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Performance of soybean varieties differs according to yield class: a case study from Southern Brazil

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Abstract

Considering environmental conditions in the selection of soybean (*Glycine max* L.) varieties is a key strategy in ensuring high crop yield. Recently, the new technology of multi-hybrid planters has been making it more practical for farmers to plant different varieties together. However, there remains a gap in understanding how different varieties perform in terms of yield class; this knowledge is essential for technology adoption. The objectives of this study were to: (i) evaluate the agronomic performance of six soybean varieties at varying yield class (YC); (ii) quantify the economic return of within-field varieties arrangement; and (iii) propose guidelines for multi-variety soybean planting in Southern Brazil. The experimental design comprised a factorial split-plot set up in a randomized complete block design, with three YC [low (LY), medium (MY) and high yielding (HY)] and six varieties, replicated three times. The main findings were: (a) soybean variety performance differed according to YC; (b) the farmer-selected variety performed well for HY and MY; (c) varieties with high plant height (PH) should be placed in LY, where PH reduction and an increase in the number of pods and yield were recorded; (d) varieties with low PH should be placed in HY, avoiding excessive plant growth and yield penalty; (e) within-field variety arrangement increased yield by 2.10% and 11.50% and economic return by US$ 26 and 137 ha^{-1} for HY and LY, respectively. The results support the emergent concept of within-field multi-variety soybean planting in Southern Brazil.

Keywords *Glycine max* L. · Multi-varieties · Seed yield · Economic return

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Introduction

In agriculture, yield class can be defined as sub-regions with differential performance of crop yield potential, generally resulting from a complex interaction between soil, weather and management practices and their respective impact on plant growth (Assefa et al. 2016; Khosla et al. 2008; Shanahan et al. 2004). By delineating yield class within-field, farmers can apply several site-specific strategies according to the spatial variability, instead of managing the whole field uniformly (Bunselmeyer and Lauer 2015; Jaynes et al. 2005; Schepers et al. 2004). This enables them to achieve greater input efficiency and increased crop yield while reducing production costs and environmental impacts (Gebbers and Adamchuk 2010; Khosla et al. 2008; Robertson et al. 2012; Shanahan et al. 2004).

Managing yield spatial variability is also a potential strategy for reducing disparities between current yield, attainable yield (i.e., yield under optimal management practices at a field level) and the yield potential (Bunselmeyer and Lauer 2015; van Ittersum et al. 2013); the last of these is defined as the crop yield when provided with non-limiting nutrients and water and with effective control of biotic stress (Evans and Fisher 1999; van Ittersum and Rabbinge 1997). It is feasible to produce these conditions within experimental plots; however, challenges remain in scaling up to the extent of a whole field, given that within-field spatial variability leads to variations in crop performance (Amado and Santi 2011; Van Roekel et al. 2015).

Globally, Brazil is the second largest producer of soybean. With 32 Mha, the soybean crop area in Brazil represents approximately 55% of the total area for grain production (Conab 2015). However, the national soybean average yield is still low, at approximately 3.0 Mg ha^{-1}. Efficiently increasing the yield is dependent on a complex combination of genetic attributes, optimal environmental conditions and crop management (Evans and Fisher 1999; van Ittersum and Rabbinge 1997; Van Roekel et al. 2015). Furthermore, farmers are being challenged to redesign crop management strategies in order to exploit recent improvements in the genetic potential of modern soybean varieties; for example, approaches related to planting date, plant density, row spacing and optimum plant nutrition have been investigated in several studies (Conley et al. 2008; Cox and Cherney 2011; Pedersen and Lauer 2004; Salmeron et al. 2014). However, little research has been conducted into strategies that take into account interactions between varieties field-scale spatial variability and environmental conditions.

In this context, fine-tuning according to yield class has potential as a new precision agriculture (PA) tool for improving soybean performance. One such approach under investigation as a new crop management strategy is the precision placement of varieties/hybrids within-field (Jeschke and Shanahan 2015; Shanahan et al. 2004). Popp et al. (2002), Norsworthy and Shipe (2005) and Thomas and Costa (2010) have reported that taking account of environmental conditions and associated with optimal plant density when placing soybean variety within a field is frequently the main driver of high yields. This possibility is now available in the form of "smart planters" technology (Jeschke and Shanahan 2015; Shanahan et al. 2004), such as the Kinze 4900 Multi-Hybrid Planter® (KINZE Manufacturing Inc., Williamsburg, IA, USA), that use an electric drive to enable on-the-go planting of two soybean varieties, while automatically adjusting for plant population parameters.

Adopting this emerging technology strictly relies on understanding the performance of different crop varieties within different yield classes. Farmers currently select the most productive variety for planting across a whole field. However, this is based on previous results, which will normally have been obtained from high yield class. The alternative multi-varieties planting approach can be better understood using the analogy of a football team, in which each player has a specific skill set that means they perform better in specific positions on the field. In considering how to apply this strategy successfully to the placement of soybean varieties within a field, it was hypothesized that robust and stress-tolerant varieties should be planted in low yielding classes, while lodging-tolerant varieties should be planted in high yielding classes. Therefore, the objectives of this study were to: (i) evaluate the agronomic performance of six soybean varieties in varying yield classes; (ii) quantify the economic return of within-field varieties arrangement; and (iii) propose guidelines to the emerging concept related to multi-variety soybean planting in Southern Brazil.

Materials and methods

Site description

Two on-farm experiments, located near Boa Vista das Missões, in the northwest of Rio Grande do Sul State (RS), Brazil, were carried out in co-operation with a farmer during the 2013/2014 growing season. Both sites comprised rainfed fields in an agro-ecoregion that is one of the major areas for soybean production in RS. The fields were located near each other: the co-ordinates were 27°42′58.42″S and 53°19′59.46″W (site 1) and 27°43′17.71″S and 53°20′43.80″W (site 2), and their area was 117.14 ha and 107.90 ha, respectively. Both fields were characterized by a rolling relief; their soil was classified as Typic Hapludox (Soil Survey Staff 2014). Soil samples were taken from each yield class before planting and analyzed using the standard methods described in Tedesco et al. (1995). The chemical and physical attributes of the soil are shown in Table 1. According to the Köppen classification, the regional climate is Cfa (humid subtropical), with an average annual temperature of 18.1 °C and average rainfall of 1919 mm (Maluf 2000). During the experiment, rainfall was recorded at a private weather station located approximately 0.5 km from the experimental fields. The accumulated rainfall was measured to be 964 mm during the soybean growing season (Fig. 1), which is satisfactory to meet the demands of soybean crops (Zanon et al. 2016).

