



Soybean Yield Gap in the Areas of Yield Contest in Brazil

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Abstract

Soybean yield is mainly influenced by the interaction among genotype, environmental conditions and management practices. Based on that, the aim of this study was to quantify the soybean yield gap caused by water deficit (YG_{WD}) and sub-optimum crop management (YG_{CM}), considering data from the areas of soybean yield contest in Brazil. Potential (Y_p) and attainable (Y_a) yields were estimated by a crop yield simulation model, whereas actual farmers yields (Y_f) were obtained from the contests conducted by the Brazilian Soybean Strategic Committee (CESB), comprising 200 sites. The YG_{WD} and YG_{CM} were, respectively, calculated by the difference between Y_p and Y_a , and Y_a and Y_f . The climate efficiency (EF_C) was obtained by the ratio between Y_a and Y_p , while crop management efficiency (EF_M) considered the ratio between Y_f and Y_a . The mean Y_f from CESB was 5021 kg ha^{-1} , higher than the national average of about 3000 kg ha^{-1} . The YG_{WD} and YG_{CM} were, respectively, 2931 and 3458 kg ha^{-1} , representing 46 and 54% of total yield gap. The weather conditions did not affect Y_f in the studied sites with lower EF_M . For sites with EF_C higher than 0.80, Y_f increased in a rate of 92 kg ha^{-1} per percentage of increase in EF_M . When comparing the national average and CESB winners, the results showed that average Y_f could be increased in 2514 and 2584 kg ha^{-1} , respectively, by closing YG_{CM} and YG_{WD} , which shows that there is room to double the present Brazilian soybean yield by adopting the technology already available to the farmers. These results can serve as reference to guide other studies about soybean yield gap around the world, helping policy makers and other stakeholders to elaborate strategies for closing yield gaps and making soybean production more sustainable.

Keywords Crop simulation model · Closing yield gap · Rainfed crop · Climate and management efficiencies

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Introduction

The increasing demand for agricultural products is forcing farmers to intensify their productions. In Brazil, soybean is the most important crop covering approximately 35 million ha (IBGE 2018) and will be required to increase at a rate of 2.6% per year from 2017 to 2026 (OECD 2017), which will be possible only by increasing crop yield since the area for expansion of this crop in the country is very limited. The main way to improve soybean yield is by reducing yield gaps caused by water deficit or sub-optimum crop management (Edreira et al. 2017). The yield gap approach considers potential (Y_p) and attainable (Y_a) yields as reference values, obtaining yield gap by water deficit from the difference between Y_a and Y_p , whereas the yield gap by sub-optimal management is quantified using actual farmers yield (Y_f), through the difference between Y_a and Y_f for rainfed conditions (Lobell et al. 2009; Sentelhas et al. 2015).

The reference yield values (Y_p and Y_a) can be quantified by crop simulations models, since well calibrated and

validated for the main genotypes used in the region of interest, or by yields obtained from the best farmers or experimental results (Lobell et al. 2009, van Ittersum et al. 2013). Using the simulation approach, Sentelhas et al. (2015) quantified the yield gaps for soybean in Brazil using a simple crop model properly calibrated with crop data from cultivar field trials. These authors observed that water deficit and crop management were responsible, respectively, for 74 and 26% of soybean yield gap in Brazil, when considering average Y_f from the national surveys.

The weather conditions during the growing season have a huge effect on soybean yield in Brazil, which has high climate variability between different regions and sowing dates (Sentelhas et al. 2015). Such conditions lead to limited understanding of which factor is more important for defining soybean yield, weather or crop management. Edreira et al. (2017) highlighted that the interactions between crop management and environmental conditions (climate and soil) make difficult to quantify the yield gap for large crop areas, and, therefore, to decide where to put efforts to reduce the yield gap.

Soybean yield contest in Brazil started in the 2008/09 growing season, promoted by the Brazilian Soybean Strategic Committee (CESB). At that season, the national champion harvested 4968 kg ha^{-1} , whereas in the 2016/17 growing season the winner's yield was 8945 kg ha^{-1} (CESB 2017). In the same period, the national average soybean yield increased from 2629 to 3364 kg ha^{-1} (CONAB 2017). These results raise two main questions: what is the real effect of weather conditions on yield for each genotype \times management system? and how effective are farmers to reach the attainable yield provided by the interaction between genotype \times environment? The only way to answer these questions is through the use of the yield gap approach, with Y_p and Y_a determined by well-calibrated crop simulation models.

Based on that, this study aimed to quantify the yield gap caused by water deficit and by crop management in the areas of Brazilian soybean yield contest, monitored by CESB; to determine climate and crop management efficiencies in the areas of Brazilian soybean yield contest; and to estimate the possible soybean yield improvement for Brazilian farmers, based on the current knowledge and available technology used by the winning farmers.

Materials and Methods

Brazilian Soybean Yield Contest and Farmers' Yield Data

Brazil Soybean Strategic Committee (CESB) organizes the soybean yield contest since 2008/09 growing season. CESB is a non-profit organization that was created by researchers

and consultants, to stimulate growers to increase their efficiency to produce soybean and to identify which would be the main crop management practices to increase soybean yield in different regions of the country. The winning farmers and consultants present their yields and share all the practices they used to reach them. In the 2016/17 growing season, CESB registered more than 4000 inscriptions for the contest in all regions of Brazil, which are divided in South, Southeast, Mid-West and North/Northeast. There is a winner for each region and among them the national winner. The harvested area needs to have at least 2 ha, which is supervised by an independent auditor, with the final yield corrected to a grain water content of 13%. Besides the winners monitoring, CESB also conducts a research network, where soybean yield, climate and all management practices are monitored. The farmers' yield data (Y_f) used in this study were obtained from the CESB participating farmers (winners and no winners), totaling 200 locations, being 30 for 2014/15, 20 for 2015/16 and 150 for 2016/17 growing seasons.

