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Characterizing Brazilian soybean-growing regions by water deficit patterns

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ABSTRACT

The use of specific crop management in a growing region according to its climate can reduce the yield gap caused by water deficit, the main cause of soybean yield gap in Brazil. Therefore, this study aimed to characterize the Brazilian soybean-growing regions based on attainable yield and water deficit patterns. The attainable yields were estimated by the crop model DSSAT-CROPGRO-Soybean, considering six sowing dates, three soil types and 33 growing seasons (1980–2013), using gridded weather data with 453 locations. The homogenous regions were defined by the cluster analysis, based on attainable yield. The water deficit pattern (WDP) was identified by a simulated 5-day running average of water stress index (WSPD) during the growing seasons across different planting dates and soil types, using the cluster analysis for each homogenous region. The attainable yield varied considerably between environments, from 0 to 3400 kg ha^{-1}. Ten environmental zones were obtained, where locations in the same zone indicated the same level and variability of the attainable yield across sowing dates, soils and growing seasons. The highest attainable yield (> 2800 kg ha^{-1}) occurred in the central-western to northern regions (zones 1, 2 and 3), covering most soybean growing areas in Brazil. The lowest attainable yield was observed in the extreme South (zone 6) and East border (zone 7) (< 1170 kg ha^{-1}). The highest attainable yield variability occurred in northern/northeastern (zones 4 and 5), eastern (zone 8) and southern (zones 9 and 10) regions. Three WDP were obtained in each environmental zone, which differed in frequency, level and moment of occurrence during the soybean growing season. Sowing dates and soil types contributed to defining the frequency of each WDP. The homogenous zones and WDP demonstrate that attainable yield and yield gap by water deficit can differ significantly across Brazilian soybean-growing regions. These patterns could be used to improve crop management, such as sowing dates, preferential soils, and irrigation requirements, as well as breeding strategies to deal with water deficit, namely deeper root systems, stomatal closure by decreased water content in the soil and drought tolerance of nitrogen fixation.

1. Introduction

Soybean has high economic importance in many countries since it has multiple uses, namely human food (oil), animal feed (high-protein fibers), biodiesel production, and raw material for several industrialized products. Brazilian soybean production is required to grow 2.6% per year from 2017 to 2026, against an average of 1.9% in the world, to supply global demand (OECD, 2017). In the 2017/2018 growing season, Brazil cultivated 35.1 million hectares of soybeans, with an output of 119 million tons (CONAB, 2018).

Weather conditions during the growing season are the main cause of soybean yield variability between crop seasons and regions, where water deficit accounts for, on average, between 46% (Battisti et al., 2018a) and 74% (Sentelhas et al., 2015) of the yield gap in the fields. Soybean yields in Brazil vary considerably between growing regions since this crop is cultivated from North (4 °N) to South (30 °S), undergoing different climate conditions (Alvares et al., 2013) during the crop cycle. Differences between crop management strategies, such as cultivars, sowing dates, pests and disease control, and the local soil cause variability of soybean yield (Battisti et al., 2017a; Teixeira et al., 2019).

The crop management system can be adapted based on homogenous soybean-growing regions and water deficit patterns to increase soybean production in Brazil. Yield increases by adjusting crop management according to water availability for plants during the crop cycle (Chauhan et al., 2013; Heinemann et al., 2016). The adjustment includes irrigation systems (Nendel et al., 2014), sowing dates (Do Rio et al., 2016), and cultivar features (Battisti et al., 2017b), including crop cycle duration (Kassie et al., 2015), drought tolerance (Battisti and Sentelhas, 2015), and N_2 fixation for drought tolerance (Sinclair et al., 2010).

The climatic risk crop zoning (CRCZ) is the main approach used for

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classifying homogenous regions for soybean cropping in Brazil. CRCZ defines homogenous areas and sowing dates wherein soybean production has lower risk of water deficit based on the relationship between actual and potential evapotranspiration (Farias et al., 2001; MAPA, 2018). Kaster and Farias (2011) used CRCZ to classify homogenous regions in Brazil for the target population of soybean environments, including latitude (photoperiod and temperature), water deficit based on actual and potential evapotranspiration during the most sensitive crop phase, altitude (temperature), and soil type. However, crop simulation models are more effective to characterize homogenous regions, as they define the dynamics of crop growth based on the photosynthesis rate, daily water deficit and final yield through the ability to integrate data on long-term climate, soil, sowing date, cultivars, and crop management (Chenu, 2014; Heinemann et al., 2016). Crop simulation models have been used in Brazil in beans (Heinemann et al., 2016), rice and maize (Heinemann et al., 2008).

We hypothesize that the soybean growing area in Brazil can be classified by the attainable yield, as yields are determined by water deficit, the main source of yield gap. Similarly, sowing dates and soil types affect the water deficit pattern in each homogenous region, where the attainable yield can be used to define effective strategies (water deficit reduction or potential yield increase) for improving soybean performance. This study aimed to: i) identify soybean homogenous regions based on the attainable yield and its variability for different growing seasons, sowing dates and soil types, simulated by a mechanistic crop simulation model; ii) characterize water deficit patterns based on relationship between actual and potential transpiration for each homogenous region, considering its intensity and frequency for different combinations of sowing dates and soil types; and iii) quantify the soybean yield gap caused by water deficit for each region, sowing date, and soil type.

2. Materials and methods

2.1. Weather and soil databases

The weather data employed in this study were obtained from the daily gridded database from Xavier et al. (2015) in a grid of 1° x 1°, totaling 453 points (locations). These points cover most soybean-growing regions in the 2015/2016 season in Brazil (Fig. 1). The data were obtained for the period between 1980 and 2013, enabling the simulation of 33 growing seasons, comprising daily minimum and maximum air temperatures, solar radiation, total rainfall, average relative humidity, and average wind speed at 2 m above the soil surface. The use of gridded weather database is appropriate for the study purpose, as indicated in previous simulations carried out by Battisti et al. (2018b).