Table 1 Soil chemical and physical properties (0.00–0.20 m soil depth) of yield class (YC) for sites 1 and 2

Site	YC	Clay	pH	P^a	K^+	Ca^{2+}	Mg^{2+}	SOM	BS	Al^{3+}	CEC
		%	H_2O 1:1	mg dm^{-3}		$cmol_c$ dm^{-3}		%		$cmol_c$ dm^{-3}	
1	High	63b*	5.4b	21.4a	60.4a	6.2a	3.9a	3.3a	60b	0.6a	15.2a
	Medium	66b	5.7a	15.5b	58.3a	6.1a	3.3a	2.7b	68a	0.3a	14.1b
	Low	76a	5.7a	9.6c	58.3a	6.2a	3.4a	2.7b	68a	0.2a	14.3b
2	High	60b	5.8b	24.0a	67.9b	7.3a	3.9a	3.2a	66a	0.3a	17.0a
	Medium	60b	6.1a	22.2a	98.8b	7.8a	4.2a	3.0b	75a	0.0b	16.2a
	Low	76a	5.8b	9.8b	175.8a	6.0a	3.4a	3.0b	67a	0.2a	14.7b

[a] *P* phosphorus extracted by Mehlich-1, *K^+* potassium extracted by Mehlich-1, *Ca^{2+}* calcium, *Mg^{2+}* magnesium, *SOM* soil organic matter, *BS* base saturation, *Al^{3+}* aluminum, *CEC* cation exchange capacity pH of 7.0

*Means followed by same letter do not differ significantly between yield class in each site (Tukey's test, $\alpha = 0.05$)

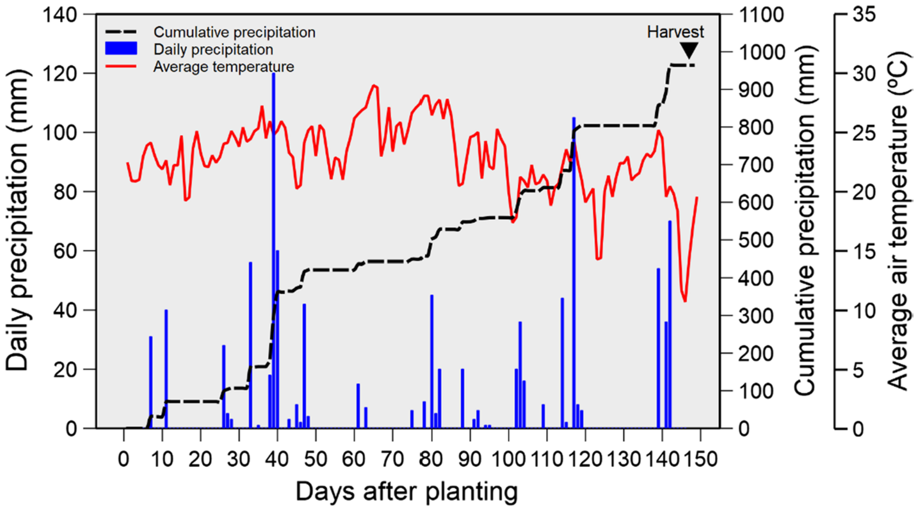

Fig. 1 Daily and cumulative precipitation, and average air temperature registered during soybean growing season for sites 1 and 2, located near each other

Both fields had previously been managed under a long-term no-tillage system (> 15 years). The cropping system was characterized by 3 years of soybean, followed by one of corn (cultivated in different years for each field) during the summer, and black oat (*Avena strigosa* L.) and white oat (*Avena sativa* L.) as a fall/winter cover crop before planting soybean. Black oat was intercropped with oil radish (*Raphanus sativus* L. var. *oleiferus* Metzg.) before planting corn, while wheat (*Triticum aestivum* L.) was used every 3 years.

Delineation of yield class

A set of yield data (yield maps) was available for the study fields, covering the period from 2008 to 2013. Yield mapping was performed using a CASE® Axial-Flow 2399 combine (CNH Industrial Group, Sorocaba, SP, Brazil) equipped with a CASE IH Advanced Farming System (AFS®), which contained an impact-based yield sensor and moisture sensor (adjusted to 130 g kg^{-1}). The yield classes (YC) were delineated using the established method of relative yield (Adamchuk et al. 2004; Molin 2002; Santi et al. 2013); in order to meet the requirements of this approach, a minimum of three yield maps from either the same or a different crop (Mantovani et al. 2007; Santi et al. 2013). The following crop yield maps were used: site 1—white oat (2008 growing season), corn (2008/2009) and corn (2012/2013); and site 2—corn (2009/2010), wheat (2012) and soybean (2012/2013). Storage issues resulted in the data gap between years in 2010 and 2011.

In order to evaluate in-field temporal variations in yield and to allow comparisons to be made between the yield maps of different crops (i.e., so that each crop type carried the same weight in the analysis), yield was treated using relative values (Amado and Santi 2011; Adamchuk et al. 2004; Molin 2002). Thus, in delineating YC, yield maps were analyzed as follows: (i) yield data for each crop in all years were filtered according to the same spatial grid cells (30 × 30 m), and data with a coefficient of variation (CV) > 30% in each cell were eliminated according to the method proposed by Blackmore and Moore (1999) and Menegatti and Molin (2004); (ii) the yield for each cell and each map was relativized—partial relative yield (RY partial)—as the ratio of the actual to average field yield (Adamchuk et al. 2004), calculated as follows:

$$\text{RY partial}\,(\%) = \frac{\text{Actual yield}}{\text{Field yield average}} \times 100 \tag{1}$$

Finally, (iii) the final relative yield—RY (%)—over time (i.e., average of all maps) was calculated as the sum of the relative yield values in each year (Eq. 1) divided by the number of the years (N) (Adamchuk et al. 2004) (Eq. 2). The value for RY (%) final was combined into a final single map (Fig. 2).

$$\text{RY final}\,(\%) = \frac{\text{RY partial}_{\text{year 1}} + \text{RY partial}_{\text{year 2}} + \text{RY partial}_{\text{year 3}}}{\text{N}} \tag{2}$$

The standardized data values calculated using Eq. 2 were grouped into three YC, which were based on relative yield levels (Molin 2002): low yielding (LY), relative yield < 95% and CV < 30%; medium yielding (MY), relative yield between 95 and 105% and CV < 30%; and high yielding (HY), relative yield higher than 105% and CV < 30% (Molin 2002) (Fig. 3). The Quantum GIS Software (QGIS Development Team 2015) was used for this approach.

