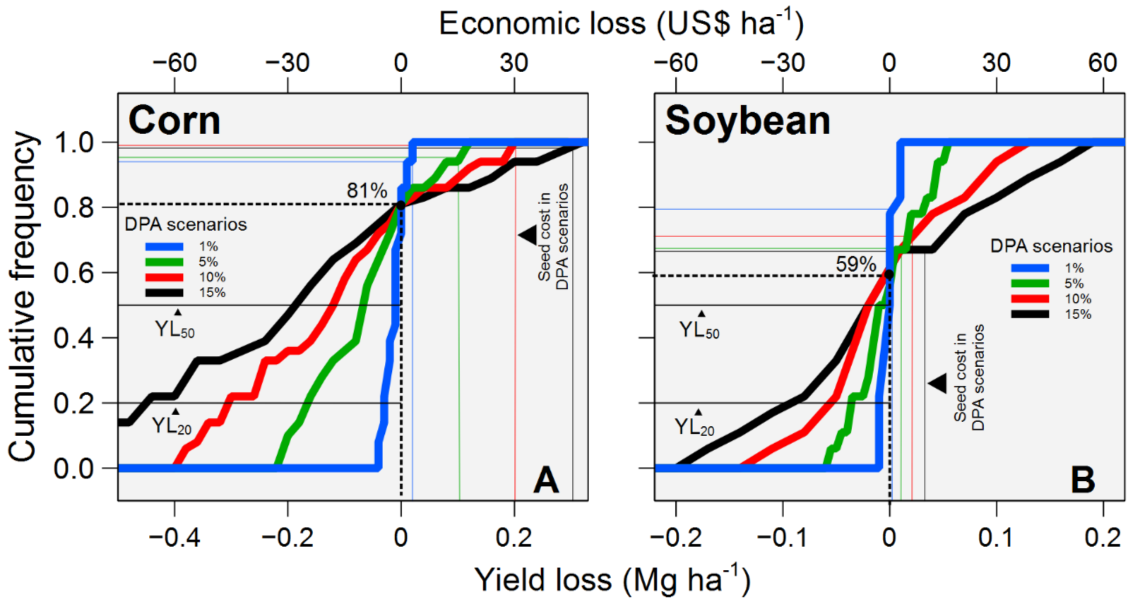

Figure 6. Cumulative frequency distribution of yield and economic loss for double-planted area (DPA) minus automatic section control (ASC) technology ($Yield_{DPA}$ – $Yield_{ASC}$) for corn (panel A) and soybean (panel B) considering the

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 Y_{L20} represent the yield loss with 50 and 20% of probability, respectively. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

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, D). For the S_{100} scenario, US presented superior ROI than Brazil (due to higher seed cost in US than Brazil), recovering this investment with 700 ha at 10% of DPA (Fig. 7A, D). 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 US (Fig. 7B, E). 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 US (Fig. 7C, F). In synthesis, for scenario of YL_{20}, ASC could be covered in 350, 250 and 190 ha with 10% of the DPA at $S_{100,}$ $C_{50}S_{50}$ and C_{100}, respectively, for US (Fig. 7 D, E, F); while for Brazil those values were 570, 300 and 205 ha (Fig. 7 A, B, C).

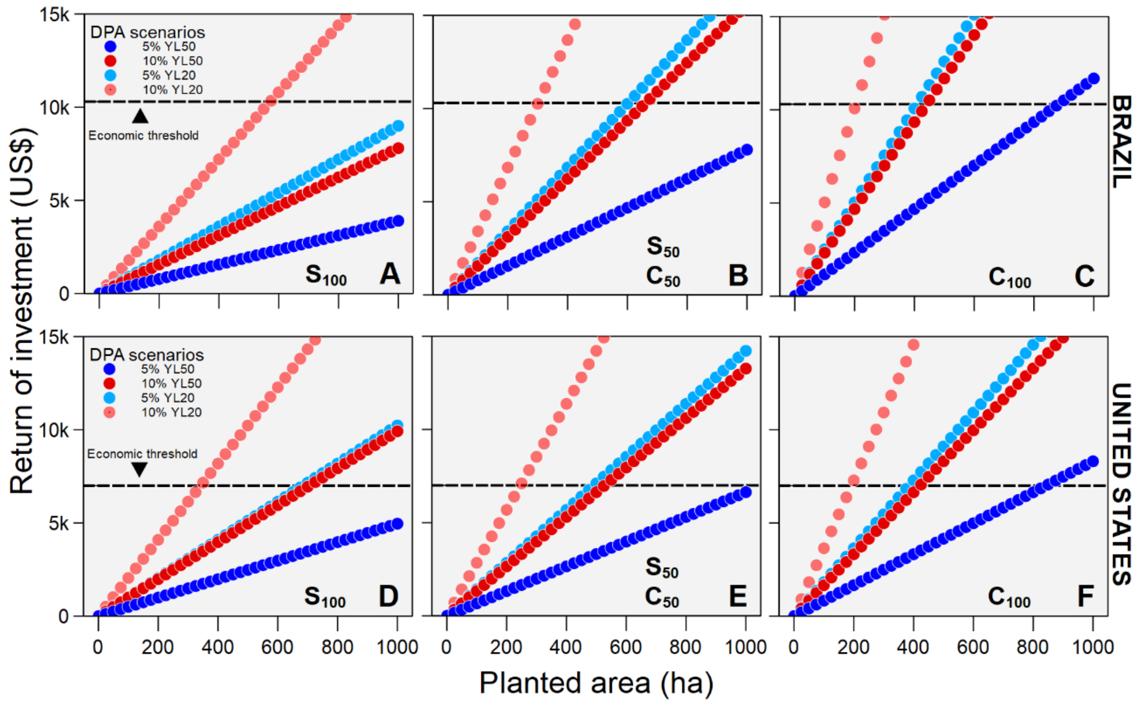

Figure 7. Return of investment (ROI) relative to planted area (ha) to recover the cost of the ASC technology considering the following farming scenarios: (S_{100}) 100% of the area planted with soybean, ($S_{50}C_{50}$) 50% with soybean and 50% with corn and (C_{100}) 100% of the area with corn, and 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. Panels A, B and C are the scenarios S_{100}, $S_{50}C_{50}$ and C_{100} for Brazil, respectively, while panels D, E and F are the scenarios S_{100}, $S_{50}C_{50}$ and C_{100} for United States (US), respectively. The ASC technology cost was considered to be US$ 10,500 for Brazil and 7,000 for US as the economic threshold based on the price of the technology for a 14-row planter in the current market. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

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 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 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 to 6 Mg ha^{-1}). Similarly, the lack of yield response to plant density was recently documented in Brazil by Ferreira et al. (2016), with changes in yield response when plant density was lower than 235 thousand plants ha^{-1} and below 3.5 Mg ha^{-1}. For US (Kansas), positive yield responses to plant density were documented when plant density was below 200 thousand plants ha^{-1} (Epler and Staggenborg, 2008).

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, D). Several researchers reported 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 soybeans, a zero-yield loss could be assumed if yields are ranging from 4 to 6 Mg ha^{-1} and plant density ranging from 200 to 300 thousand 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. (2017) between US and Brazil, comparable yield losses for DPA should be expected to occur in US.

Economic analysis from ASC technology in planters

Savings were related to the seed cost and yield gain for corn, but only related to seed cost for soybeans (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., 2012; 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).

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.

Field characteristics	Traditional system†			ASC technology‡		
	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 7 reference fields planted with ASC (row-by-row) in the planter

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 value reported in this study relative to the aforementioned US 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., 2013; Velandia et al., 2013; Larson et al., 2016), reinforcing the benefits of the ASC for planters for the southern Brazil region.