Due to its continental dimension, Brazil has a huge variability of soil types, which affects both soil chemical and physical attributes. Different physical attributes lead to distinct soil water holding capacities (SWHC) (Supplementary Materials - Figure S1a). Thus, three basic soil types were used in all locations to represent the great diversity in Brazilian soils. These three soil types have SWHC 1.5, 1.0, and 0.6 mm cm^{-1} (See total range for Brazil in Supplementary Materials - Figure S1b). The maximum plant-available soil water capacity was obtained by multiplying SWHC by the maximum root depth of 80 cm, as proposed by Battisti et al. (2017c) during soybean crop model calibration, and identified by Battisti and Sentelhas (2017) at different farms and specialized references. The three soil types had maximum plant-available soil water capacity of 48, 80 and 120 mm, respectively, for sandy-loam, sandy-clay, and clayey soils. The maximum plant-available soil water capacity values used here are within the range observed in the assessed regions in Brazil (Supplementary Materials - Figure S1c), when considering the actual soil depth, limited to 80 cm or lower (Supplementary Materials - Figure S1d). The soil profiles required by the crop simulation model were built based on data from Battisti and Sentelhas (2017) (Supplementary Material Table S1).

2.2. Crop model simulations

The crop model CROPGRO – Soybean (Boote et al., 1998; Boote et al., 2003), part of the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003), was used to simulate soybean growth and development. This model provided more accurate yield estimates among five crop simulation models compared by Battisti et al. (2017c) for Brazilian conditions. The CROPGRO parameters used in the simulations were obtained from Battisti (2016) and Battisti and Sentelhas (2017). These parameters were obtained for relative soybean maturity groups 5.8, 6.8 and 7.8, which were used to simulate yields, respectively, for latitudes between 23° and 32°S, 15° and 22.9°S, and 4° and 14.9°S (Supplementary Material Table S2). These maturity groups resulted in soybean crop cycles ranging from 110 to 130 days, from sowing to maturity across Brazil (Battisti and Sentelhas, 2017).

The simulations considered the following sowing dates: 15 Sep; 15 Oct; 15 Nov; 15 Dec; 15 Jan; and 15 Feb, following the soybean sowing dates recommended by Agroclimatic Risk Zoning from the Ministry of Agriculture, Livestock and Food Supply (MAPA, 2018) and the maximum sowing window possible for soybean in Brazil. We used 28 plants m^{-2} with row spacing 0.45 m, as recommended by EMBRAPA (2011). The simulations considered multiple/single year run, with simulations starting six months before the first sowing date, using an initial soil water content of 75% of maximum plant-available soil water capacity. Potential and attainable yields were simulated, as described by Sentelhas et al. (2015). For the potential yield, the water balance module was switched off, whereas for the attainable yield, it was switched on.

2.3. Data analyses

2.3.1. Homogenous soybean-growing regions

Homogenous soybean-growing regions were determined based on the attainable yield simulated by crop model for combinations of 33 growing seasons, and the same six sowing dates and three types of soil for 453 points in Brazil (Fig. 1). The attainable yield was used because most soybean is grown under the rainfed condition, and yield is linked to water deficit across production regions. The simulated attainable yields were organized in a matrix, where the rows represent the points (n = 453), which were grouped, and the columns are the attainable yields from the combination of six sowing dates, three soil types and 33 growing seasons (n = 594), totaling 269,082 results.

The cluster analysis was carried out considering the Ward method and Euclidean distance. The criterion used to define the number of homogenous regions was a pre-defined number of groups between 5 and 10, based on the mean attainable yield and the spatial distribution of each region according to the groups. After grouping in homogenous zones, 453 locations were plotted in the map generating the soybean-growing macro regions in Brazil.

Afterwards, the homogenous soybean-growing macro regions were characterized by the potential and attainable yields, potential and actual transpirations, and relative and absolute yield gaps from water deficit. The macro-regions were evaluated by comparing yield tendency from microregion level, considering the mean attainable yield simulated with actual yield obtained from 2007 to 2016 (IBGE, 2018). The soybean yields obtained by IBGE (2018) considered a sample of mean yield at a farmer level in each Brazilian microregion by means of interviews with farmers, agents and cooperatives, regarding multiple soils, cultivars and sowing dates.

2.3.2. Water deficit pattern per region

The water deficit patterns were identified separately per homogenous region using the simulated water deficit index (WSPD), which is an output of the DSSAT model based on the actual and potential transpiration. WSPD is used for penalizing daily photosynthesis (Boote et al., 1998). WSPD was obtained from soybean sowing to maturity, considering a 5-day mean value. The water deficit pattern was defined based on the cluster analysis,