Experimental design, soybean varieties and growing conditions

The experiments were set up on each site as a factorial split-plot in a randomized complete block design, with three replicates. The replicates were nested within the main plots, which comprised three YC (LY, MY and HY). The YC were each divided into sub-plots of six soybean varieties: BMX Ativa RR® (Brasmax Genetics, Passo Fundo, RS, Brazil), Fundacep 65 RR® (CCGL Technology, Cruz Alta, RS, Brazil), FPS Urano RR® (Fundação Pró sementes, Passo Fundo, RS, Brazil), FPS Júpiter RR® (Fundação Pró sementes, Passo Fundo, RS, Brazil), NA 5909 RG® (Nidera seeds, São Paulo, SP,

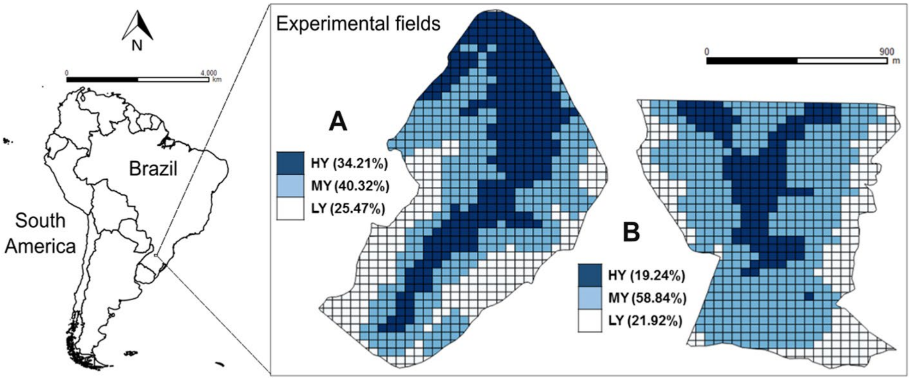

Fig. 2 Location and spatial distribution of yield class delineated by multi-year yield analysis and classified according to relative yield level. Low yielding (LY), relative yield < 95%, and CV < 30%; medium yielding (MY), relative yield between 95 and 105% and CV < 30%; and a high yielding (HY), relative yield higher than 105% and CV < 30% (Molin 2002). A) site 1, and B) site 2

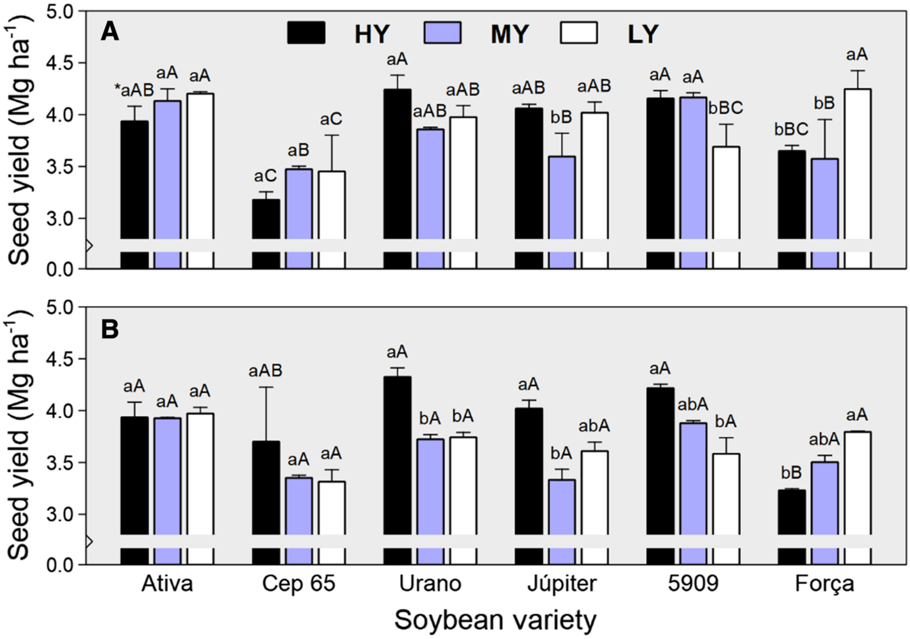

Fig. 3 Seed yield of six soybean varieties in three yield classes (*HY* high yielding, *MY* medium yielding, *LY* low yielding) for site 1 (**a**) and site 2 (**b**). *Different lowercase letters indicate significant difference between yield class for each variety, and different uppercase letters indicate significant difference between soybean varieties within each yield class, according to Tukey's test (α = 0.05). Error bars represent the standard deviation

Brazil) and BMX Força RR® (Brasmax Genetics, Passo Fundo, RS, Brazil). Each variety was planted in plots of area 19.25 m^2. Table 2 sets out the agronomic characteristics of these soybean varieties; the commercial (shortened) names are used to refer to the soybean varieties throughout this manuscript.

The seeds were chemically treated using a formulated mixture of Fludioxonil (25 g a.i. L^{-1}) + Metalaxyl-M (10 g a.i. L^{-1}) at a dose of 0.1 l 100 kg^{-1} of seeds, and Thiamethoxam (350 g a.i. L^{-1}) at a dose of 0.2 l 100 kg^{-1} of seeds. All seeds were also treated with *Bradyrhizobium japonicum*. Soybean varieties were planted on November 26, 2013, at site 1 and November 28, 2013, at site 2. Rows were spaced 0.50 m apart, and the plant density was that recommended for each variety (Table 2), taking into account germination tests performed in the seed lot (Table 3).

Mineral fertilization was based on the average soil fertility and a yield prospect of 4.8 Mg ha^{-1}, in agreement with the farmer's preference. The fertilizer inputs were 16.5 kg N ha^{-1} and 78 kg P_2O_5 ha^{-1} (mono-ammonium phosphate [MAP]) (11-52-00, N-P_2O5-K_2O), placed along the plant rows and 120 kg K_2O ha^{-1} [potassium chloride (KCl)] (00-00-60, N-P_2O5-K_2O), which was broadcast on the soil surface 10 days before planting. Variability between YC was therefore maintained by ensuring uniform treatment. The farmer undertook control of weeds, insects and disease as required, according to best management practice, using herbicides, insecticides and fungicides specifically recommended for soybean crops. These control activities were applied to the whole field.

Table 2 Agronomic characteristics of soybean varieties tested in sites 1 and 2

Feature[a]	BMX Ativa RR	Fundacep 65 RR	FPS Urano RR	FPS Júpiter RR	NA 5909 RG	BMX Força RR
Seed Company	Brasmax Genetics	CCGL Technology	Brasmax Genetics	Brasmax Genetics	Nidera Seeds	Brasmax Genetics
Commercial name	Ativa	CEP 65	Urano	Júpiter	5909	Força
Height	Low	Low	Low	Medium	Medium	High
Maturity Group	5.6	5.9	6.2	5.9	5.9	6.2
Growing season (days)	125	130	135	130	130	135
Growth habit[b]	D	D	D	I	I	I
1000-seed weight (g)	174	144	164	142	155	174
Flower color	Purple	White	Purple	White	Purple	White
Required soil fertility	High	High	Medium/High	High	Medium/High	Medium/High
Branching ability	Low	Medium/High	Medium/High	Medium/High	High	High
Plants ha^{-1} recommended[c]	350 000	300 000	300 000	350 000	300 000	300 000

[a] Based on the macro-region 1 (Southern Brazil) and physiographic sub-region 102 (Northwest of Rio Grande do Sul)