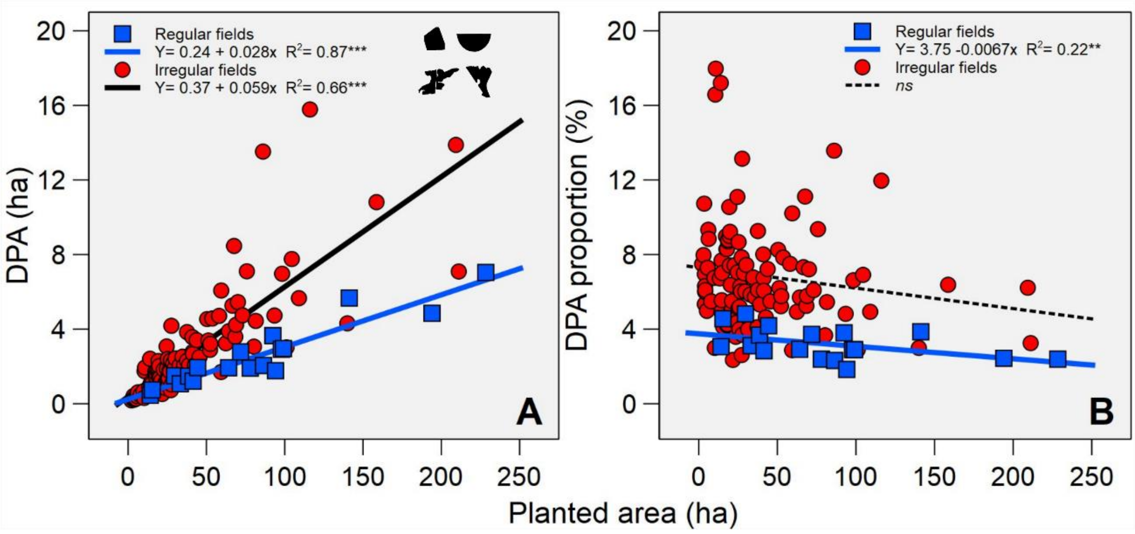

Figure 8. Relationship between planted area (ha) and double-planted area (DPA, ha) for regular (n=18) and irregular (n=103) fields (panel A); and between planted area (ha) and DPA proportion for regular and irregular fields (panel B). The perimeter/area ratio (P/A ratio) was used to classify the fields (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 panel A, after their respective legends. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

Overall, the findings from this study support the adoption of ASC technology for planters, mainly is situations of irregular fields and when corn is the main crop. These outcomes highlight the benefits of using this technology, in agreement with previously published studies (Fulton et al., 2011; Jernigan, 2012; Shockley et al., 2012; 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 compared to corn and soybean in the rotation or only soybean; 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.

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3. ARTIGO II

OPTIMUM SOYBEAN SEEDING RATES BY YIELD ENVIRONMENT IN SOUTHERN BRAZIL

Artigo apresentado seguindo a normas da revista Agronomy Journal

ABSTRACT

Optimizing seed inputs while increasing yields is the main purpose of variable rate seeding (VRS) technology adoption. Optimum seeding rate by yield environment models have been recently documented for corn (*Zea mays* L.); however, are still a knowledge gap for soybean [*Glycine max* (L.) Merr.] crop. Therefore, using a dataset gathered from 109 replicated field experiments from Southern Brazil (2,180 data points), the objectives of this study was to: (i) identify the optimum seeding rate at varying yield environments, and (ii) explore the contribution of management factors (i.e., seeding rate, planting date, row spacing, maturity groups, growing season, yield environment, and ecological region) on soybean seed yield. Hierarchical modeling and Bayesian statistical inference were used as the approach to predict optimum seeding rate across yield environments, while conditional inference tree analysis was explored to identify significant sources of yield variation. The main results were: a) soybean seeding rate prescription can be optimized across yield environments; b) optimum seeding rate increased from high to low yielding environment; c) based on modern soybean varieties, seeding rate could be reduced by 18% in high-yielding environments (>5 Mg ha^{-1}) relative to low-yielding ones (<4 Mg ha^{-1}), without penalizing yields. Future research studies should investigate the

physiological mechanisms underpinning yield environment-specific yield to seeding rate response, with the primary role of improving the understanding of the main factors (soil x plant x weather) causing the differential optimum seeding rate response for soybeans.

Abbreviations: DOY, day of the year; HY, high yielding; LY, low yielding; MY, medium yielding; VRS, variable rate seeding

INTRODUCTION

Globally, soybean is one of the most cultivated field crops, planted on 120 million hectares (FAO, 2016). Among the primary producing countries, Brazil is the second highest producer with a production near 115 million metric tons (CONAB, 2017). Seed yield potential is associated with genetic attributes, environmental conditions (i.e., geographical position, soil, weather), management practices (i.e., plant density, row spacing), and their interactions (van Ittersum and Rabbinge, 1997; Evans and Fisher, 1999; Vanlauwe et al., 2003; Rowntree et al., 2013; Van Roekel et al., 2015). At the field-level, management practices are applied as a strategy to reduce the gap between current and attainable yields (i.e., yield under optimal management practices) (van Ittersum et al., 2013; Bunselmeyer and Lauer, 2015).

Among management practices, seeding rate is one of the main factors controlled by growers (Egli, 1988; Lee et al., 2008; Walker et al., 2010; Cox and Cherney, 2011; Mueller et al., 2014; Thompson et al., 2015). Consequently, many studies have been conducted globally on the effect of seeding rate on final soybean yields (Egli, 1988; Carpenter and Board, 1997; Pires et al., 2000;

Pedersen and Lauer, 2004; Heitholt et al., 2005; Heiffig et al., 2006; Lee et al., 2008; De Bruin and Pedersen, 2008; Epler and Staggenborg, 2008; Kuss et al., 2008; Walker et al., 2010; Coulter et al., 2011; Rahman et al., 2011; Cox and Cherney, 2011; Thompson et al., 2015; Werner et al., 2016; Ferreira et al., 2016). Conceptually, soybean yield response to plant density can be separated into three different models (Duncan, 1986): i) yield-density model where there is no competition among plants; with yield primarily depending on the individual contribution of each plant; ii) yield-density model at canopy-scale, which is a community of plants increasing light interception until yield is plateauing; and iii) yield-density model after yield has plateaued when further seeding rate improvement does not increase yield (Duncan, 1986).

Environmental conditions such as yield potential could play an important role on the optimum seeding rate prescription (Egli, 1988; Pedersen and Lauer, 2004; De Bruin and Pedersen, 2008; Lee et al., 2008; Walker et al., 2010; Van Roekel and Coulter, 2011; Rowntree et al., 2013; Thompson et al., 2015). Currently, little is known about the opportunity of adjusting optimum seeding rate according to yield environments for soybean. There are farmers who increase soybean seeding rates in lower yield parts of fields (Lowenberg-DeBoer, 1999), but this practice has not been well-documented with research. Improved understanding on this topic could shed light on optimizing overall use of inputs by productive management zone, as well as increasing the return of investment. This study can provide a better foundation for the adoption of VRS, a precision agriculture technology available for modern planters (McBratney et al., 2005; Khosla et al., 2008; Gebbers and Adamchuk, 2010; Hörbe et al., 2013; Shearer and Pitla, 2014). Yield-density models by yield environment allowing implementation of VRS technology were recently published for corn (Assefa et al., 2016; Schwalbert et al., 2018) and canola (Assefa et al., 2017); but these responses for soybeans are still a knowledge gap. Therefore, the main goal of this study was to identify the optimum seeding rate at varying yield environments. Following this rationale, Bayesian statistical inference models were utilized as the main approach to predict the probability of changing seeding rates across yield environments that optimized or did not penalize yield. Lastly, a conditional inference tree analysis was explored to account the main management factors evaluated in this study across yield environments.

MATERIALS AND METHODS

Data description

Soybean seeding rate data were aggregated (n=2,180 data points) from a combination of 15 site-years for soybean seeding rate trials performed by Embrapa between 2012-13 to 2016-17 growing seasons, in six dryland sites from South Brazil (Table 1). Soybean seeding rate trials were placed in two contrasting ecological regions (Fig. 1) based on the adaptability of soybean cultivars in the region (Kaster and Farias, 2012). The gathered database resulted in 109 site-years by cultivar combination. All research trials were performed in a split-plot design with a randomized block arrangement with four replications. Cultivars were the main-plot, and five seeding rates were the sub-plot level. Five seeding rates ranged from 100,000 to 500,000 seed ha^{-1} in a plot size of 3-m width by 5-m long.