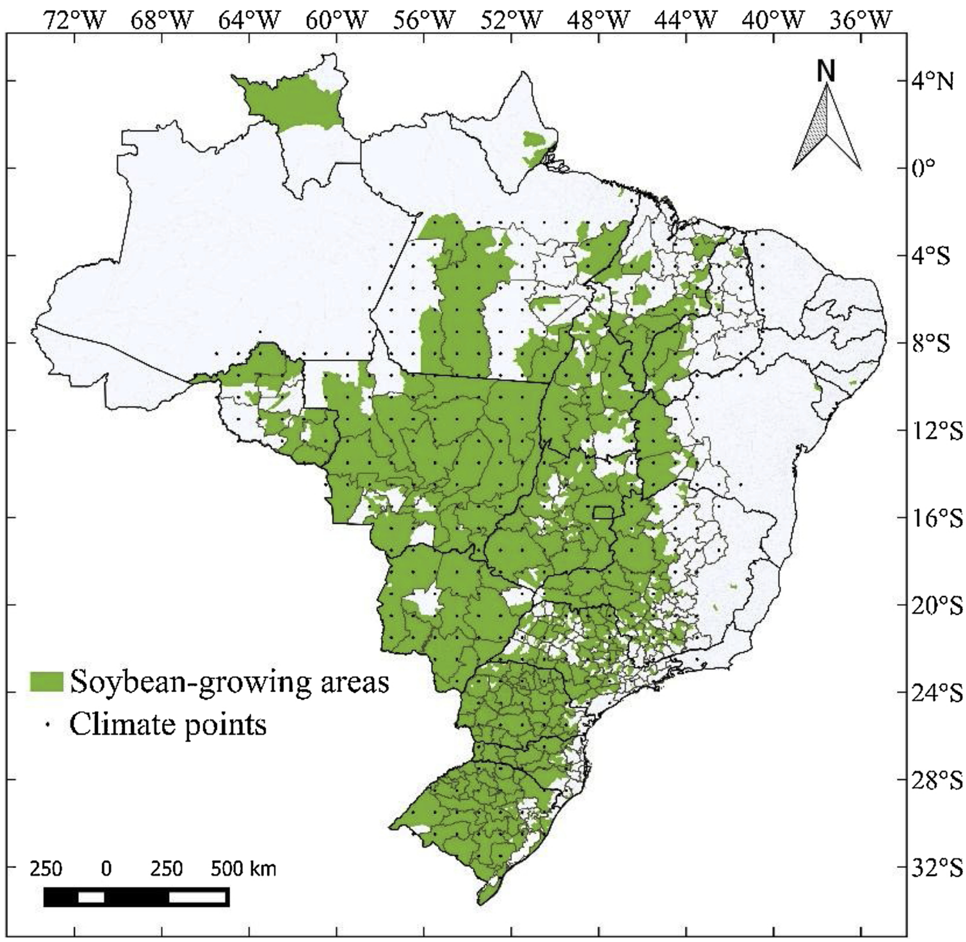

Fig. 1. Brazilian soybean growing areas in the 2015/2016 season (IBGE, 2018) and points from daily gridded weather database used in the simulations.

considering the Ward method and Euclidean distance. The matrix was built considering the combination of six sowing dates, three soil types and 33 crop seasons in the rows (n = 594), and in the columns, the combination of locations and 5-day mean WSPD from sowing to maturity. The number of columns varied according to the size of each homogenous region. The criterion used to define the water deficit patterns was a pre-defined number of groups between 3 and 5 for each homogenous region (defined following the approach presented in 2.3.1), and the 5-day mean WSPD value during the crop cycle. Afterward, each water deficit pattern was described by WSPD during the soybean cycle, considering its probability of occurrence, based on the number of crop seasons (n = 33), potential and attainable yields, and relative yield gap by water deficit for each sowing date (n = 6) and soil type (n = 3), totalizing a combination of 18 scenarios.

3. Results

3.1. Soybean-growing regions

3.1.1. Environmental zones

The attainable soybean yield varied considerably across the Brazilian regions (Fig. 2a), with lower mean values ranging between 0 and 1400 kg ha^{-1} in the southern, eastern and northeastern borders of soybean-growing regions. These regions also had the highest inter-annual variability, with coefficients of variation (CV) above 56% (Fig. 2b). When the percentile 25% was considered for the attainable yield, the area with lower yields increased substantially (< 1400 kg ha^{-1}), mainly in the southern and eastern borders (Fig. 2c).

The highest mean values ranged between 2801 and 3400 kg ha^{-1} in the Central-West, including most of Mato Grosso (MT) and Rondônia (RO) states (Fig. 2a). The lowest CV also occurred in these regions, including southwestern Pará (PA) (Fig. 2b). For the attainable yield at the percentile 75%, the highest yields were observed in most of the country, except for the borders in the southern, eastern, and northeastern regions, where the attainable yields were lower than 2400 kg ha^{-1} (Fig. 2d).

The clustering of simulated soybean attainable yield formed ten environmental zones (Supplementary Materials - Figure S2), which resulted in the zoning map presented in Fig. 3. Each environmental zone is a set of a different numbers of gridded points. The size of the environmental zones was based on attainable yield values, regarding their level and variability for the combination of six sowing dates, three soil types and 33 growing seasons. The environmental zones from 1 to 10 had, respectively, 85, 46, 74, 41, 40, 19, 31, 28, 43 and 46 gridded points (locations) (Fig. 3) from where climate data were obtained in a grid resolution of 1° x 1°.

When different locations are in the same environmental zone, yield level and variability were similar (Fig. 4), considering the characteristics of inputs in the simulations and the use of cultivar maturity group adapted for that region. Zone 3, for instance, comprises locations in latitude from 8 °S to 24 °S, with similar attainable yields, even considering the different maturity groups used according to the latitude. The zones followed the climate conditions and allowed a great soybean yield variability in the same state. For example, in Mato Grosso (MT), the state with the largest soybean production area in Brazil, four environmental zones were identified (1, 2, 3 and 10) (Fig. 3), which is a consequence of the huge size of the state and the different climate patterns that it has. On the other hand, in the states of Paraná (PR) and Santa Catarina (SC), only one zone (9) was identified due to the similarity of the climate in these two states, since they are basically affect by the same meteorological phenomena.