[b] Growth habit: D = Determined; I = Indetermined

[c] Information obtained from company

Table 3 Seed vigor and germination of soybean varieties used in the experiments

	Soybean variety					
Parameters[a]	Ativa	CEP 65	Urano	Júpiter	5909	Força
Seeds vigor (%)	89	86	86	84	85	85
Seeds germination (%)	92	89	88	87	90	91

[a] Tests based on Brazilian rules for seed analysis (Brasil 2009)

Plant measurements and sampling

The leaf area index (LAI) of the vegetative canopy was measured at the soybean R2 (full flowering) stage (Fehr et al. 1971), using an LAI-2200C Plant Canopy Analyzer (LI-COR Corporate, Lincoln, NE, USA). Six sets of LAI measurements (each comprising a single above-canopy and four below-canopy measurements) were acquired at random locations in each plot. Seed yield measurements were based on hand-harvested plots and obtained from an area of 13.5 m^2 in each plot, excluding the borders. Seed moisture was determined and adjusted to 130 g kg^{-1}. In addition, ten plants per plot were collected during harvesting (the R8 stage) and evaluated individually to determine the following yield components: plant height (PH), number of pods per stem (NPS), number of pods on branches (NPB), number of pods per plant (NPP) and 1000-seed weight (TSW, g) adjusted to 130 g kg^{-1}.

Economic analysis

The soybean selling price was based on the Brazilian market price and set at US$ 0.30 kg^{-1} in the economic analysis (economic return—EC), which also took account of the seed cost for each variety: US$ 34.8 ha^{-1}, US$ 20.8 ha^{-1}, US$ 25.8 ha^{-1}, US$ 25.8 ha^{-1}, US$ 24.2 ha^{-1} and US$ 27.2 ha^{-1} for the varieties Ativa, CEP 65, Urano, Júpiter, 5909 and Força, respectively. Seed price was also based on regional market prices. Based on the selling price and seed cost, and the seed yield obtained from each variety in each YC, the EC was individually calculated for all varieties, and into each YC. Variety 5909 was assumed to be the traditional variety for the purposes of the study since the farmer selected it for planting in the remainder of the field in both sites 1 and 2.

Statistical approach

Data were analyzed by analysis of variance (ANOVA), using SAS software version 9.4 University Edition (SAS Institute 2016). Data normality and the data for each dependent variable were tested using UNIVARIATE and GLIMMIX procedures in the SAS software, respectively. The YC and soybean varieties were considered as fixed effects, while replicates (blocks nested within the YC) were considered as random effects. When differences among treatments were detected ($P \leq 0.05$), Tukey's test ($\alpha = 0.05$) was used to identify significant differences among means, using SLICE statement in the SAS software (SAS Institute, 2016). The relationship between seed yield and yield components were evaluated using REG procedure (SAS Institute, 2016). Due to the difference in yield maps used for the delineation of YC in each experimental site (i.e., different crops were used in each site) as well as the difference on planting data, the statistical analysis was performed separately for each site.

Results and discussion

Soybean seed yield and yield components

The results from ANOVA revealed significant interaction between YC and soybean varieties (SV) for seed yield at both sites (Table 4). At site 1, in the HY, the variety Urano showed the highest seed yield (4.24 Mg ha^{-1}), but this was not significantly different from varieties 5909 (farmer-selected), Júpiter and Ativa, which achieved seed yields of 4.16, 4.06 and 3.94 Mg ha^{-1}, respectively (Fig. 3a). In the MY of site 1, the varieties 5909, Ativa and Urano attained superior yields compared with the other varieties evaluated. The documented yields for these varieties were 4.17, 4.13 and 3.86 Mg ha^{-1}, respectively. Lastly, in the LY of site 1, the varieties Força, Ativa, Júpiter and Urano presented the highest response, yielding 4.25, 4.20, 4.02 and 3.98 Mg ha^{-1}, respectively, while the varieties CEP 65 (3.37 Mg ha^{-1}) and 5909 (3.69 Mg ha^{-1}) comprised the lowest yield group (Fig. 3a). At site 2, the varieties Urano, 5909, Júpiter and Ativa showed the highest performance in the HY (4.25, 4.20, 4.02 and 3.98 Mg ha^{-1}, respectively), whilst in the MY

Table 4 Probabilities of seven agro-morphological traits on three yield classes (YC) and six soybean varieties (SV) and their interactions in sites 1 and 2

Site	Parameter	Source of variation[a]			CV[b]
		YC	SV	YC × SV	
1	Leaf area index	0.0048**	< 0.0001**	0.0258*	13.64
	Plant height (cm)	0.0047**	< 0.0001**	0.5250^{ns}	5.51
	Pods^{-1} plant	0.7323^{ns}	< 0.0001**	0.1553^{ns}	13.60
	Pods^{-1} stem	0.9453^{ns}	0.0533ns	0.0011**	14.02
	Pods^{-1} branches	0.7367^{ns}	< 0.0001**	0.5081^{ns}	25.66
	1000 seeds weight (g)	0.0498*	< 0.0001**	0.1470^{ns}	5.33
	Seed yield (Mg ha^{-1})	0.1478^{ns}	< 0.0001**	< 0.0001**	5.07
2	Leaf area index	0.0266*	0.0462*	0.0269*	22.15
	Plant height (cm)	0.6807^{ns}	< 0.0001**	0.6575^{ns}	6.50
	Pods^{-1} plant	0.0802^{ns}	0.0014**	0.1442^{ns}	15.77
	Pods^{-1} stem	0.0955^{ns}	< 0.0001**	0.0135*	10.86
	Pods^{-1} branches	0.0307*	0.0034**	0.2484^{ns}	34.00
	1000 seeds weight (g)	0.8213^{ns}	< 0.0001**	0.5398^{ns}	4.94
	Seed yield (Mg ha^{-1})	0.0086**	0.0005**	0.0208*	7.44

[a] Degrees of freedom: YC = 2, SV = 5, YC × SV = 10

[b] Coefficient of variation (%)

*Significant at $P < 0.05$

**Significant at $P < 0.01$

^{ns}not significant

and LY, no significant difference was found between varieties. At site 1, YC showed no significant effect on seed yield for Ativa, CEP 65 and Urano, despite a slight increase (6.27%) for Urano in the HY compared to MY and LY (Fig. 3a). The variety 5909 yielded 11.21% more ($P \leq 0.05$) in the HY than LY but with no difference when compared to the MY (Fig. 3a). Conversely, the result for Força was in contrast to this, yielding 14.06 and 14.83% higher in the LY than HY for sites 1 and 2, respectively (Fig. 3).