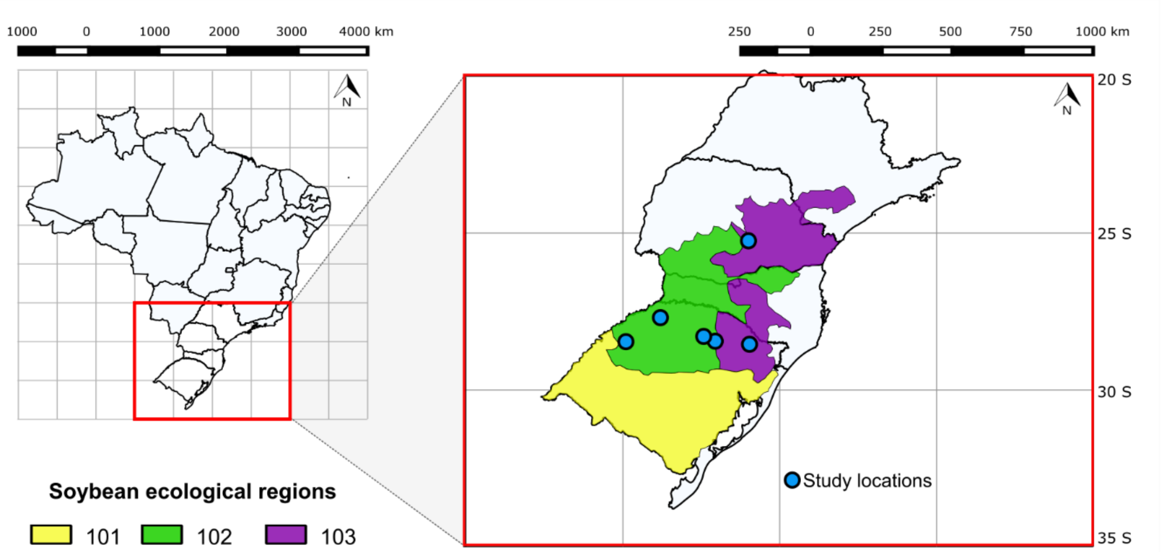

Figure 1. Map of locations where experimental seeding rate trials were performed. The ecological regions (i.e., 101, 102, and 103) as proposed by Kaster and Farias (2012). The current classification is large-scale adopted to test the adaptability of soybean cultivars; the main characteristics are presented as follows: ecological region 101) located in the state of Rio Grande do Sul, represents the highest latitudes in the country, low altitudes (close to 100 m or less) and climate as Cfa according to Köppen's classification (Alvares et al., 2013). Ecological region 102 cover a 24 to 29.5° S latitude range (states of Paraná, Santa Catarina and Rio Grande do Sul), medium to high altitudes (from 150 to 900 m), and Cfa and Cfb as the Köppen's climate classification (Alvares et al., 2013). Lastly, the ecological region 103 cover partially the states of São Paulo (south), Paraná (northeast), Santa Catarina (central) and Rio Grande do Sul (northeast), and superior altitudes (>600 m), and Cfb as the Köppen's climate classification (Alvares et al., 2013). Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

Plots were uniformly fertilized with all recommended nutrients following regional recommendations (Salvadori et al., 2016). Weed, insect and disease control were also performed as needed and according to the best management practices for soybean. For each site-year combination, in addition to seeding rates three main management variables were considered in this analysis: planting date (ranging from October 5 to December 15), row spacing (ranging from 20 to 45 cm), and maturity group (ranging from 4.2 to 6.3). Seed yield was recorded on the central two-rows for each plot and adjusted to 130 g kg^{-1} moisture. Not all planting date, row spacing, and maturity groups were tested in each site-year.

Table 1. Sites, soybean ecological region, growing season, and number of genotypes, maturity groups, and seeding rates evaluated for each site-year in South Brazil.

Site	Soybean ecological region †	Growing season	Number of genotypes	Maturity groups	Seeding rate (×1000 ha^{-1})
Campo Novo, RS (27º 39' S; 53º 49' W)	102	2014/15	10	9 (from 4.2 to 6.3)	100, 230, 300, 360, 490
		2015/16	8	5 (from 5.3 to 6.2)	100, 230, 300, 360, 490
		2016/17	7	5 (from 5.6 to 6.2)	100, 230, 300, 360, 490
Gentil, RS (28º 26' S; 52º 02' W)	102	2015/16	8	5 (from 5.3 to 6.2)	100, 230, 300, 360, 490
		2016/17	6	4 (from 5.7 to 6.2)	100, 230, 300, 360, 490
Passo Fundo, RS (27º 14' S; 52º 24' W)	102	2012/13	2	1 (5.6)	100, 200, 300, 400, 500
		2013/14	2	1 (5.6)	100, 230, 300, 360, 490
		2014/15	12	9 (from 4.2 to 6.3)	100, 200, 300, 400, 500
		2015/16	8	5 (from 5.3 to 6.3)	100, 230, 300, 360, 490
		2016/17	8	5 (from 5.6 to 6.2)	100, 230, 300, 360, 490
São Luiz Gonzaga, RS (28º 23' S; 54º 59' W)	102	2015/16	7	4 (from 5.7 to 6.2)	100, 230, 300, 360, 490
		2016/17	6	4 (from 5.7 to 6.2)	100, 230, 300, 360, 490
Vacaria, RS (28º 27' S; 50º 56' W)	103	2015/16	8	5 (from 5.3 to 6.2)	100, 230, 300, 360, 490
		2016/17	7	5 (from 5.6 to 6.2)	100, 230, 300, 360, 490
Guarapuava, PR (25º 25' S; 51º 31' W)	103	2014/15	10	9 (from 4.2 to 6.2)	100, 230, 300, 360, 490

† Ecological region 102 cover partially the states of Paraná, Santa Catarina and Rio Grande do Sul, represents medium to high altitudes (from 150 to 900m), and Cfa and Cfb as the Köppen's climate classification (Alvares et al., 2013); Ecological region 103) cover partially the states of São Paulo (south) Paraná (northeast), Santa Catarina (central) and Rio Grande do Sul (northeast), represents high altitudes (>600m), and Cfb as the Köppen's climate classification (Alvares et al., 2013).

Data analysis

The yield data (Fig. 2A) was divided in three yield environments following the terciles of data distribution (<33%, 33-66%, and >66%) for low (LY), medium (MY) and high (HY) yielding levels (Fig. 2B). The average yield from each site–

year combination was used as the approach to determine the yield environment (Assefa et al., 2016). This type of approach represents the site and environmental conditions within year and the yield variation is only due to treatments (Assefa et al., 2016). The classification was based on frequency of the yield data distribution. A motivation behind this classification was to allow balanced data across a similar number of data points across yield environments.