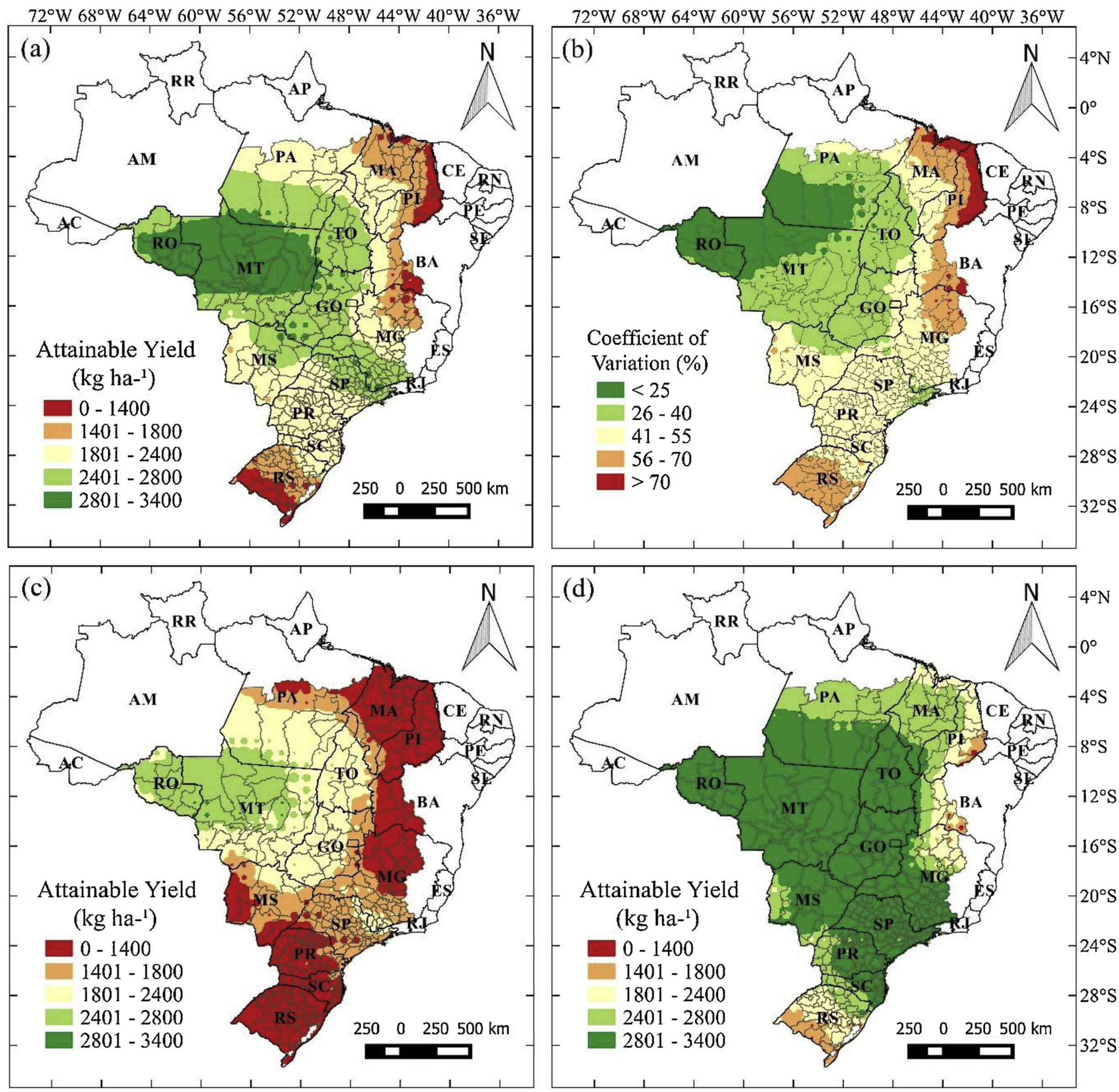

Fig. 2. Average (a), coefficient of variation (b), percentile 25% (c) and percentile 75% (d) for soybean attainable yield simulated for Brazil, considering the results from combination of six sowing dates (15 Sep, 15 Oct, 15 Nov, 15 Dec, 15 Jan and 15 Feb), three soil types (clayey, sandy-clay and sandy-loam) and 33 growing seasons (1980–2013). Percentile is the yield value that divided the datasets by 25% and 75% of all data.

The effects of climate variability across sowing dates, soils types and growing seasons can result in different attainable yield levels (Fig. 4). For example, Zone 1 had an attainable yield above 2000 kg ha^{-1} and below 3500 kg ha^{-1} for the combination of all sowing dates, soil types and growing seasons (Fig. 4), while for Zone 9, yields ranged from 500 to 4000 kg ha^{-1}. These results indicate that ten soybean zones have their locations with similar yield patterns and levels across sowing dates, soils types and growing seasons.

3.1.2. Environmental zones description

The soybean potential yield ranged from 1244 to 4600 kg ha^{-1} (Fig. 5a) considering all environmental zones. Zone 4 had the lowest mean potential yield, with 2654 kg ha^{-1} and the lowest variability, with values ranging from 2164 to 3074 kg ha^{-1}. On the other hand, Zones 6 and 9 presented the highest potential yield variability, respectively, from 1244 to 4449 kg ha^{-1}, and from 1304 to 4335 kg ha^{-1} (Fig. 5a). The highest average attainable yield was obtained in Zone 2, with 3155 kg ha^{-1}, followed by Zones 1 and 3, with values around 2800 kg ha^{-1} (Fig. 5b). These three zones cover most soybean-growing areas in Brazil (Fig. 3). Zones 4 and 5 (North and Northeast) showed a reduction of average attainable yield and increased variability in relation to Zones 1, 2 and 3 (Fig. 5b). The lowest attainable yield was observed in Zones 6 and 7 with 1169 and 945 kg ha^{-1}, respectively (Fig. 5b), representing the worst zones for soybean production in Brazil. The highest attainable yield variability occurred in Zones 8, 9 and 10 with values ranging from 395 to 4064 kg ha^{-1} (Fig. 5b).

As expected, attainable yield (Fig. 5b) had an inverse trend in relation to relative water stress impact (Fig. 5c) and directly associated to actual/potential soybean transpiration ratio (Fig. 5d). Zone 7 had the highest water stress impact on yield, with an average yield loss of 72%, mainly due to a reduction of actual transpiration because of low soil water availability. For Zone 7, the mean actual/potential transpiration ratio was 0.40 (Fig. 5d). On the other hand, Zone 1 lost, on average, less than 10% of potential yield by water deficit (Fig. 5a), with the mean actual/potential transpiration ratio of 0.97 (Fig. 5d).

3.1.3. Simulated versus measured soybean yields at microregion level

The consistency of each zone in relation to the simulated yields was obtained by using measured yields from IBGE (2018) at microregion level.