Farms Locations, Soils and Weather Data

The sites selected for this study are those of the winners and also from the CESB research network, covering the main soybean Brazilian growing areas, from South to North (Fig. 1). As previously mentioned, a total of 200 farms were selected and their data (geographical coordinates, sowing and harvesting dates, soil type, and weather) were used to simulate Y_p and Y_a and to determine soybean yield gaps, as will be described in the next sections.

The soil analysis was performed in only 30% of the 200 locations, where clay soil content ranged from 200 to 900 g kg^{-1} (Fig. 2a). A soil water holding capacity (SWHC) of 1.16 mm cm^{-1} was admitted, considering the soil types studied by Battisti and Sentelhas (2017). The total SWHC was calculated then considering a root system depth of 150 cm, as observed in the areas of the winning farmers (Battisti and Sentelhas 2017), with a linear root depth increase from sowing (15 cm) to flowering (R1) (150 cm) (Fig. 2b).

The daily weather data employed in this study for soybean yield simulation were: rainfall; mean air temperature; incoming solar radiation; wind speed at 2-m height; and mean relative humidity (See Supplemental material). These data were obtained from Brazilian Meteorological Service (INMET) automatic weather stations close to each analyzed farm, except for rainfall, which was measured by rain gauges installed inside the soybean fields. As the crop simulation model requires also the variable sunshine hours, it was estimated based on incoming solar radiation, extraterrestrial solar radiation and photoperiod based on

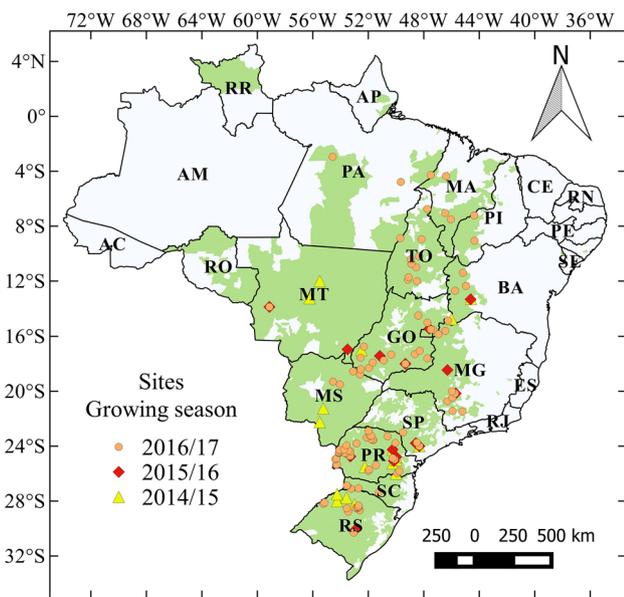


Fig. 1 Location of the farms from where actual soybean yields (Yf) were obtained for the 2014/15 (n=30), 2015/16 (n=20) and 2016/17 (n=150) growing seasons, as well as, all the data for the potential and attainable yields and yield gap simulations. The green area represents where soybean is cultivated in Brazil

latitude and day of the year by using Angström-Prescott equation. The net radiation, used for estimating reference evapotranspiration by FAO Penman-Monteith, was calculated based on shortwave and longwave radiation balances, as recommended by Allen et al. (1998).

Soybean Yield Model

The crop yield model used for estimating Yp and Ya was an adaptation of the original FAO Agroecological Zone model (Kassam 1977), which estimates Yp as a function of the interaction between genotype and environmental conditions (solar radiation, air temperature and photoperiod) and Ya by using a water deficit yield depletion model (Doorenbos and

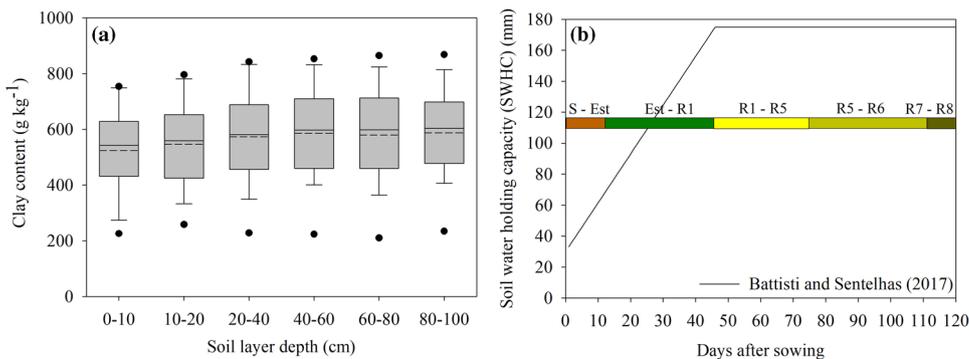
Kassam 1979; Rao et al. 1988). This adapted crop model was chosen due to its satisfactory performance to simulate soybean yield for Brazilian conditions (Battisti and Sentelhas 2015; Sentelhas et al. 2015; Battisti et al. 2017b). The crop model parameters were obtained from Battisti et al. (2017b). Additional calibrations for higher soybean yields were done for simulating deeper root system (Battisti and Sentelhas 2017), higher photosynthesis rate caused by quick leaf area increase and its stabilization, with leaves staying photosynthetically active until the end of the cycle, and higher dry mass partitioning for the grain (harvest index). Details about equations, parameters, and steps used to simulate soybean yield are described in the Supplementary Material.