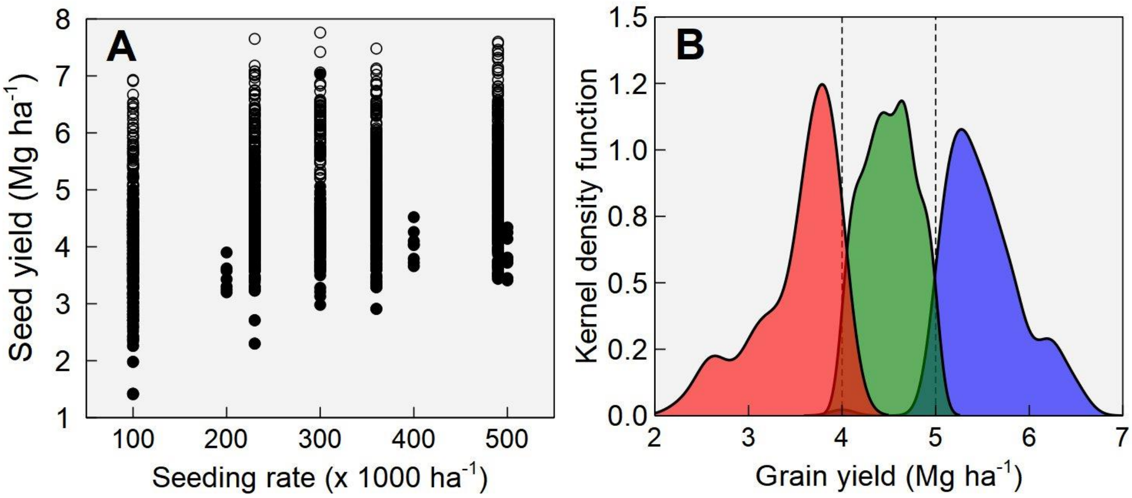

Figure 2. Dataset of soybean seeding rate vs. seed yield aggregated from a combination of 15 site-years (Panel A) and frequency distribution classification of soybean yield for three yield environments: low (LY, <4 Mg ha^{-1}), medium (MY, 4-5 Mg ha^{-1}), and high (HY, >5 Mg ha^{-1}). Yield environments were delineated by average of site-year yield approach. Yield environments were classified by terciles (<33%, LY; 33-66%, MY; >66%, HY). Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

To identify seed yield variation accounted by known factors such as yield environment, growing season, ecological region, seeding rate, planting date (DOY, day of the year), row spacing, maturity group, and their respective interactions, the variance was estimated using the *nlme* procedure and *VarComb* package in R program (R Development Core Team, 2013). The variance components were represented by yield environment, ecological region within a yield environment, growing season within a yield environment, and the interaction ecological region × growing season within yield environment. Management practices such as DOY, plant density, row spacing, and maturity group were analyzed separately. These factors (management practices) were treated as fixed effects, whereas yield environment, growing season, and ecological region were considered as random variables.

Hierarchical modeling and Bayesian Statistical inference

Hierarchical Bayesian models were implemented to quantify the yield response to seeding rate. Hierarchical models represent environmental interactions using a series of conditional probability distributions (Kyveryga and Blackmer, 2014). A more detailed explanation about hierarchical models is described by Kyveryga et al. (2013). The model comprised three hierarchical levels: field-level (site-year), yield environment-level (high, medium and low), and regional-level. First, regression models were fitted to the field-level. As a second step, those models were aggregated to a higher hierarchical level (i.e., environment and regional level). Therefore, three statistical models were tested individually for all the *n* fields to identify the yield-seeding rate relationship: linear with plateau, quadratic, and quadratic with plateau. These models were selected based on the typical yield to seeding rate relationship for soybeans (Popp et al., 2006; De Bruin and Pedersen, 2008; Cox and Cherney, 2011; Thompson et al., 2015). Soybean yield is assumed to increase at a decreasing rate until a specific seeding rate, the points at which yield is expected to either plateau or decrease (Thompson et al., 2015). Intercept, linear, angular coefficients and breakpoint were assumed to follow a normal distribution with μ_n and precision λ_n unique for each field. The precision parameter was defined as the reciprocal of variance (i.e., the higher the precision), the lower the variation (Kyveryga and Blackmer, 2014). The yield environment coefficients were expressed as conditional distribution of field means μ_n, given regional mean μ_0 and regional precision λ_0. Finally, for the regional process model (global model), the yield environment precision parameters λ_n were assumed to follow a gamma distribution with parameters α and β (Kyveryga and Blackmer, 2014).

All prior distributions were assumed to be "diffuse", which means that these prior distributions were assumed to present large variances, having little influence on the analysis relative to the observed data (Kyveryga et al., 2013). A Markov-chain Monte Carlo simulation was used for this approach (Gelman and Hill, 2007) following a Gibbs sampling algorithm with 15,000 random draws after a warm up period of 5,000 interactions. The *rjags* package (Plummer, 2016) was used to build the models in the R program. All models were run in the Beocat Research Cluster at Kansas State University due to the high demand for computing power. Based on prior distributions, that were built to represent the possible values of observations using Bayesian analysis, we updated these values in a posterior predictive probabilities distribution (Kyveryga et al., 2013) for each yield environment. Since the main focus of the work was to investigate the yield and seeding rate response models in a given yield environment, the hierarchical regional-level was not explored.

Conditional inference trees

A conditional inference regression tree analysis was performed to examine important interactions as well as significant source of variation for the yield and seeding rate factors. This approach is an alternative to overcome bias since does not make statistical assumptions are not made relative to the data distribution. The conditional inference regression tree can be implemented using categorical and continuous explanatory variables and is robust for outliers, missing data, exposing variable interactions (Hothorn et al., 2006; Tittonell et al., 2008; Hastie et al., 2009). In addition, this approach has been recently implemented to identify yield constraints in field crops (Lobell et al., 2005; Ferraro et al., 2009; Mourtzinis et al., 2018). A more detailed explanation of the benefits of use conditional inference regression tree methodology was recently described by Mourtzinis et al. (2018). The *partykit* package (Zeileis and Hothorn, 2015) in the R program was used. The criterion for the independence test was based on univariate *p-values* (α= 0.05). The number of intermediate, terminal nodes, and the maximum tree depth were set according *partykit* package default (Zeileis and Hothorn, 2015).

RESULTS

Yield variability across site-years was largely (ICC=0.69) explained by yield environment (e.g., HY, MY, and LY) (Table 2). The DOY and plant density (both within yield environment, growing season, and ecological region effects) were the second and third main factors in order of importance, accounting for 7 and 5% of yield variability, respectively (Table 2). Across all factors evaluated, growing season (year) and soybean ecological region (e.g., 102 and 103) accounted for a small yield variation relative to the other sources of variability. Similar results were found for row spacing and maturity group, both (combined) accounting for 2% of yield variability. The amount of variability accounted by unexplained factors (high level interaction and residual) was 17% (ICC=0.17) (Table 2).

Table 2. Estimation of soybean yield variance components in an environmental-based (yield environment, ecological region, and growing season) and management factors-based (DOY, plant density, row spacing, maturity group).

Covariance effect	Variance	ICC [a]
Yield environment	0.862	0.69
Ecological region (yield environment)	0.000	0.00
Growing season (yield environment)	0.000	0.00
Ecological region × growing season (yield environment)	0.000	0.00
DOY (yield environment growing season ecological region)	0.082	0.07
Plant density (yield environment growing season ecological region)	0.063	0.05
Row spacing (yield environment growing season ecological region)	0.020	0.01
Maturity group (yield environment growing season ecological region)	0.161	0.01
High level interaction and residual	0.209	0.17

[a] interclass correlation coefficient (ICC= yield variance effect / yield variance total)

Among the statistical models evaluated, the linear with plateau model best explained the yield-density relationship across yield environments; however, the average seeding rate at yield-plateau (breakpoint) point was quite variable across yield environments (Fig. 3).

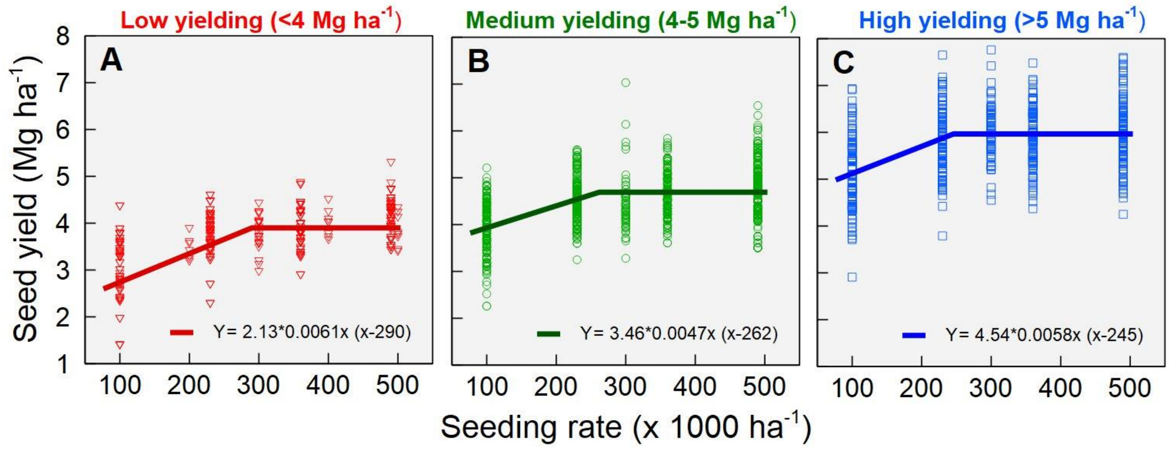

Figure 3. Bayesian regression models from soybean seeding rate vs. seed yield obtained at for low (yield <4 Mg ha^{-1}) (A), medium (yield 4-5 Mg ha^{-1}) (B), and high (yield >5 Mg ha^{-1}) (C) yield environments. The model represents the most probable response across site-years × cultivar combination evaluated. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