The better performance of Força in the LY was probably associated with certain of its characteristics, such as superior height and higher branching capacity when compared to the other varieties investigated (Table 2). In the LY, this variety appeared to use reduced growth and an increase in the number of pods as a compensatory mechanism for the low yield environment (Board 2000; Carpenter and Board 1997; Kasperbauer 1987). This hypothesis was supported by a linear regression analysis, which revealed a negative relationship between yield and PH for the variety Força at both sites (Table 5). Additionally, Força showed a positive trend between seed yield, NPP and NPS (Table 5). These results could also be related to the distinct soil fertility levels among the YC, since HY (regardless of site) presented superior soil organic matter (SOM) content and phosphorus (P) levels than LY (Table 1). The seed yield and dry mass production of soybean increases in soils with higher levels of available P (Anthony et al. 2012; Corrêa et al. 2004), while SOM content is an integrated soil quality indicator (Franzluebbers 2002), contributing to increases in

Table 5 Significant linear regressions between seed yield and yield components of six soybean varieties for sites 1 and 2

Site	Variety	Yield component[a]			
		NPP	NPS	NPB	PH
1	Júpiter	–$^{(ns)}$	–	–	–
	5909	–	–	$y = -18.74 + 1.62x - 0.028x^2$ $R^2 = 0.70$*	–
	CEP 65	–	–	$y = 4.38 - 0.067x$ $R^2 = 0.48$*	–
	Urano	–	–	–	$y = 40.5 - 1.14x + 0.0089x^2$ $R^2 = 0.72$*
	Ativa	–	–	$y = 3.67 + 0.045x$ $R^2 = 0.61$*	–
	Força	$y = 2.48 + 0.029$ $R^2 = 0.55$*	$y = 2.75 + 0.041x$ $R^2 = 0.52$*	–	$y = 6.48 - 0.034x$ $R^2 = 0.45$*
2	Júpiter	–	–	–	–
	5909	–	–	$y = 2.92 - 0.055x$ $R^2 = 0.48$*	–
	CEP 65	–	–	–	–
	Urano	–	–	–	–
	Ativa	–		–	–
	Força	$y = 2.42 + 0.023x$ $R^2 = 0.45$*	$y = 2.35 + 0.037x$ $R^2 = 0.60$*	–	$y = 6.56 - 0.030x$ $R^2 = 0.44$*

[a] *NPP* Number of pods per plant, *NPS* number of pods per stem, *NPB* number of pods on branches, *PH* plant height (cm)

*Significant $P < 0.05$

**Significant $P < 0.01$

^{ns}not significant

chemical (Kaiser et al. 2008), physical (Bronick and Lal 2005), hydric (Rawls et al. 2003), and biological (Hargreaves 2003) soil properties. Greater soil fertility in the HY resulted in an excessive vegetative growth of Força variety, causing a yield disadvantage.

Compact soybean plants are photosynthetically more efficient, once they are able to extend the photosynthetic capacity in the bottom layer of their leaves (Board 2000; Carpenter and Board 1997; Kasperbauer 1987), resulting in a superior NPP (Liu et al. 2010). This might explain the negative relationship between PH and seed yield observed for the Força variety (Table 5). In experiments carried out in Kentucky (USA), Egli (2013) concluded that until up to a critical number of nodes, photosynthetic capacity is more relevant to pod production than the number of nodes. Thus, in deciding on the correct variety placement for each YC, it is necessary to consider compensation mechanisms of each soybean variety as intrinsic factors (Board 2000; Carpenter and Board 1997; Salmeron et al. 2014).

Following the same trend reported for site 1, in site 2, 5909 showed a yield increase in the HY of 15.01%, in comparison with the LY (Fig. 3). A relationship between greater yield and HY (i.e., high yield environment) has been commonly reported for corn (Assefa et al. 2016; Hörbe et al. 2013), but less often for soybean (Smidt et al. 2016); this is probably a function of distinct performance among varieties (Van Roekel et al. 2015). In this study, the variety Urano showed a better yield performance (13.45%) in HY compared to LY (Fig. 3B). Urano presents a similar maturity group to Força, but with a lower PH, which can justify the former's better performance in the HY. A negative relationship between seed yield and PH was found for Urano (site 1) and Força (both sites) (Table 5). This suggests that medium- to short-height soybean varieties (bush-type), such as Ativa, Urano, and 5909 (Table 2) should preferentially be placed in a greater YC, because the superior soil fertility (i.e., P and SOM content) (Table 1) does not induce excessive vegetative plant growth and consequent yield penalty. Souza et al. (2013) reported that when growth reducers were applied to reduce PH in soybean, the result was an increase in plant lodging tolerance, NPP, seeds per pod and seed weight. This strategy (i.e., use of soybean growth reducers) was not evaluate in the current study; however, it should be considered in further studies as an alternative method of reducing PH in high YC. Ativa was the most productive and stable variety at both sites, showing similar yields across all three YC (Fig. 3). Thus, Ativa could be classified as a defensive variety, given its stable performance between different YC. This effect is probably related to the superior plant density recommended for this variety (Table 2), which could compensate at some levels for the lower single plant yield in LY (Board 2000; Cox and Cherney 2011).

The distinct performance of soybean varieties between YC documented in the present study is in agreement with results reported for corn (Assefa et al. 2016; Hörbe et al. 2013). Maddonni et al. (2001) and Sangoi et al. (2002) reported that planting a modern corn hybrid does not always provide a greater yield than other hybrids; hybrids differ in their architecture, optimum plant density and comparative relative maturity, all of which drive differences in performance depending on factors such as water supply, environmental conditions and site-specific soil attributes. For soybean, the relationship between variety and environmental conditions has less frequently been explored, but could also play a role in reducing within-field seed yield variability (Anthony et al. 2012; Smidt et al. 2016). Recently, Salmeron et al. (2014) have reported that environmental conditions were responsible for close to 40% of observed yield variation, while the interaction between soybean varieties and the environment was responsible for more than 20%.

Despite the significant interaction ($P < 0.05$) between SV and YC for LAI, only 5909 (site 1) and Força (site 2) varieties presented significant differences between YC (Fig. 4). No relationship between LAI and seed yield was observed for the varieties evaluated