Quantification of Yield Gaps

The yield gaps were quantified based on simulated Yp and Ya, and Yf obtained from the CESB research network as well as from the regional and national yield contest winners. The yield gap caused by water deficit (YG_{WD}) was obtained by subtracting Ya from Yp, whereas the yield gap caused by sub-optimum crop management (YG_{CM}) was calculated by the difference between Ya and Yf. In order to have an achievable yield for general farmers, the value of 80% from Yfs reached by the CESB’s winners was used to quantify the opportunity of yield increase for soybean in Brazil (Espe et al. 2016).

Besides the YGs, the climate efficiency (EF_c) was calculated for each location, considering the ratio between Ya and Yp, whereas crop management efficiency (EF_m) was calculated by the ratio between Yf and Ya (Battisti et al. 2012, 2013). These efficiencies were correlated with Yf for grouping the assessed locations according to the following intervals of EF_c and EF_m: above 80%; between 60 and 80%; and below 60%. Such analysis allows identifying the yield response for each level of EF_c and EF_m, which makes possible to evaluate the interactions between climate and crop management, and their effects on soybean yield.

Fig. 2 Clay content for different soil layers (a) and soil water holding capacity for soybean crop during its cycle (b). In a, the percentile values are the point for 5–95%, the bars for 10–90%, the box for 25–75%, and dashed and full line are, respectively, for mean and median



Results

Soybean Yield Model Calibration for High Yields

The soybean yield model used in this study was calibrated by Battisti (2016), with harvest index (C_H) ranging between 0.25 and 0.53 as function of days from sowing to maturity (Figure S3—Supplemental Material). As Y_a for some locations was lower than Y_f (Fig. 3a), which is not theoretically possible, a new C_H calibration was performed for ensuring that $Y_f \leq Y_a$. Such calibration was performed after to incorporate a deeper root system and a higher photosynthesis rate, caused by quick leaf area increase and its stabilization until the end of the cycle (Supplemental Material). The calibrated C_H resulted in the relationship presented in Fig. 3b, where Y_a ranged from 5442 to 11,296 kg ha⁻¹ and Y_f from 2700 to 8945 kg ha⁻¹.

Soybean Yield Range

Figure 4 presents soybean Y_p , Y_a and Y_f for all the locations assessed for the growing seasons of 2014/15 (30 locations), 2015/16 (20 locations) and 2016/17 (150 locations). The Y_p values ranged considerably according to the growing season and location, from 7595 to about 13,378 kg ha⁻¹, which were conditioned by solar radiation, air temperature, photoperiod and crop cycle variations. Y_a values, which are the Y_p penalized by water deficit, also had an expressive variation when considering all locations and growing seasons, from 5442 to 11,296 kg ha⁻¹. Similarly, Y_f values, which are Y_a penalized by sub-optimum crop management, also varied, with the following averages and ranges: 5693 kg ha⁻¹ (ranging from 3704 to 8507 kg ha⁻¹) in 2014/15; 4883 kg ha⁻¹ (ranging from 2862 to 7204 kg ha⁻¹) in 2015/16; and 4548 kg ha⁻¹ (ranging from 2700 to 8945 kg ha⁻¹) in 2016/17 (Fig. 4). For all these locations, the mean $Y_{G_{WD}}$ was 2931 kg ha⁻¹. The highest $Y_{G_{WD}}$ occurred in the state of Paraná (#121, Fig. 4c), with 6482 kg ha⁻¹. In this location, Y_p and Y_a were, respectively, of 13,151 and 6669 kg ha⁻¹. In average, $Y_{G_{CM}}$ was 3458 kg ha⁻¹, ranging from 28 to 8370 kg ha⁻¹.

The lowest $Y_{G_{CM}}$ occurred in the state of Rio Grande do Sul (#16, Fig. 4c), whereas the highest was in the state of Pará (#148, Fig. 4c).

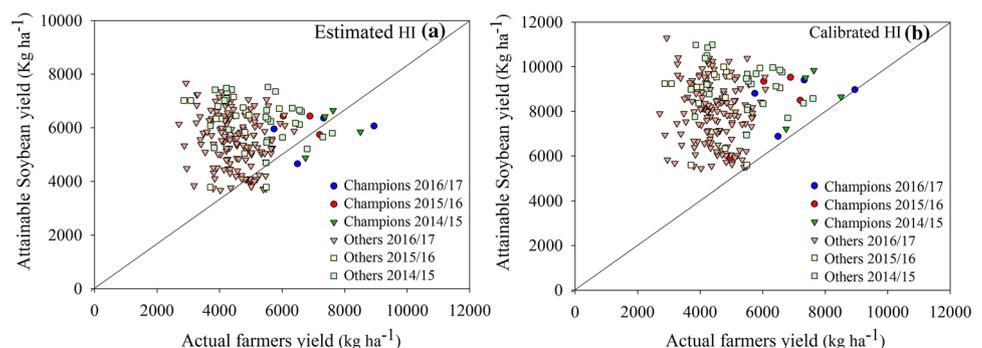
Climate and Agricultural Efficiencies for Soybean Production in Brazil

The efficiencies related to the climatic conditions (EF_c), determined by the relationship between Y_a and Y_p , and to the crop management (EF_m), determined by the relationship between Y_f and Y_a , were classified in nine groups, based on three levels of each one (Table 1). EF_c was higher than 0.80 in 36% of the locations, between 0.60 and 0.80 in 50.5% and lower than 0.60 in only 13.5% of them (Table 1). On the other hand, 56.5% of the locations had EF_m lower than 0.60, 32.5% with EF_m between 0.60 and 0.80, and only 11% of the sites with EF_m higher than 0.80. The highest frequency of sites (28%) presented EF_m lower than 0.60 and EF_c between 0.60 and 0.80 (Table 1). For this combination, Y_p , Y_a and Y_f were, respectively, 11,694, 8321 and 4125 kg ha⁻¹, with an average EF_c of 0.71 and EF_m of 0.50 (Table 1).