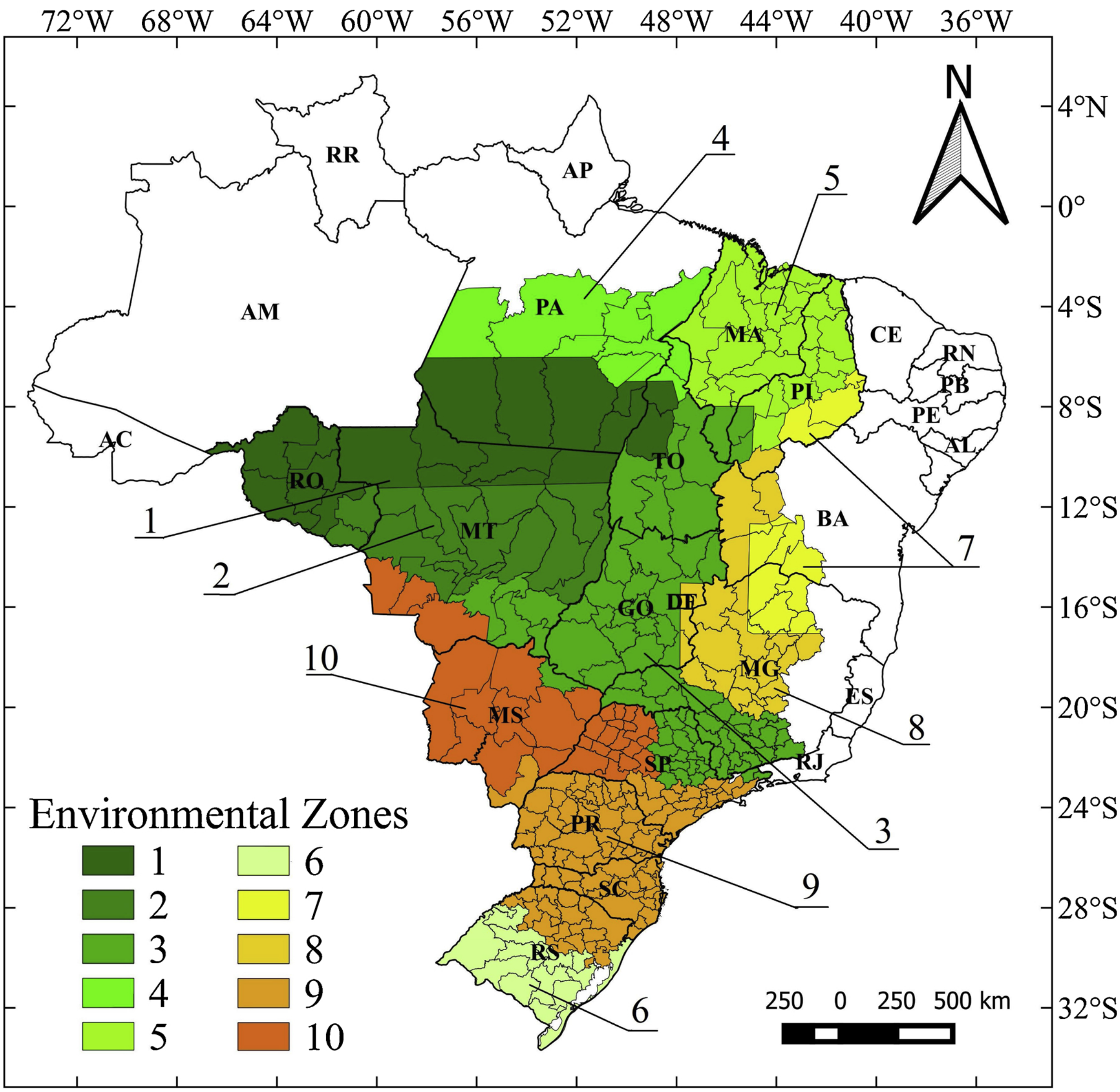

Fig. 3. Environmental homogenous soybean zones determined by the cluster analysis, based on attainable yield simulated for six sowing dates, three soil types and 33 growing seasons.

There was a strong correlation for most zones between measured and simulated soybean yields when considering the micro regions of each homogenous zone (Fig. 6). The climate effect was evidenced by the proximity of yields simulated and measured for microregion of each zone (Fig. 6). For example, Zone 2 showed the highest measured and simulated yields, with values around 3000 kg ha^{-1}, and correlation coefficient (r) of 0.56. On the other hand, Zone 6 showed the lowest simulated and measured yields with a higher correlation between each other (r = 0.62); however, with a large difference between simulated and measured yields (Fig. 6). The worst correlation was observed for Zone 4 (r = 0.04) with only five micro regions. Zone 4 is an area where soybean is starting to be grown, where there is limited data for observed soybean yield. In the majority of the assessed zones, the crop model simulated lower yields than those observed in the fields, which was associated with the large sowing window used for simulations and the use of three types of soils. Therefore, this study does not present the yields obtained only for the best sowing dates and soil types, which are normally used by farmers.

3.2. Water deficit patterns per zone

The cluster analysis for the simulated water stress index (WSPD) resulted in three homogenous patterns for each environmental zone. The cluster results for each zone are presented in Supplementary Material - Figure S3. The three water deficit patterns had a different number of yield results from the six sowing dates, three soil types and 33 growing seasons used in the simulations, where water deficit patterns (WDP) 1, 2 and 3 had different standards between the ten homogeneous regions, being not possible to characterize them by a general way. However, the sowing dates, soil types and growing seasons in the same WDP (1, 2 or 3) had similar WSPD, based on the level and moment of water deficit occurrence during the crop cycle in each one of 10 homogeneous zones.