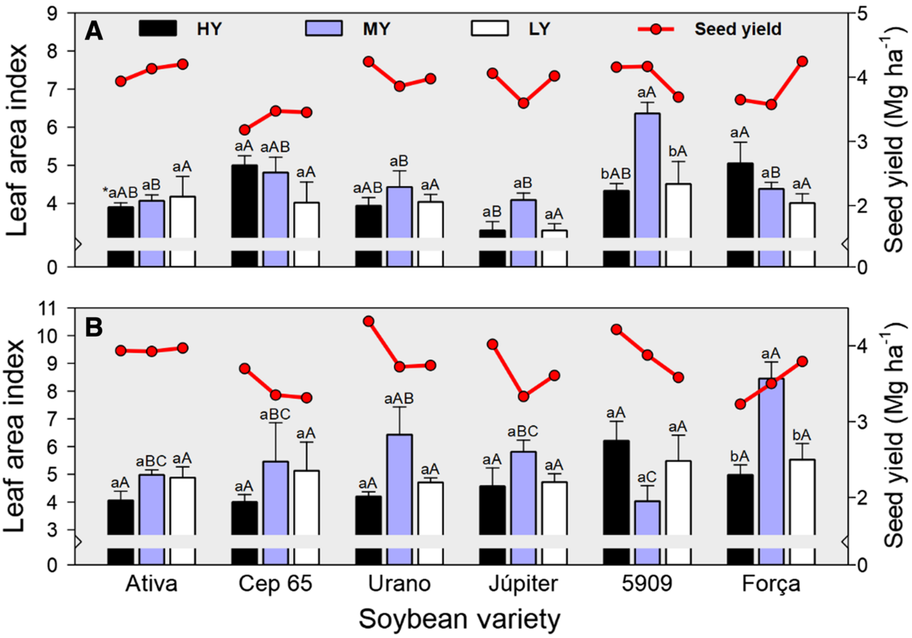

Fig. 4 Leaf index area (LAI) of six soybean varieties in the three yield classes (*HY* high yielding, *MY* medium yielding, *LY* low yielding) for site 1 (**a**) and site 2 (**b**). *Different lowercase letters indicate significant difference between yield class for each variety, and different uppercase letters indicate significant difference between soybean varieties within each yield class, according to Tukey's test (α = 0.05). Red dots connected by straight lines indicate the average seed yield of varieties across yield classes. Error bars represent the standard deviation

(Table 5). According to Board and Harville (1992), LAI values ranging between 3.5 and 4.0 during R1 and R2 reproductive stages, result in a suitable light interception, resulting in satisfactory net rates of photosynthesis, and consequently improved seed yield (Board and Harville 1992; Heiffig et al. 2006). In the present study, all investigated varieties reached appropriate LAI levels (3.5 to 4.0) at the R2 stage. Thus, probably the factors that affected the grain filling are not consistently connected with the factors that contribute to LAI. On the other hand, superior LAI levels (above optimum) can occur in HY. The resultant self-shading could decrease the lifespan of the lower leaves and therefore decrease the photosynthetic capacity of the plant (Board 2000). In addition, leaf diseases could also increase in severity (Lima et al. 2012), decreasing yield (De Bruin and Pedersen 2008; Walker et al. 2010).

The varieties Ativa and 5909 shared the highest TSW at both sites (Table 6). TSW is one of the components driving soybean yield (Ludwing et al. 2010; Thomas and Costa 2010); however, no significant relationship was found between TSW and seed yield for varieties investigated (Table 5). There is a variety-dependent relative contribution of each yield component on seed yield. In general, for soybean, the number of pods, number of seeds per pod and the seed weight are the most important components (Navarro Junior and Costa 2002; Thomas and Costa 2010). On average, TSW was numerically higher in the LY in comparison with other YC for site 1, with a similar result for site 2 (Table 6). De Bruin and Pedersen (2008) reported that the number of seeds per plant is generally more relevant

Table 6 Yield components of six soybean varieties and three yield classes for sites 1 and 2

	Site 1				Site 2			
	PH[a]	NPB	NPP	TSW	PH	NPB	NPP	TSW
Soybean varieties								
Ativa	61.0 c*	8.7 d	33.3 d	149.4 a	63.4 d	13.1 ab	40.2 ab	150.6 a
CEP 65	76.4 b	15.2 bc	37.3 cd	126.9 c	70.3 cd	16.6 a	36.6 b	133.8 cd
Urano	61.5 c	15.0 bc	42.0 bc	138.1 b	63.6 d	16.6 a	47.5 a	145.0 ab
Júpiter	74.2 b	11.0 cd	35.6 cd	150.2 a	85.7 b	8.8 b	37.6 b	140.5 bc
5909	66.0 c	29.2 a	50.3 a	152.2 a	76.6 c	18.7 a	39.8 ab	148.9 ab
Força	89.2 a	19.4 b	45.4 ab	128.7 bc	100.7 a	16.2 a	47.7 a	125.7 d
Yield class[b]								
HY	71.7 ab	16.3 ns	40.5 ns	137.5 b	77.2 ns	12.1 b	38.9 ns	140.4 ns
MY	73.5 a	15.9	40.1	141.4 ab	75.8	17.6 a	43.9	141.6
LY	68.9 b	17.0	40.5	143.8 a	77.1	14.6 ab	42.0	140.3

[a] *PH* plant height (cm), *NPB* number of pods on branches, *NPP* Number of pods per plant, *TSW* thousand seed weight (g)

[b] *HY* high yielding, *MY* medium yielding, *LY* Low yielding

*Means followed by the same letter do not differ significantly (Tukey's test, α = 0.05)

ns not significant

than seed weight for soybean yield, due to the dependence of crop management (Board and Maricherla 2008). This explains the greater yield of Força variety in the LY in the present study. Despite its lower TSW compared to other varieties, it showed an increase in NPS in the LY (Fig. 5). On average, Força showed the highest PH at both sites (Table 6), a result which is related to its phenotypical characteristics. This variety also showed a yield reduction in the HY (with superior soil quality), due to excessive vegetative crop growth (Table 5). This finding could be used as an indicator concerning the outcomes of the variable rate seeding in soybean (Smidt et al. 2016), which suggest reducing and increasing plant densities in HY and LY environments, respectively. This approach can achieve the goal of equalizing vegetative growth in both YC. This hypothesis should be tested in future studies.

Partial EC for within-field soybean multi-variety arrangements

The results of a partial EC analysis considering the seed cost and yield obtained in each YC are shown in Table 7. In the HY at both sites, a superior net income was obtained with 5909 and Urano (Table 7), a result associated with the superior yield and low seed cost of these varieties (Fig. 3). Força and CEP 65 provided the lowest net income in the HY, regardless of site. In the MY, 5909 and Ativa provided the highest net income, while Ativa and Força provided a higher net income in the LY of sites 1 and 2, respectively. Despite the higher cost of their seed, Ativa and Força were the most productive in the LY (Fig. 3), resulting in superior results from the EC.