Y_f had a low rate of increase, 13 kg ha⁻¹ per decimal increment of EF_c for the group with EF_m lower than 0.60 (Fig. 5a). For the sites with EF_m between 0.60 and 0.80, Y_f increased in a rate of 53 kg ha⁻¹ per decimal increment of EF_c , whereas the group with EF_m above 0.80 reached a rate of 71 kg ha⁻¹ per increment of EF_c (Fig. 5a). When the locations were grouped by EF_c , the results showed an Y_f increase rate of 92 kg ha⁻¹ per decimal increment of EF_m for the sites with EF_c higher than 0.80 (Fig. 5b). For locations with EF_c between 0.60 and 0.80, and lower than 0.60, the Y_f increase rates were, respectively, 74 and 62 kg ha⁻¹ per decimal increment of EF_m . In summary, these results show that better the climate conditions during the soybean crop cycle, better the response of the crop to the management practices.

EF_c and EF_m did not present any regional pattern of distribution (Fig. 6). For EF_c above 0.80 (Fig. 6a), the most of the sites showed EF_m below 0.60. For the locations where EF_c was between 0.60 and 0.80, more of them presented

Fig. 3 Relationship between actual farmers (Y_f) and attainable (Y_a) soybean yield, when using estimated (a) and calibrated (b) harvest index (HI) in the crop model for high yields



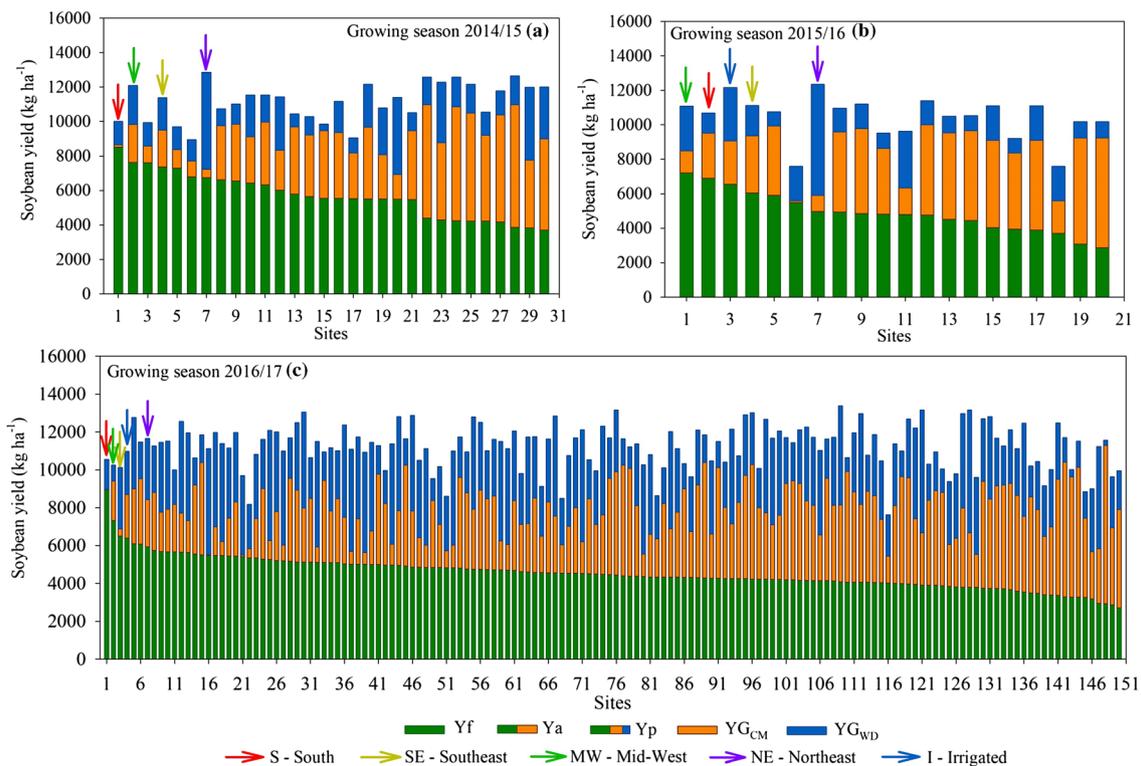


Fig. 4 Soybean potential (Y_p), attainable (Y_a) and actual farmer (Y_f) yields and the respective yield gaps by crop management ($Y_{G_{CM}}$) and by water deficit ($Y_{G_{WD}}$) for 2014/15, 2015/16 and 2016/17 growing

seasons in the areas monitored by CESB in Brazil. The arrows are indicating the soybean yield winners for each growing season

EFm between 0.60 and 0.80 (Fig. 6b). For the locations where EFc was below 0.60 (Fig. 6c), even under more water deficit, some of them presented EFm above 0.80. Similar tendency was observed for EFm, with sites having the same level of EFm for different levels of EFc (Fig. 6d–f).