Using the Bayesian inference within each yield environment, the average yield at the plateau phase followed the order: LY>MY>HY (Fig. 3). The average seeding rate at the plateau was 10% greater for the LY (290 thousand seeds ha^{-1}) than MY (262 thousand seeds ha^{-1}), and 18% greater for the LY than HY (245 thousand seeds ha^{-1}) (Fig. 3). The slope for the linear function was also slightly superior for the LY (0.061) compared to MY (0.047) and HY (0.058) (Fig. 3).

Considering all the site-specific effects (plot-level data from the site-years × cultivar combination) the interquartile range (between 25 and 75 quartiles) for the optimal seeding rate (yield plateau) was 274 and 303 thousand seeds ha^{-1} for LY, 252 and 269 thousand seeds ha^{-1} for MY, and 238 and 262 thousand seeds ha^{-1} for HY environments (Fig. 4A). Based on prior distributions, we updated these values in a form of posterior cumulative distributions as an approach to predict the probabilities of optimal seeding rate across yield environments (Fig. 4B). Our results showed that at HY seeding rates from 180 to 270 thousand seeds ha^{-1} were needed to attain the yield plateau with a probability of 90% at HY; For a MY, this point was achieved with an optimal seeding rate ranging from 220 to 270 thousand seeds ha^{-1} (Fig. 4B). To reach the yield plateau, a requirement of greater seeding rate was documented at LY (seed yield < 4 Mg ha^{-1}) (Fig. 4B). Cumulative probabilities showed that in 90% of the times the LY yield plateau was obtained with a range from 230 to 320 thousand seeds ha^{-1} (Fig. 4B). This probability level could be considered as a threshold for on-farm prescriptions in the region, since these results suggest a low probability of superior yield can be expected with further increase in seeding rate (Fig. 4B). Reduction in seeding rate (<250,000 seeds ha^{-1}) had less influence on seed yield for HY compared to MY and LY (Fig. 4B).

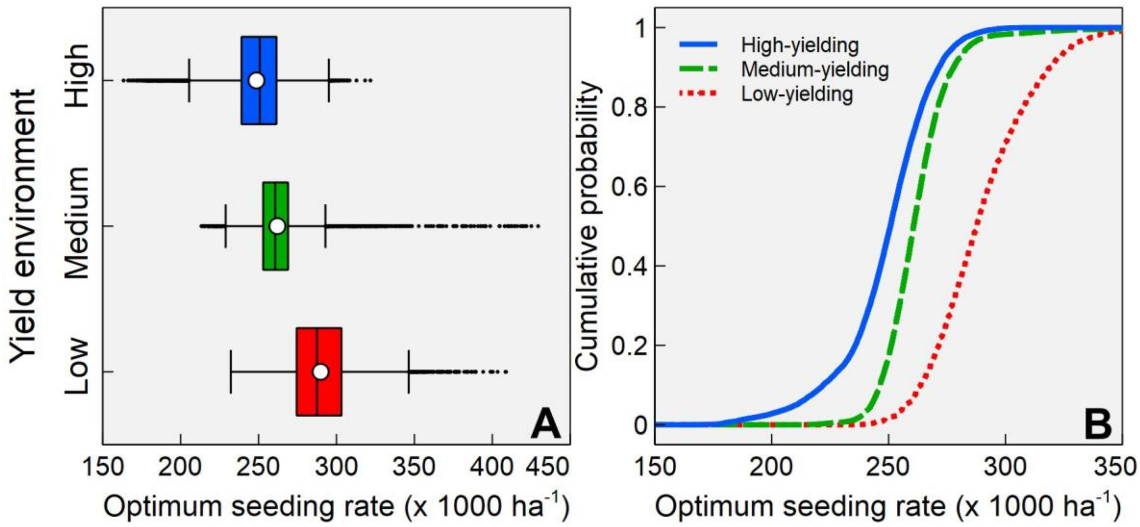

Figure 4. Panel A denotes optimum seeding rate range obtained from site-years × cultivar combination to attain the yield plateau for low (yield <4 Mg ha^{-1}), medium (yield 4-5 Mg ha^{-1}), and high (yield >5 Mg ha^{-1}) yield environments. In each boxplot, the central rectangle extends from the first to third quartile (percentiles 25 and 75). The circle inside the rectangle represents the mean value of seeding rate to attain the yield plateau across site-years and for each yield environment. Whiskers extend between the smallest and the largest non-outlier values. Black points before and after whiskers denote outliers. Panel B is the posterior predictive probabilities of optimum seeding rate to achieve the yield plateau at low, medium, and high yield environments. Yield environments were delineated by average of site-year yield approach. Note: For understanding of the references to color in this figure legend, the reader is referred to the colored version of this document.

The conditional inference tree was fitted to identify and quantify other sources of yield variation across all experiments. Thus, all the known, measured factors (i.e., yield environment, ecological region, growing season, DOY, plant density, row spacing, and maturity group) were included in the model. All the exploratory variables were treated as continuous factors, which means that the criteria to "node establishment" was based on the model and their respective significance (α= 0.05). The results suggested that seeding rate and DOY were the significant factors influencing yield and seeding rate relationships across yield environments. Other important regional- (ecological region) as well as management- factors such as maturity group were not significant, reflecting an opportunity to provide more universal recommendations.

Based on the regression tree model (RMSE= 0.56 Mg ha^{-1}), results revealed that under the HY environment, seeding rates around 100 thousand seeds ha^{-1} represented a slight reduction in yield than other rates evaluated (Fig. 5). However, as mentioned above, seeding rates greater than 250 thousand seeds ha^{-1} were likely an unnecessary cost for HY since low probability of yield increase is expected (Fig. 4B). For the HY environment, the model showed that planting after November 18 (DOY= 322) resulted in lower yields than planting earlier (before November 18) regardless of the seeding rate evaluated (Fig. 5). Yield reduction due to planting delay was greater (15%) for the lower seeding rate (≤100 thousand seeds ha^{-1}) relative to the other seeding rates (yield reduction= 7%) (Fig. 5). The DOY was not a significant factor for MY and LY environments, but seeding rate was a critical factor. For MY, the use of seeding rates lower than 100 thousand seeds ha^{-1} represented a yield decrease of about 18% compared with higher seeding rates (Fig. 5). At LY, a linear increase in yield was documented with the increase in seeding rate from 200 to 360 thousand seeds ha^{-1} (yield gain= 23%) (Fig. 5). Overall, these results indicate that a limited number of management practices (seeding rate and planting date) can affect soybean yield response to seeding rate across yield environments.