The numerical difference shown for the EC between the investigated varieties and traditional variety selected by the farmer (5909; baseline) is shown in Fig. 6. The traditional variety showed a satisfactory economic output in the HY, but the variety Urano showed

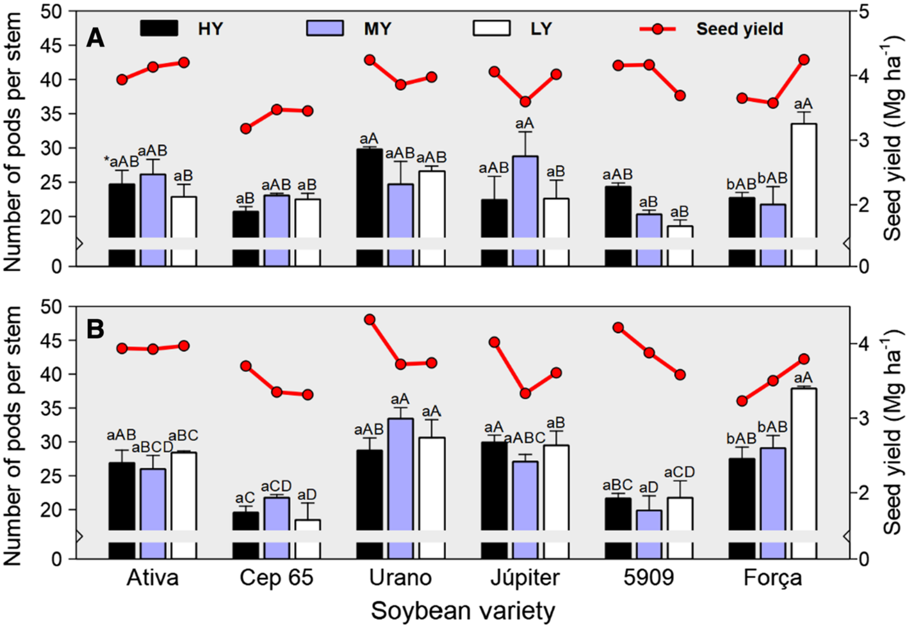

Fig. 5 The number of pods per stem (NPS) of six soybean varieties in the three yield classes (*HY* high yielding, *MY* medium yielding, *LY* low yielding) for site 1 (**a**) and site 2 (**b**). *Different lowercase letters indicate significant difference between yield classes for each variety, and different uppercase letters indicate significant difference between soybean varieties within each yield class, according to Tukey's test ($P < 0.05$). Red dots connected by straight lines indicate the average seed yield of varieties across yield classes. Error bars represent the standard deviation

a slightly higher net return value of US$ 22.84 ha^{-1} (1.8%) and US$ 28.90 ha^{-1} (2.30%) for sites 1 and 2, respectively (Fig. 6). It is important to highlight that a satisfactory performance by the traditional variety in the HY was expected because the farmer selected this variety based on results (i.e., seed yield of each variety) of a private company rank test; these tests are usually carried out in high YC. Yield reductions might, therefore, be expected when these varieties are planted in low YC. For site 1, the highest EC in the MY was obtained with variety 5909, while Ativa showed a slightly higher result in site 2. Conversely, the EC for 5909 was not satisfactory in LY, similar to the performance of CEP 65.

Compared to the farmer-selected variety, the highest EC for the LY was provided by Força (15.24%) and Ativa (10.13%) at sites 1 and 2, respectively (Fig. 6). The superior seed yield of these varieties (i.e., Força and Ativa) increased the EC to US$ 166.8 ha^{-1} (site 1) and US$ 107.5 ha^{-1} (site 2) (Fig. 6), which is economically significant. The superior EC for the LY in relation to the other YC is in agreement with previous studies carried out for corn in Brazil (Hörbe et al. 2013).

Based on yield results of soybean varieties and YC, a new approach was theorized. The data was up-scaled to a whole-field scale (Table 8) and the yield and gains in EC using a multi-variety strategy (MVS) was simulated. Despite the difference in the optimal number of soybean varieties between sites, the results for both sites 1 and 2 revealed that MVS provided a better outcome than a single-variety strategy (Table 8). At site 1, the MVS (using three varieties) increased the seed yield and EC by 4.2%, while at site 2, the MVS

Table 7 Partial net economic return attributed to six soybean varieties planted according to yield class (high yielding - HY, medium yielding - MY, and low yielding - LY) for sites 1 and 2

Yield class	Soybean variety	Seeds ha^{-1} (kg)	Seed cost (US$ ha^{-1})	Seed yield (Mg ha^{-1})	Gross income (US$ ha^{-1})	Net income (US$ ha^{-1})
Site 1						
HY	Ativa	60.9	34.80	3.93	1190.9	1156.1
	CEP 65	43.2	20.76	3.18	963.6	942.9
	Urano	49.2	25.56	4.24	1284.9	1259.3
	Júpiter	49.7	25.82	4.06	1230.3	1204.5
	5909	46.5	24.16	4.16	1260.6	1236.6
	Força	52.2	27.12	3.65	1106.1	1078.9
MY	Ativa	60.9	34.80	4.13	1251.6	1216.7
	CEP 65	43.2	20.76	3.47	1051.6	1030.8
	Urano	49.2	25.56	3.85	1166.7	1141.1
	Júpiter	49.7	25.82	3.59	1087.9	1062.1
	5909	46.5	24.16	4.17	1263.7	1239.5
	Força	52.2	27.12	3.57	1081.8	1054.7
LY	Ativa	60.9	34.80	4.20	1272.7	1237.9
	CEP 65	43.2	20.76	3.45	1045.5	1024.7
	Urano	49.2	25.56	3.98	1206.1	1180.5
	Júpiter	49.7	25.82	4.02	1218.2	1192.4
	5909	46.5	24.16	3.69	1118.2	1094.0
	Força	52.2	27.12	4.25	1287.9	1260.8
Site 2						
HY	Ativa	60.9	34.80	3.94	1193.9	1159.1
	CEP 65	43.2	20.76	3.70	1121.2	1100.5
	Urano	49.2	25.56	4.32	1309.1	1283.5
	Júpiter	49.7	25.82	4.02	1218.2	1192.4
	5909	46.5	24.16	4.22	1278.8	1254.6
	Força	52.2	27.12	3.23	978.8	951.7
MY	Ativa	60.9	34.80	3.93	1190.9	1156.1
	CEP 65	43.2	20.76	3.35	1015.2	994.4
	Urano	49.2	25.56	3.72	1127.3	1101.7
	Júpiter	49.7	25.82	3.33	1009.1	983.3
	5909	46.5	24.16	3.88	1175.8	1151.6
	Força	52.2	27.12	3.50	1060.6	1033.5
LY	Ativa	60.9	34.80	3.97	1203.0	1168.2
	CEP 65	43.2	20.76	3.31	1003.0	982.3
	Urano	49.2	25.56	3.74	1133.3	1107.8
	Júpiter	49.7	25.82	3.61	1093.9	1068.1
	5909	46.5	24.16	3.58	1084.9	1060.7
	Força	52.2	27.12	3.79	1148.5	1121.4

increased seed yield by 3.4% and the EC by 2.8% (Table 8). Recently, Beck's Hybrids® (Beck's Hybrids, Atlanta, IN, USA) has reported preliminary results from experiments carried out in 2013 and 2014 using MVS (Practical Farm Research (PFR), available from