Assessing the CESB Soybean Yield Winners

Considering all winner (14 sites) and growing seasons, the average EFc and EFm were, respectively, 0.81 and 0.77 (Fig. 7). The lowest EFc (0.48) was observed for the winner in the Northeast region during the 2015/16 growing season, whereas the highest one (0.92) was observed for the winner in the Mid-West region during the 2016/17 growing season (Fig. 7). The lowest EFm (0.64) occurred in the Mid-West region in the 2015/16 growing season, whereas the highest one (0.99) was observed during the 2016/17 growing season in the South region, reaching the maximum value (Fig. 7). In order to understand in which proportion climate and crop management affect soybean yield, four winner sites were selected to illustrate that: Southeast (SE) and Northeast (NE) winners in the 2015/16 growing season; and South (S) and

Mid-West (MW) winners in the 2016/17 growing season (Fig. 7).

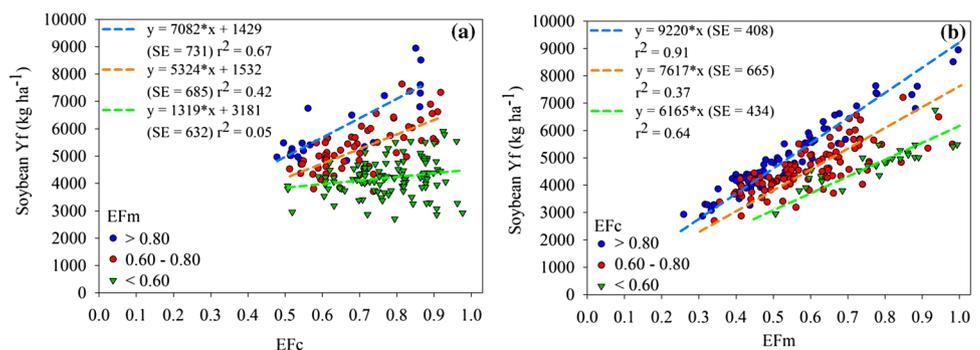
In the growing season of 2015/16, the winner in NE region had a Y_f of 4967 kg ha⁻¹ (Fig. 4b, site 7), lower than in SE, which had 7204 kg ha⁻¹ (Fig. 4b, site 1). These sites had the same EFm of 0.85 (Fig. 7). Such aspect was controlled by the values of Y_p and Y_a , with the NE winner having, respectively, 12,347 and 5907 kg ha⁻¹, and SE winner 11,077 and 8494 kg ha⁻¹ (Fig. 4b). The EFc values for these regions were, respectively, of 0.48 and 0.77 (Fig. 7). These results evidenced that the difference of Y_f between these two regions was caused by the higher water deficit in NE than in SE, because the sub-optimum crop management allowed both to obtain the same Y_f/Y_a . For this growing season, the NE winner’s soybean crop had an accumulated water deficit of 118 mm during grain filling period (R5–R6) (Fig. 8a), against 54 mm in the winner’s field SE region (Fig. 8b).

In 2016/17 growing season, the winners of MW and S regions had Y_f of 7332 and 8944 kg ha⁻¹, respectively (Fig. 4c—sites 2 and 1). In these sites, Y_p and Y_a were very close, being, respectively, of 10,251 and 9412 kg ha⁻¹ for the winner in MW region, and of 10,544 and 8973 kg ha⁻¹ for the winner in S region (Fig. 4c). Based on

Table 1 Percentage of sites in each combination of climate (EFc) and crop management (EFm) efficiencies, and average and standard deviation (SD) for actual (Yf), attainable (Ya) and potential (Yp) yields for each combination of EFc and EFm for the areas monitored by CESB in Brazil, during the 2014/15, 2015/16 and 2016/17 growing seasons

EFc	EFm			Total
	>0.80	0.60–0.80	<0.60	
% of sites				
>0.80	2.5	7.0	26.5	36.0
0.60–0.80	2.5	20.0	28.0	50.5
<0.60	6.0	5.5	2.0	13.5
Total	11.0	32.5	56.5	100
Average Yf (±SD)				
>0.80	7832 (±879)	6299 (±803)	4338 (±720)	4962 (±1329)
0.60–0.80	5874 (±958)	5104 (±707)	4125 (±546)	4599 (±840)
<0.60	5291 (±504)	4584 (±446)	3731 (±556)	4772 (±725)
Total	6001 (±1243)	5273 (±893)	4211 (±645)	4753 (±1040)
Average Ya (±SD)				
>0.80	8457 (±471)	9272 (±626)	9540 (±780)	9412 (±781)
0.60–0.80	6507 (±1222)	7434 (±947)	8321 (±912)	7880 (±1072)
<0.60	6000 (±460)	6403 (±623)	6579 (±548)	6250 (±574)
Total	6674 (±1209)	7655 (±1248)	8831 (±1117)	8211 (±1392)
Average Yp (±SD)				
>0.80	9827 (±581)	10,727 (±792)	10,968 (±839)	10,842 (±858)
0.60–0.80	9117 (±1441)	10,910 (±1376)	11,694 (±1040)	11,256 (±1342)
<0.60	11,372 (±801)	11,355 (±906)	12,420 (±923)	11,520 (±912)
Total	10,508 (±1339)	10,946 (±1204)	11,379 (±1024)	11,142 (±1155)
Average EFc (±SD)				
>0.80	0.86 (±0.01)	0.87 (±0.04)	0.87 (±0.04)	0.87 (±0.04)
0.60–0.80	0.71 (±0.04)	0.68 (±0.06)	0.71 (±0.06)	0.70 (±0.06)
<0.60	0.53 (±0.03)	0.56 (±0.03)	0.53 (±0.04)	0.54 (±0.03)
Total	0.65 (±0.14)	0.70 (±0.11)	0.78 (±0.10)	0.74 (±0.12)
Average EFm (±SD)				
>0.80	0.92 (±0.06)	0.68 (±0.06)	0.46 (±0.08)	0.53 (±0.16)
0.60–0.80	0.91 (±0.06)	0.69 (±0.05)	0.50 (±0.07)	0.59 (±0.13)
<0.60	0.88 (±0.06)	0.72 (±0.07)	0.56 (±0.04)	0.77 (±0.13)
Total	0.90 (±0.06)	0.69 (±0.06)	0.48 (±0.08)	0.60 (±0.16)