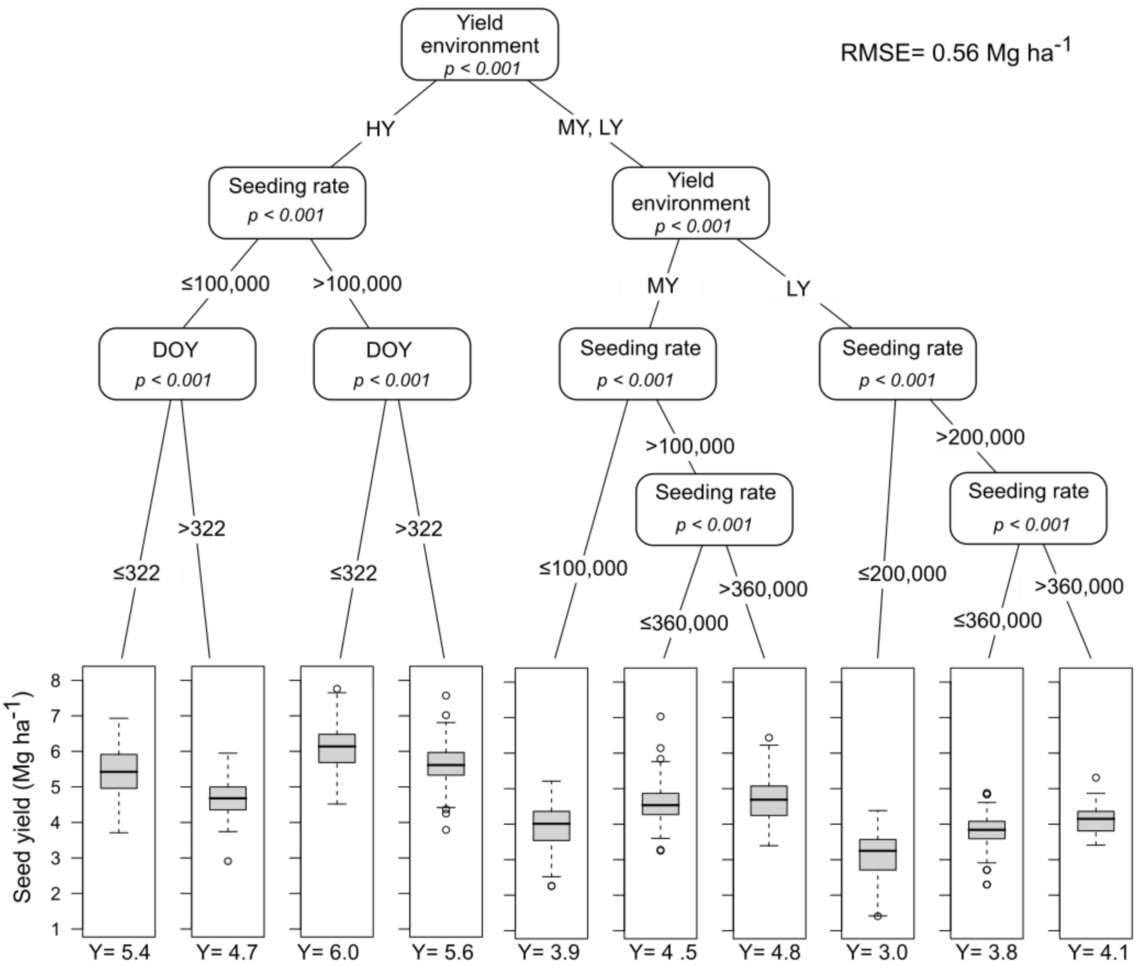

Figure 5. Conditional inference tree across the 15 site-years evaluated. Boxplots in the bottom of the figure represents the soybean seed yield. In each boxplot, central rectangle extends the first to the third quartile. The solid line inside the rectangle represent the mean yield (numerical value is shown at the boxplot bottom). The vertical lines above and below the rectangle denote the maximum and minimum, respectively. Circles represent outliers. The criterion for the independence test was based on univariate *p-values* ($\alpha = 0.05$). Note: HY= high-yielding environment, MY= medium-yielding environment, LY= low-yielding environment, and DOY= day of the year.

DISCUSSION

Predicting the opportunity to modify seeding rate by yield environment could represent an opportunity to increase soybean profitability. Thus, the utilization of a large database in combination with hierarchical modeling and Bayesian inference was a powerful statistical approach (Kyveryga et al., 2013; Kyveryga and Blackmer, 2014) to evaluate soybean yield response to seeding rates. At the regional-level, a low probability of increasing yield was recorded for seeding rates above 330 thousand seed ha^{-1}. For the entire database, 90% of the yield plateau was obtained in the seeding rate range from 170 to 320 thousand seeds ha^{-1}. Our findings are in agreement with several studies worldwide (De Bruin and Pedersen, 2008; Epler and Staggenborg, 2008; Lee et al., 2008; Cox et al., 2010; Cox and Cherney, 2011; Luca and Hungría, 2014; Luca et al., 2014; Thompson et al., 2015; Ferreira et al., 2016). Furthermore, conditional inference trees revealed that seeding rate had more influence than maturity and row spacing across yield environments.

Advances in precision agriculture technologies are allowing growers to use site-specific management (Shanahan et al., 2004; McBratney et al., 2005; Khosla et al., 2008; Gebbers and Adamchuk, 2010) such as VRS prescriptions on-the-go to optimize yields and input costs (Shanahan et al., 2004; Hörbe et al., 2013; Butzen, 2016; Smidt et al., 2016). Yield-seeding rate response models across yield environments have been documented for some major crops, such as corn (Hörbe et al., 2013; Assefa et al., 2016; Schwalbert et al., 2018) and canola (*Brasica napus* L. cv. ‘Canola’) (Assefa et al., 2017). Theoretical models recently published for corn, revealed that increasing seeding rate at LY should result in flat or negative yield response (Assefa et al., 2016); while at greater yield environments, a higher number of seed per unit area benefitted yields. Overall, for VRS in corn the optimum seeding rate should follow the order: HY>MY>LY (Hörbe et al., 2013; Assefa et al., 2016; Schwalbert et al., 2018). For canola, yield-to-plant density relationship showed a smaller effect for HY (>2.5 Mg ha^{-1}) and MY (1.5–2.5 Mg ha^{-1}), but a quadratic model was the best fit for the LY environment (Assefa et al., 2017). For soybeans, due to lack of a clear relationship between productivity level, fields are often seeded at a single rate (Smidt et al., 2016). The current study provides more clarity with yield response to seeding rate following the trend: LY>MY>HY environments. When there was a relationship between productivity and seeding rate, Smidt et al. (2016) found similar responses. These outcomes are similar to the response presented in canola (Assefa et al., 2017), but opposite or inverse of that for corn (Hörbe et al., 2013; Assefa et al., 2016; Schwalbert et al., 2018).

A few hypotheses can be postulated for the soybean yield-seeding rate response at the LY. One of them (i) involves the lower ability to compensate for low final stands with more pods and seeds per plant such that yields depend on the individual production per plant (i.e., poor ability of the plants to compensate for the lack of resources); this condition can also be aggravated by potential self-thinning of plants occurring during the growing season due to factors limiting growth. In other words, LY impairs the plants ability to grow faster and reduces inter and intraspecific competition. The results are shorter plants, with less canopy coverage, and lower yield potential. Another important hypothesis (ii) is increased risk of stand failure at LY, limiting stand establishment and increasing the need of seeds to compensate for the lower germination and emergence efficiency.

In soybeans, the compensation mechanism is activated by red/far red light ratios within the canopy during early stages, increasing the dry mass partitioning to branches and consequently, benefiting the pod production per plant (Ball et al., 2000; Board, 2000; Carpenter and Board, 1997; Corassa et al., 2018; Cox et al., 2010; Kasperbauer, 1987; Lehman and Lambert, 1960; Norsworthy and Shipe, 2005; Weber et al., 1966). Overall, plants compensate by developing more seeds per plant with fewer plants. The opposite response occurs at supra-optimal plant densities (Luca and Hungría, 2014; Corassa et al., 2018). Thus, based on the first hypothesis, is probable that the compensation is strongly manifested at HY due to a greater availability of resources, while at LY, it is greatly limited and the increase in seeding rate is the only way to increase yield.