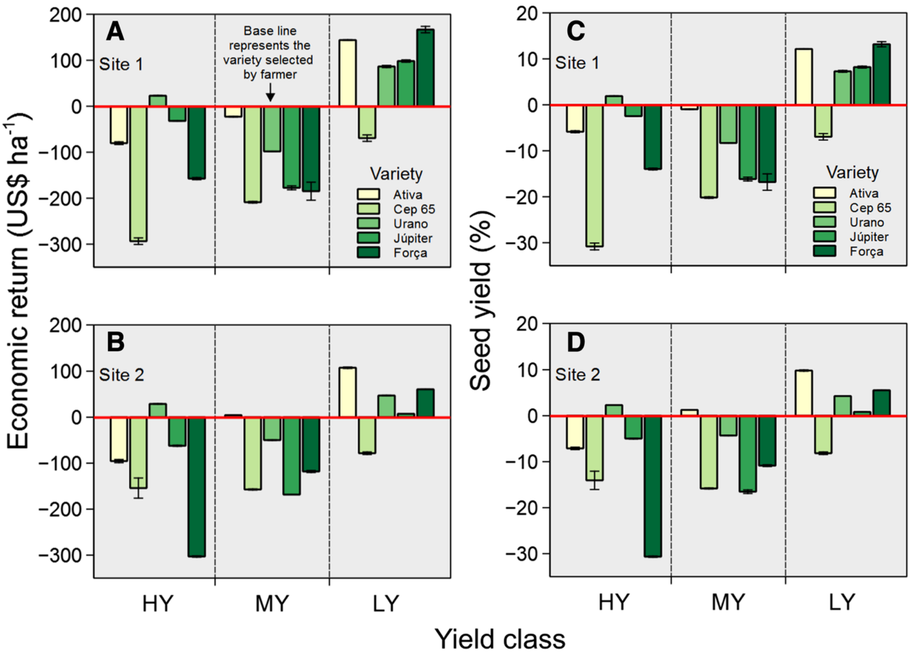

Fig. 6 Difference of partial net economic return and relative seed yield for soybean varieties compared with the soybean variety selected by the farmer (baseline) in three yield classes (*HY* high yielding, *MY* medium yielding, *LY* low yielding) for site 1 (**a** and **c**) and site 2 (**b** and **d**). Error bars represent the standard deviation

www.beckshybrids.com). The results of this report showed that precise placement of varieties increased yield by close to 0.2 Mg ha^{-1}, and the EC by US$ 95.08 ha^{-1}. In the present study, the EC was increased by US$ 50.3 ha^{-1} and US$ 31.8 ha^{-1} for sites 1 and 2, respectively (Table 8). Overall, the optimum spatial arrangement of varieties provided an increase in the EC of US$ 5,892 and US$ 3,431, for sites 1 (117.14 ha) and 2 (107.90 ha), respectively.

The results from this research study provide a new insight related to the arrangement in which varieties are planted, based on yield class (Fig. 7). The findings support the emerging concept of within-field multi-variety planting. Future research focused on multi-variety approach should be conducted using contrasting soybean varieties, locations, and yield classes. The environmental responses could be included as a factor to making new varieties prescriptions. This information should help farmers in making better decisions, as well as increase their profits.

Conclusions

This study provided a field-level analysis on the performance of soybean varieties according to yield class. The key findings were: (a) the performance of soybean varieties differed according to yield class; (b) the traditional variety selected by the farmer performed well in the HY, but poorly in the LY environment; (c) in comparison with the variety selected

Table 8 Crop performance and economic return of multi-variety arrangement according to yield class (high yielding—HY, medium yielding—MY and low yielding—LY) for sites 1 and 2

Number of varieties within-field	Yield class			Crop performance and economic return				
				Field average		Gain to the single variety		
	HY	MY	LY	Yield[b] (Mg ha^{-1})	EC[c] (US$ ha^{-1})	Yield[b] (Mg ha^{-1})	EC[c] (US$ ha^{-1})	Total (US$)
	Soybean variety							
Site 1								
One[a]	5909	5909	5909	4.04	1,201.4	–	–	–
Two	5909	5909	Força	4.19	1,243.9	0.14	42.5	4,979
Three	Urano	5909	Força	4.21	1,251.7	0.17	50.3	5,892
Site 2								
One	5909	5909	5909	3.88	1,151.5	–	–	–
Two	Urano	Ativa	Ativa	4.01	1,183.3	0.13	31.8	3,431
Three	Urano	5909	Ativa	3.98	1,180.3	0.10	28.8	3,108

The planting of one variety (selected by farmer) in the whole field represents the traditional practice, while the planting of two and three varieties according to yield classes represents the new multi-variety approach

[a] Traditional variety selected by farmer

[b] Seed yield

[c] Economic return

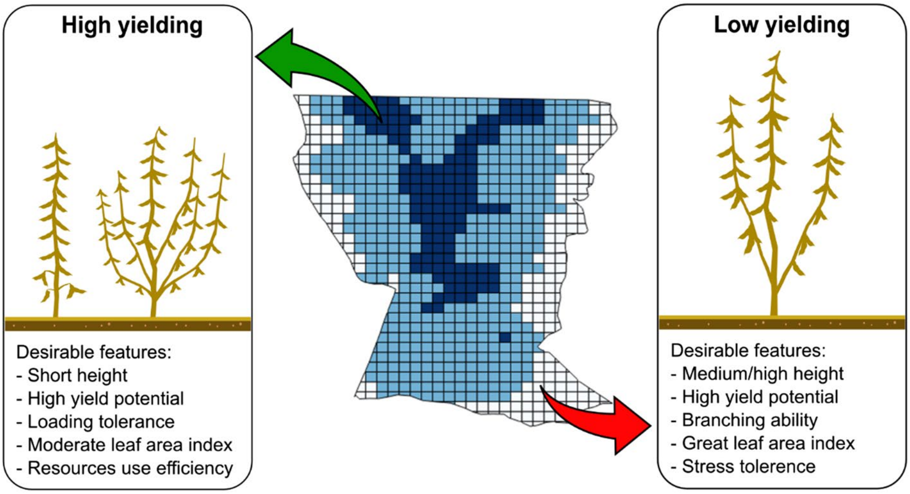

Fig. 7 Theoretical framework for soybean varieties arrangement according to yield class (low and high) in Southern Brazil. Varieties with high plant height should preferably be placed in low yielding locations since results demonstrated a plant height reduction and an increase in the number of pods; the last one consequently benefited the seed yield. Varieties with low plant height (bush-type) as well as with high yield potential should be placed in high yielding locations, avoiding excessive vegetative plant grow, self-shading of the lower leaves, and decrease on photosynthetic capacity, factors that decrease soybean seed yield. This approach is based on results from varieties explored in this study

by the farmer, used across the whole field (site 1 and 2), the multi-variety arrangement increased seed yield by 2.10% in HY and 11.50% in LY; (d) varieties with high PH should preferentially be placed in LY, because the consequent reduction in PH and increase in the number of pods promoted superior yield; (e) within-field variety arrangements increased the economic return by US$ 26 and US$ 137 ha^{-1} in HY and LY, respectively, therefore improving the economic gains by US$ 32 and US$ 50 ha^{-1} for sites 1 and 2, respectively. Overall, the findings support the emerging concept related to within-field multi-variety soybean planting as a new approach to precision agriculture.

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