Fig. 5 Relationship between climate efficiency (EFc) and groups of crop management efficiency (EFm) (a), and between EFm and groups of EFc (b), for soybean crop grown in different locations in Brazil. SE is the standard error of the equation's estimates



that, it is clear that water deficit was not a pronounced limiting factor in these sites, with EFc reaching 0.92 for the MW winner and 0.85 for the S winner (Fig. 7). For both locations, the water deficit during growing season was

lower than 20 mm for each soybean crop phase (Fig. 8c, d). On the other hand, the EFm obtained by the MW winner was 0.78, whereas S winner reached 1.00 (Fig. 7). Even with compensation between EFc and EFm in these two

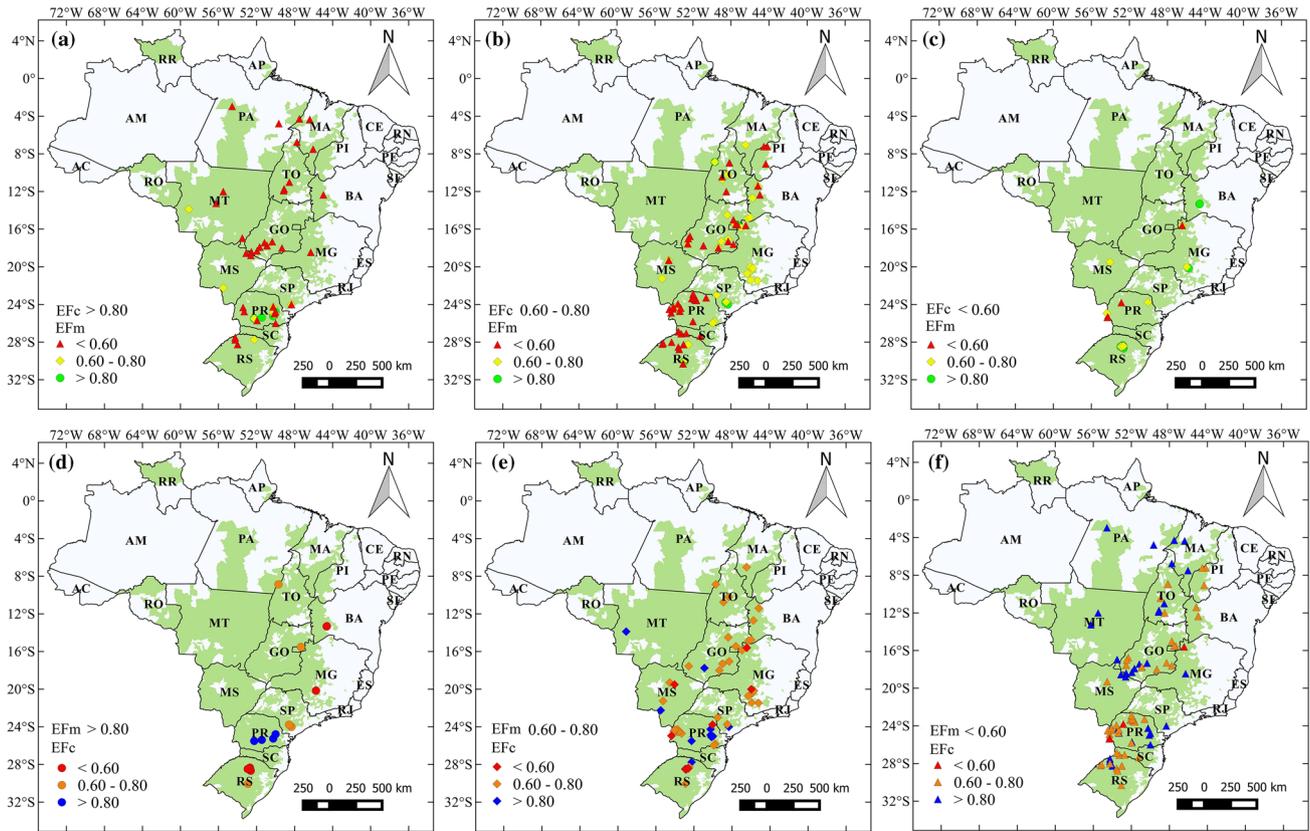
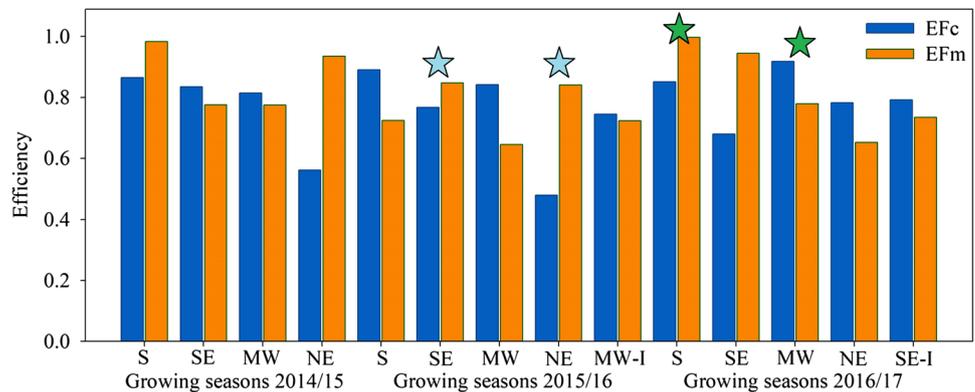