Environmental Zones 1 to 5 had at least one WDP with low WSPD during the soybean crop cycle (Fig. 7). For example, Zone 2 had WDP 1 with WSPD increasing from 40 days after sowing to reach the maximum (around 20%) at 80 days after sowing (Fig. 7c). WDP 2 showed higher WSPD at the beginning of the cycle, whereas WDP 3 had almost no WSPD (Fig. 7c). WDPs in Zone 2 had possible WSPD occurrence varying according to sowing dates and soils types (Fig. 7d). WDP 1 had a higher probability of occurrence for the sowing in 15 Feb for sand-loam and sandy-clay soils. For WDP 2, higher probability was in the sowing of 15 Sep for all soil types, and for WDP 3, for sowings of 15 Oct, 15 Nov, 15 Dec and 15 Jan for all soils types (Fig. 7d). The soil types influenced WSPD probability of occurrence in each WDP, which reduced the

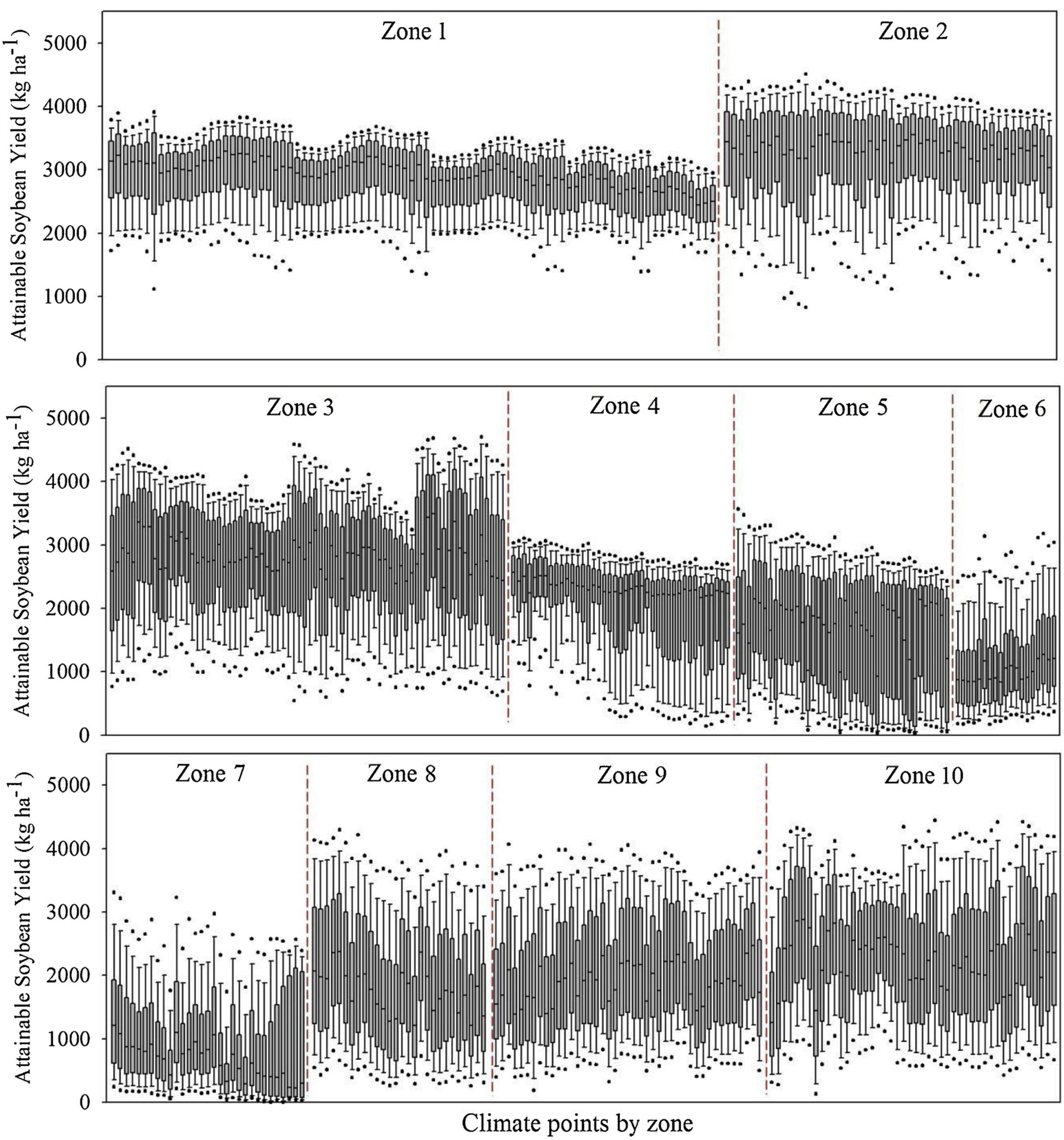

Fig. 4. Attainable soybean yield simulated for all assessed locations by homogenous zone in Brazil. For boxplot, the full central line is the percentile 50%, bars are the percentiles 25% and 75%, vertical lines are the percentiles 10% and 90%, and black points refer to percentiles 5% and 95%. Each bar represents one location (total of 453) from gridded weather data (Fig. 1), to where yield was simulated for the combination of six sowing dates, three soil types and 33 growing seasons, totalizing 594 yield results by assessed location.

probability of WSPD occurrence for WDP 1 and WDP 3 when soil water availability was increased from sandy-loam to clayey soils (Fig. 7d).

For Zones 6 to 10 (Fig. 8), all WDPs had some level of WSPD along the crop cycle, reaching maximum WSPD mean value around 60% in Zone 6 for WDP 2 (Fig. 8a), meaning that 60% of daily photosynthesis was penalized by water deficit. For example, Zone 8 had three distinct WDPs (Fig. 8e). WDP 1 had higher WSPD occurrence around 80 days after sowing (Fig. 8e) with the highest occurrence frequency for sowing in 15 Feb and soils with lower water available to the crop (sandy-loam and sandy-clay) (Fig. 8f). WDP 2 and WDP 3 had the highest WSPD occurrence, respectively, at the beginning and at the end of the crop cycle (Fig. 8e). WDP 2 had the highest WSPD frequency for sowing in 15 Sep for all soil types, whereas WDP 3 predominated in the sowings from 15 Oct to 15 Jan in sandy-clay and clayey soils types, respectively (Fig. 8f).