Recent studies performed at high-yielding environments in Brazil showed that soybean was able to maintain yields even under low densities (Luca et al., 2014; Werner et al., 2016). A reduction in the number of plants by 75% resulted in a yield decrease of 16%, but in two other of three cropping seasons yield losses did not occur (Luca et al., 2014). Similarly, a recent study documented that at lower plant densities (88 thousand seeds ha^{-1}) soybean showed a potential to quadruple both photosynthesis and biological nitrogen fixation, resulting in similar yield per unit area than higher densities (362 thousand seeds ha^{-1}) (Luca and Hungría, 2014). Studies with low densities attaining the yield plateau were also found in the U.S. (Thompson et al., 2015).

The second relevant hypothesis to be considered is the higher risk of stand failure at LY; thus, more seed is required to attain a satisfactory stand. Several field and growing season factors not assessed in this analysis might be related to the poor emergence, germination, establishment, or poorer plant survival at LY compared to HY, such as soil temperature and moisture, compaction, and fertility (Butzen, 2016; Smidt et al., 2016; Sivarajan et al., 2018), as well as early-season plant diseases and weed pressure (Gaspar and Conley, 2014; Thompson et al., 2015; Butzen, 2016). Also, some growers find that for LY higher node heights with higher seeding rates for lower ponds within the canopy of these short plants enables greater capability to combine harvest these seeds. Thus, future research should be pursued to better understand the soil, plant, weather and other factors behind the higher seeding rate need at LY than HY across global regions and to provide more precise data layers to VRS prescription on soybeans (Smidt et al., 2016).

Overall, our findings showed an opportunity for within-field VRS prescription across yield environments. Due to the low probability of increased yield with densities >330 thousand seeds ha^{-1} for modern soybean varieties, the main opportunity behind VRS in soybean is based on the possibility of reducing seeding rate in the prescription at HY. In this study, approximately 18% lower number of seeds could be used at HY (> 5 Mg ha^{-1}) compared to LY (< 4 Mg ha^{-1}) without penalizing yields. As mentioned above, adjustments in seeding rates to achieve desired final stand densities should be assumed for environments with high risk of stand losses.

CONCLUSIONS

To the extent of our knowledge, this is the first assessment of a large data set of soybean seed yield response to seeding rate for South Brazil. We concluded that seeding rate prescription can be optimized when yield environment is considered. The most probable optimum seeding rate should follow the trend from high to low: LY>MY>HY. Overall, seeding rate could be reduced by 18% at HY relative to LY environments, without penalizing yields. There may also be instances where growers should increase seeding rates above current levels in LY environments; however, a low probability of yield increase was documented when seeding rates were above 330 thousand seeds ha^{-1}. In this study we provided a new insight for improving soybean profitability by adopting of variable rate seeding. Currently, soybean is among the most important field crops worldwide and seed costs have increased around 80% in the last decade. Following this rationale, the opportunity of seed savings while maintaining yields in HY environments should be considered. However, local considerations such as weed control competition and adjustments in seeding rates to achieve desired final stand densities with stand loss risks are also key factors. Among the covariates evaluated, planting date interacted with seed yield. At high-yielding environments (> 5 Mg ha^{-1}), planting delay after 18 November decreased yields regardless of the seeding rate.

Future research studies should investigate the physiological mechanisms underpinning the yield to seeding rate response related to the yield environments, with the primary role of improving the understanding of the main factors (soil x plant x weather) causing the differential optimum seeding rate response for soybeans.

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4. DISCUSSÃO

Em um contexto agrícola, a adoção de novas tecnologias raramente ocorre de forma imediata (PIERPAOLI et al., 2013). Esse processo ocorre de forma ainda mais lenta, quando a taxa de geração e transferência de informações referentes a aplicabilidade e rentabilidade de tal tecnologia não ocorrem de forma efetiva. Nos últimos anos, inúmeras tecnologias foram disponibilizadas ao mercador agrícola consumidor; grande parte, associadas ao sensoriamento das maquinas/implementos agrícolas. Estas tecnologias visam principalmente a redução de erros durante as operações agrícolas, bem como, a geração de um grande número de informações/dados em um curto espaço de tempo (*big data*). Este último, tem como principal objetivo fornecer suporte para que as decisões futuras sejam cada vez mais precisas e assertivas. De modo geral, mesmo em um cenário de rápido avanço tecnológico e de maior acessibilidade a informação, certas tecnologias – mesmo que promissoras – tem apresentado uma baixa taxa de adoção por parte dos produtores rurais.

Tecnologias que apresentam resultados diretos e que não necessitam habilidades complexas para a sua implementação e/ou funcionamento, são geralmente adotadas de forma mais efetiva. Neste sentido, a tecnologia de desligamento automático de seção, por exemplo, tem recebido destaque no âmbito agrícola mundial. Devido a conectividade entre os sensores embarcados e o sistema de posicionamento da máquina, a tecnologia é capaz de promover economia no uso de insumos, uma vez que reduz a taxa de sobreposição, e consequentemente, o custo de produção. O desligamento automático de seção tem sido amplamente adotado em operações de pulverização, controlando automaticamente os bicos de aplicação (BATTE; EHSANI, 2006; LUCK et al., 2010; LARSON et al., 2016); Este mesmo conceito tecnológico foi recentemente implementado em semeadoras (i.e., controlando automaticamente as linhas), contudo, até o presente momento, poucas informações estavam disponíveis. Neste sentido, o primeiro estudo (artigo I), buscou avaliar os benefícios da tecnologia de desligamento automático de seção em semeadoras para a culturas de milho e soja.

De modo geral, a tecnologia se mostrou altamente promissora, espacialmente para a cultura do milho, onde além da economia de sementes, locais sem sobreposição se mostraram mais produtivos. Assim, do ponto de vista econômico, o retorno do investimento sobre a tecnologia ocorre em um ritmo mais rápido quando o milho for a cultura principal. Outro ponto importante e que contribui para taxa de retorno da tecnologia, diz respeito ao nível de irregularidade dos campos de produção. Campos irregulares, elevam a possibilidade de sobreposição e, portanto, aumentam os benefícios da tecnologia. Neste estudo, o percentual médio obtido para sobreposição durante o processo de semeadura foi de 5,5%. É importante ponderar, no entanto, que mesmo com benefícios claros e palpáveis para com os produtores rurais, especialmente os da região sul do Brasil, onde predominam campos irregulares, um dos grandes entraves para a adoção da tecnologia em larga escala está associado ao seu custo de aquisição. Mesmo assim, é possível prever que em um curto espaço de tempo a tecnologia seja ofertada ao mercado consumidor por um número maior de empresas, bem como, torne-se item de série em novas semeadoras. Tais fatores devem resultar em custos menores e consequentemente, elevar a taxa de adoção da tecnologia por parte dos agricultores. Até onde sabemos, este é o primeiro estudo científico brasileiro focado nesta temática, e por isso os resultados obtidos devem servir como base teórico/prática para novas pesquisas relacionadas ao controle automático de seção em semeadoras, bem como, servir como fonte de auxilio no processo de tomada de decisão sobre a aquisição da tecnologia.

Seguindo uma linha de raciocínio similar e com foco na geração de resultados aplicáveis, e que até o momento, eram considerados vagos na literatura científica, o artigo II teve por objetivo propor diretrizes para a taxa variada de sementes na cultura da soja. Assim, com base em uma abordagem estatística diferenciada, incluindo modelos de inferência bayesiana, o artigo II buscou identificar modelos de resposta da produtividade em função da taxa de semeadura em distintos ambientes de produtividade. A análise foi realizada sob um grande conjunto de dados experimentais (2.180 parcelas), e considerou ainda, fatores secundários que compuseram o banco de dados, como: data de semeadura, espaçamento entre linhas, grupos de maturação, ano agrícola e o local onde os experimentos foram realizados e suas respectivas regiões sojícolas.