Fig. 6 Locations in Brazil with different soybean crop management efficiencies (EFm) under climate efficiencies (EFc) above 0.80 (a), between 0.60 and 0.80 (b) and below 0.60 (c); and locations with dif-

ferent climate efficiencies under crop management efficiencies above 0.80 (d), between 0.60 and 0.80 (e) and below 0.60 (f). The green area represents where soybean is cultivated in Brazil

Fig. 7 Climate (EFc) and crop management (EFm) efficiencies for the CESB soybean yield winners in the 2014/15, 2015/16 and 2016/17 growing seasons in different regions of Brazil: S—South; SE—Southeast; MW—Midwest; NE—Northeast. The winner for irrigated soybean is represented by I. The stars with the same color are representing the locations used for the comparative analysis



soybean fields, the yield of the winner in the S region was higher due to the better EFm.

Closing Yield Gaps

The opportunities of soybean yield increase in the winners' regions and also at national level were quantified considering Ya estimated by the crop model for the winners and Ya

as 80% of the average Yf of the winners during the three growing seasons for the country as a whole (Fig. 9). By closing yield gap by crop management in the winners regions, the Yf could reach more than 8000 kg ha⁻¹, independently of the growing season (Fig. 9). On the other hand, when considering Ya as 80% of average winners Yf, the national soybean Yf could be increased between 2000 and 3000 kg ha⁻¹, depending of the growing season (Fig. 9). Furthermore,

Fig. 8 Water deficit and water surplus accumulated from daily water balance during the soybean crop phases for the winners in the Southeast (a) and Northeast (b) regions in the 2015/16 growing season and in the South (c) and Midwest (d) regions in the 2016/17 growing season

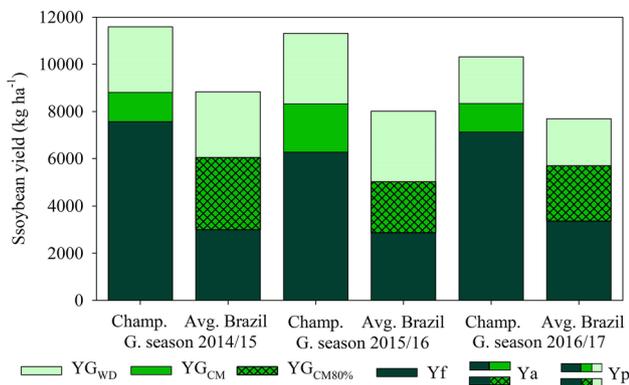
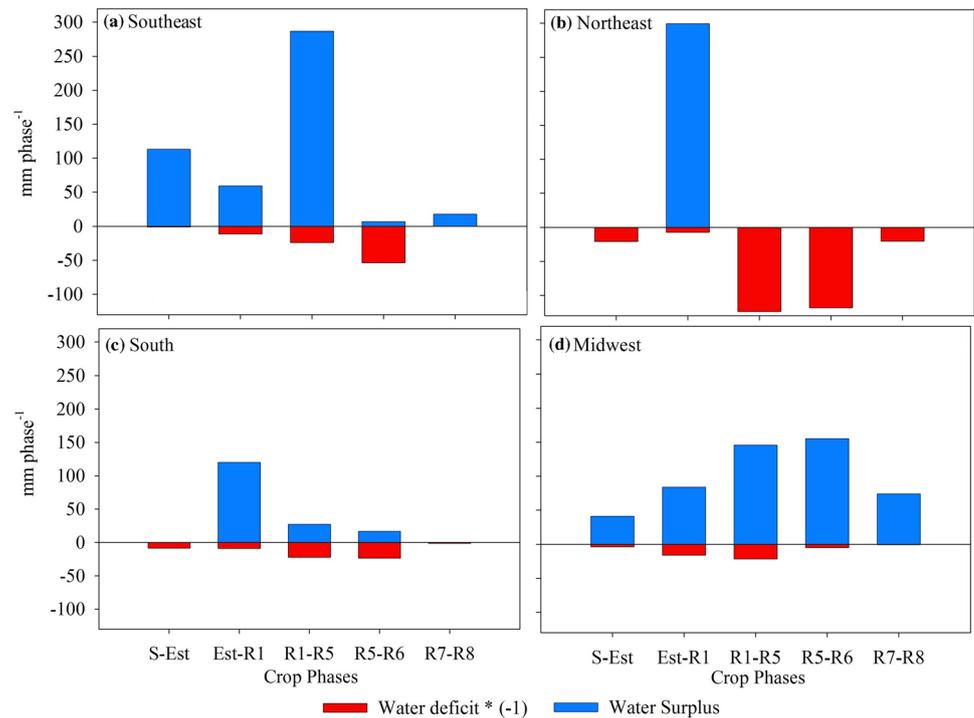


Fig. 9 Actual soybean yield (Yf) for the CESB winners and at national level during the growing seasons of 2014/15, 2015/16 and 2016/17 in Brazil, yield gap by crop management (YG_{CM}), yield gap by water deficit (YG_{WD}) and yield gap by crop management considering Ya as 80% of the average Yf of the winners during the three growing seasons

soybean growers could improve the yield of their fields by adopting strategies to reduce the YG_{WD}, such as making their soil profile deeper, which, in average, could increase Yf by 2500 kg ha⁻¹ (Fig. 9), even in the winners' fields. When considering soil profile, we are referring to practices to reduce soil compaction, soil acidity and aluminum toxicity, to control nematodes and to improve soil microbiota (Franchini et al. 2009). Moreover, other crop management practices are also important to close yield gaps, such as the choice of the best genotype for the region (maturation group and

growth habit), soil fertilization and seed inoculation with *Bradyrhizobium* (Barth et al. 2018), and crop protection for reducing pests and diseases damages (Sentelhas et al. 2017).