The lowest yield gap caused by water deficit occurred in Zone 1 for WDP 2, which had only 1% of soybean potential yield, on average, penalized by water deficit, from 2974 kg ha^{-1} to 2947 kg ha^{-1} (Table 1). WDP 2 had higher frequency of occurrence for sowing dates between 15 Oct and 15 Dec, mainly for sandy-clay and clay soils (Fig. 7b). WDP 3 had the highest average potential yield, 3239 kg ha^{-1}; however, due to water deficit during the crop cycle, yield losses reached 10%, resulting an attainable yield of 2912 kg ha^{-1}, which was lower than WDP 2, despite a higher potential yield (Table 1).

The highest yield losses occurred in Zone 5 for WDP 3, which had a potential yield of 3219 kg ha^{-1} and an attainable yield of 379 kg ha^{-1}, which means more than 80% of reduction caused by water deficit (Table 1). WDP 2 also had high yield losses with an average of 71%. WDP 2 and WDP 3 had a high frequency of occurrence, respectively, on

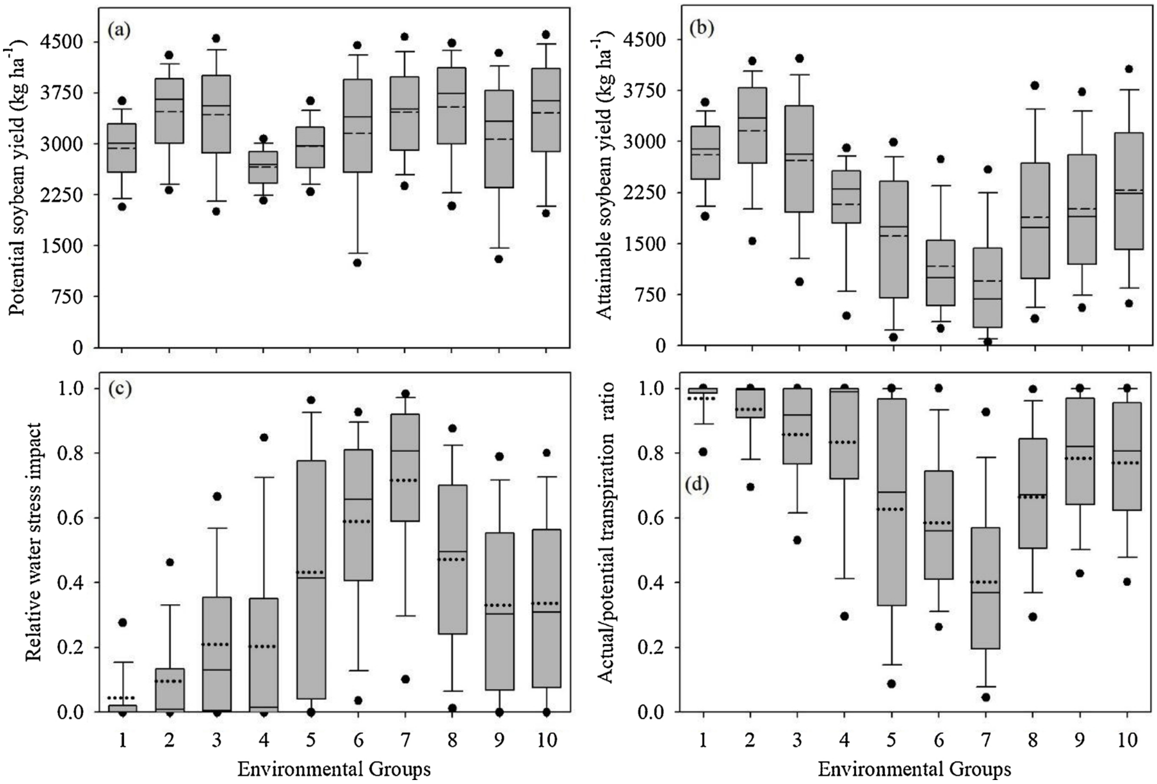

Fig. 5. Potential (a) and attainable (b) soybean yields, relative water stress impact on soybean yield (c) and actual/potential soybean transpiration ratio (d) for ten environmental zones in Brazil. In boxplot, dashed central line is the mean value, central full line is the percentile 50%, bars are the percentiles 25% and 75%, lines are the percentiles 10% and 90%, and black points refer to percentiles 5% and 95%. The range for all variables is associated with soil types, sowing dates and growing seasons. The environmental zones, from 1 to 10, are presented in Fig. 3 and the attainable yield for each climate point by environmental zone is shown in Fig. 4.

sowing dates 15 Sep and 15 Oct (Fig. 8j), which need to be avoided because of yield losses caused by water deficit. On the other hand, WDP 1 for Zone 5 (Fig. 8i) had the highest frequency of occurrence on sowing dates 15 Nov, 15 Dec, 15 Jan and 15 Feb (Fig. 8j), causing potential yield losses by water deficit of only 24% (Table 1), being the preferential sowing dates currently used in this region.

4. Discussion

Soybean attainable yields showed considerable variation in the Brazilian growing regions (Fig. 2), which is mainly conditioned by climatic conditions, as also observed by Sentelhas et al. (2015) and Battisti et al. (2018a) in Brazil and by Ray et al. (2015) in other regions around the world. In Brazil, the northwest of the assessed region, which include south