De modo geral, os resultados revelaram que em ambientes de alta produtividade (>5 Mg ha^{-1}), a número de sementes ha^{-1} poderia ser reduzido em 18% em comparação a ambientes de baixa produtividade (<4 Mg ha^{-1}), sem penalizar a produtividade. No tocante as prescrições para taxa variada de sementes, as diretrizes obtidas para a cultura da soja são semelhantes as documentadas para a cultura da canola (ASSEFA et al., 2017); contudo, opostas as documentadas para a cultura do milho (ASSEFA et al., 2016; HÖRBE et al., 2013; SCHWALBERT et al., 2018). Ainda, os modelos indicaram uma baixa probabilidade de aumento na produtividade quando as taxas de semeadura estiveram acima de 330 mil sementes ha^{-1}, independente do ambiente de produtividade. É importante ponderar que os modelos devem ser continuamente melhorados, atendendo critérios locais, bem como, condições específicas. Assim, pesquisas futuras devem investigar os mecanismos fisiológicos envolvidos na resposta da taxa de semeadura x produtividade em função dos ambientes produtivos, visando melhorar a compreensão de principais fatores (solo x planta x clima) que conduzem a uma reposta diferenciada. Atualmente, a taxa variada de semente deve ser entendida como uma prática de manejo para propriedades rurais com sistemas de produção ajustados, que já tenham experiência em outros processos de agricultura de precisão (taxa variada de fertilizantes, geração de mapas de colheita) e onde, portanto, problemas básicos de manejo não estejam ocorrendo. Para a adoção da taxa variada de sementes, o conhecimento detalhado das áreas agrícolas é peça chave para o sucesso. Diferentemente de outras tecnologias – como o desligamento automático de seção em semeaduras (artigo I) - a taxa variada de sementes requer um elevado grau de informação e detalhamento das áreas agrícolas para sua aplicabilidade seja plena e satisfatória.

Por fim, os resultados obtidos nos artigos I e II devem contribuir para o avanço do conhecimento a para a adoção de novas técnicas relacionadas a agricultura de precisão. Neste estudo, foram demostrados os benefícios da tecnologia de controle automático de seção em semeadoras, bem como, propostas certas diretrizes para adoção da taxa variada de sementes na cultura da soja. Fatores técnicos, econômicos e aqueles relacionados a resposta fisiológica das plantas foram apresentados e discutidos; no entanto, novos estudos voltados para esses tópicos devem ser conduzidos em diferentes regiões agrícolas do mundo, visando e melhoria continua dos processos.

5. CONCLUSÕES GERAIS

Na extensão do nosso conhecimento, este é o primeiro estudo brasileiro tratando sobre os benefícios da tecnologia de controle automático de seção em semeadoras, bem como uma das análises mais abrangentes sobre a prescrição da taxa ótima de semeadura em soja por ambiente de produtividade, fornecendo diretrizes para a adoção da taxa variada de sementes no sul do Brasil. Os principais resultados obtidos foram:

Artigo I: a) a utilização de controle automático de seção em semeadoras aumentou a rentabilidade das culturas de milho e soja; contudo, em milho os benefícios estiveram ligados a economia de sementes e a maior produtividade em áreas sem sobreposição, enquanto que, na cultura da soja, os mesmo estiveram ligados apenas a economia de sementes; b) as perdas de produtividade em milho em áreas com sobreposição foram maiores em ambientes de baixa produtividade, com perdas associadas à redução no número de grãos por espiga e em menor grau, ao peso de mil grãos; c) as produtividades de soja foram menos sensíveis às áreas com sobreposição devido a uma compensação proporcional no número de sementes por unidade de área; d) quando apenas a cultura do milho foi considerada no sistema de produção, o retorno econômico da tecnologia foi recuperado com uma menor área semeada; e) a proporção média de sobreposição em áreas comerciais foi de 5,5%; no entanto, a sobreposição aumentou significativamente em campos irregulares.

Artigo II: a) a prescrição da taxa de semeadura pode ser otimizada na cultura da soja quando o ambiente de produtividade é considerado; a prescrição de sementes por ambiente mais provável seguiu a tendência: baixo>médio>alto ambiente de produtividade; b), de modo geral, a taxa de ótima de sementes poderia ser reduzida em 18% em ambiente de alta produtividade quando comparados ao ambiente de baixa produtividade, sem penalizar a produtividade; c) para as cultivares de soja testadas, uma baixa probabilidade de aumento de produtividade foi documentada quando as taxas de semeadura estiveram acima de 330 mil sementes ha^{-1}, independente do ambiente de produtividade; d) em ambientes de alta produtividade, além do número de sementes, a data de semeadura mostrou-se um fator significativo sobre a produtividade; a semeadura tardia (após 18 de novembro) resultou em reduções médias de até 15%.

Por fim, o presente estudo oferece uma abordagem sobre o uso de novas ferramentas de agricultura de precisão, visando contribuir para a geração de novos conhecimentos, técnicas de manejo, bem como, para a melhoria da rentabilidade do setor agrícola. As informações aqui geradas devem ajudar produtores rurais, profissionais, e industrias na melhoria continua de seus processos, bem como, contribuir para a tomada de decisões futuras.

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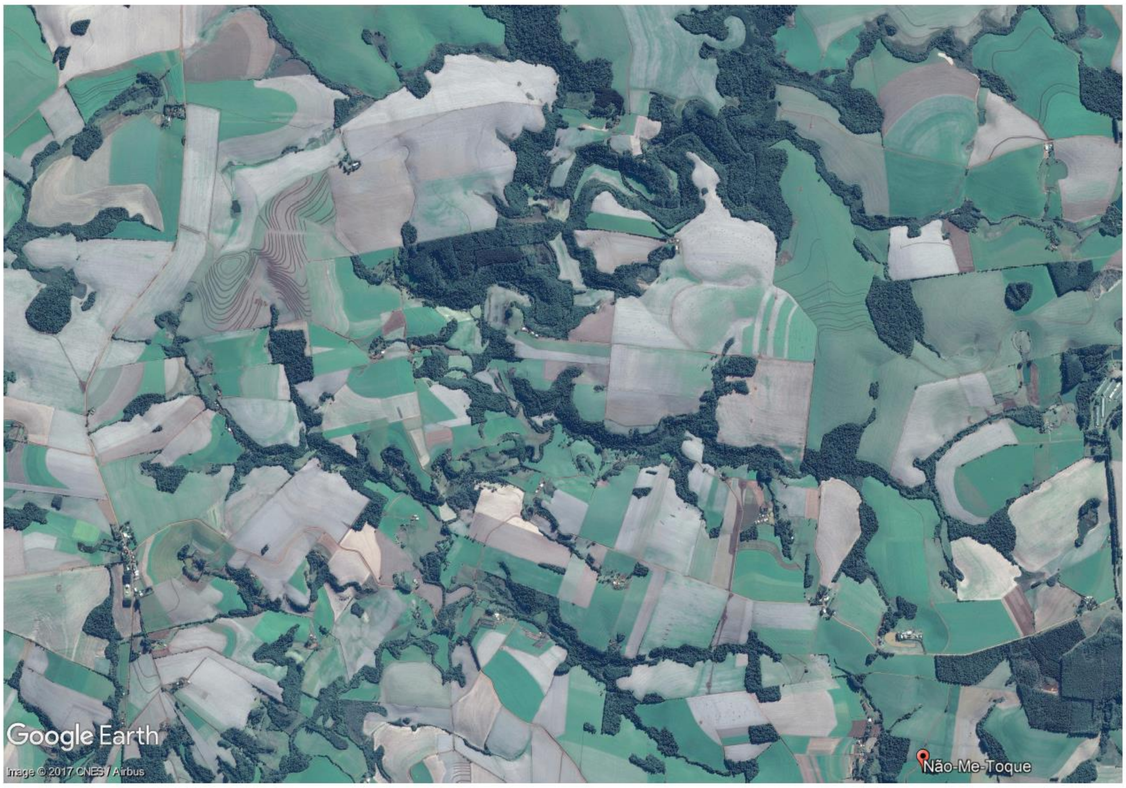
APÊNDICE A – ILUSTRAÇÃO DA FREQUÊNCIA DE CAMPOS IRREGULARES (CONTORNO) EM ÁREAS DE PRODUÇÃO DE GRÃOS NO SUL DO BRASIL



Supplemental Figure 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.

APÊNDICE B – LICENÇA PARA USO DE CONTEÚDO PROTEGIDO POR DIREITO AUTORAIS (ARTIGO I)

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