Discussions

The FAO Agroecological zone model has been very efficient for estimating soybean yield in Brazil, as presented in the studies conducted by Monteiro and Sentelhas (2014), Sentelhas et al. (2015), Battisti and Sentelhas (2015) and Battisti et al. (2017b). However, in the present study additional calibration was required to simulate the high soybean yield obtained in CESB winners' fields in different Brazilian regions. The high yields were only well simulated when green leaf area was increased and prolonged till the end of the crop cycle, C_H was increased by about 48% from Battisti (2016), limited between 0.25 and 0.55, and deeper root system was simulated, reaching 1.5 to 2.0 m (van Roekel et al. 2015; Battisti and Sentelhas 2017). After calibration, the soybean yields simulated by the crop model were equal or higher than obtained in the fields (Fig. 3). As suggested by Lobell et al. (2009), van Ittersum et al. (2013) and Edreira et al. (2017), the yields from fields with minimum YG_{CM} were assumed as reference to adjust the crop model, limiting Ya to be equal or lower than Yf. The sites with low YG_{CM} can also be used to identify the preferential crop managements to guarantee higher yields where YG_{CM} is high (Hall et al. 2013; van Ittersum et al. 2013).

A total of 200 sites were assessed during three growing seasons, resulting in a considerable range of climates and crop managements, being a good sample of how soybean crop is cultivated in Brazil. The average soybean Yf (4753 kg ha⁻¹) was higher than national average yield (\approx 3000 kg ha⁻¹) (CONAB 2017). Based on that, the soybean yields from CESB contest and from national surveys are important references for estimating yield gap for this crop, complementing the results already obtained by Sentelhas et al. (2015).

The high yields used as reference to calibrate the crop model resulted in higher YG_{WD} and YG_{CM} than those found by Sentelhas et al. (2015). These authors obtained a rate between YG_{WD} and total YG and between YG_{CM} and total YG of, respectively, 74 and 26%, whereas in the present study these rates were 46 and 54%. The main cause for these differences were the higher root depth consider in present calibration, of 1.5 to 2.0 m in the winners' fields (Battisti and Sentelhas 2017), against the superficial root system (\approx 0.50 m) considered by Sentelhas et al. (2015) to represent the mean conditions for most farms in Brazil.

The assessed sites were classified by EFc and EFm levels to identify the most frequent type of limiting factor in each of them. The most sites were characterized as having intermediate (0.60–0.80) to higher (> 0.80) EFc and low (< 0.60) to intermediate (0.60–0.80) EFm. These results show that crop management was a major limiting factor for obtaining soybean high yields in the assessed fields. Under suitable climate conditions and deep soil profiles, soybean plants use the resources more efficiently, mainly the nutrients available in the soil (Novák and Vidovic 2003). However, where climate conditions are the main limiting factor, the soybean yield will be negatively affect in all crop management conditions, but much more under shallow soil profile.

The soybean yield response to better climatic conditions was small for the sites with lower EFm. It is a consequence of sub-optimum crop management, which makes the plants to face shortage of nutrients and higher pests and diseases pressures (La Menza et al. 2017). On the other hand, sites with the excessive rainfall can also be affected by sub-optimum crop management, since it increases disease pressure (Del Ponte et al. 2006) and makes agricultural practices, such as sowing, pest/disease control and harvest, less efficient (Battisti et al. 2012; Monteiro et al. 2014).

Yf had a linear improvement with the increase of EFm when considered the three groups of EFc. In this case, it was observed a higher Yf gain by improving EFm, when the climate conditions for the crop was better (high EFc). The results showed that favorable climate conditions can improve Yf for the same level of EFm. It occurs since under favorable climate conditions the soybean crop can minimize other limiting factors, improving nitrogen fixation (Sinclair

et al. 2007), leaf area index, translocation of nutrients to the grains and photosynthesis under high transpiration rates (van Roekel et al. 2015). Also, enough water availability for the plants avoids anticipation of the cycle caused by water deficit (Battisti et al. 2017c).

EFm and EFc did not show a regional distribution tendency, which is a consequence of the high variability of possible combinations among cultivars, sowing dates and crop managements adopted by Brazilian farmers (Battisti et al. 2017a). Such variability makes difficult to identify which are the aspects of crop management that most affect soybean yield. Therefore, for a better understanding of how much crop management affects Yf, this kind of analysis should be done at farm level to have a better control of the agricultural practices used, as well as the cultivars and sowing dates adopted. Only with this approach will be possible to identify what differentiates the CESB soybean yield winners from the regular growers, making possible to improve crop planning and management for having better soybean yields in Brazil, as well as in other producing regions around the world.

Final Remarks

Soybean yield gap by water deficit and sub-optimum crop management were quantified for the farms that took part of the Brazilian Soybean Yield Contest. The best farmers' yields were used as yield reference to quantify the yield gaps caused by water and crop management deficiencies. Both yield gaps had a similar contribution for total yield gap. The climate efficiency was the main controller of soybean yield, but when agricultural efficiency increased there was a higher rate of yield improvement in the locations with better climate efficiency. According to our findings, the current soybean yield can be doubled in Brazil when considering 80% of the mean yield from the winners as reference yield for the near future. The winners showed to be an important reference for regular farmers, allowing those to identify which are the factors that are limiting or reducing their yields.

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