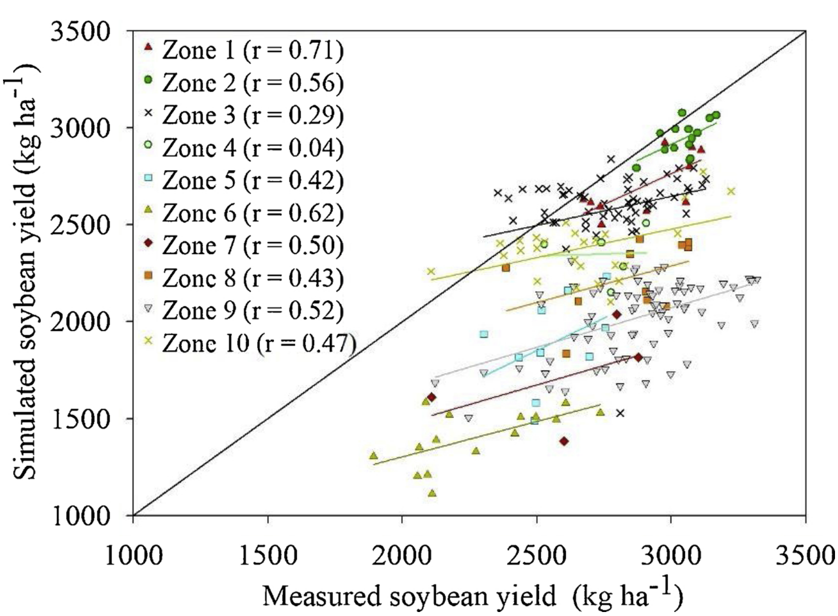

Fig. 6. Relationship between average measured soybean yields from IBGE (2018) and average simulated soybean yields from each microregion within the homogenous zones in Brazil.

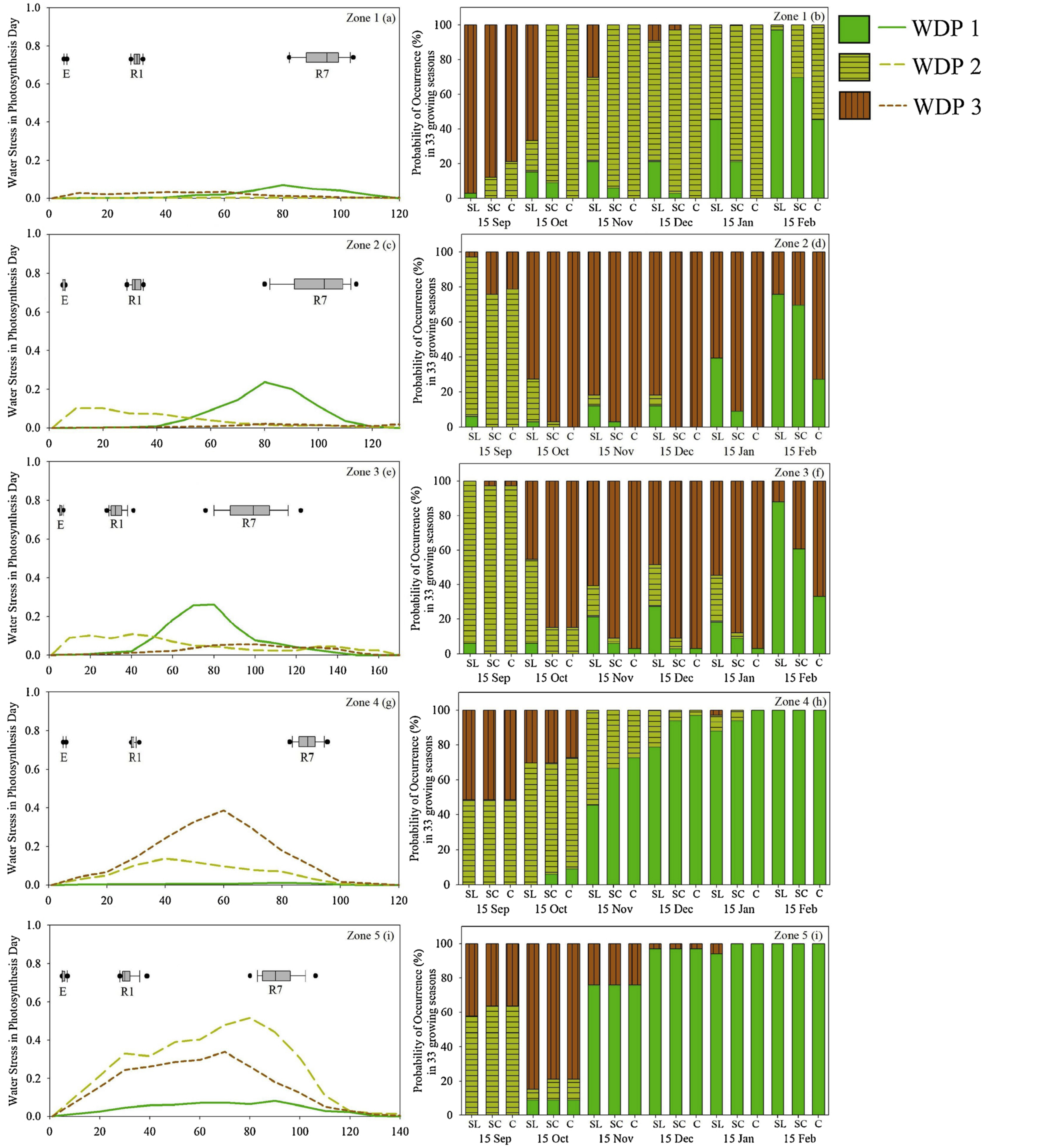

Fig. 7. Three water deficit patterns (WDP) based on water stress for daily photosynthesis (WSDP) (a, c, e, g and i) and their probability of occurrence for 33 growing seasons per sowing date and soil type (b, d, f, h and j) in the environmental zones 1 (a and b), 2 (c and d), 3 (e and f), 4 (g and h) and 5 (i and j). The horizontal bars in Fig. 7a, c, e, g, and i indicates the percentiles (5, 10, 25, 50, 75, 90, 95%) for days after sowing for the occurrence of emergence (E), beginning of flowering (R1), and maturation (R7) across zones and sowing dates. In the right-hand figures the column 100% represent the 33 growing seasons and the probability of occurrence of each WDP by sowing date and for sandy-loam (SL), sandy-clay (SC) and clayey (C) soil types.

of Pará, north of Mato Grosso and great part of Rondônia (Fig. 2), had the highest and more stable attainable yield across regions, basically due to the climate conditions that prevail there (Am and Aw according to Köppen´s climate classification). This region is a tropical zone with very regular rainfall distribution during soybean growing season, from October to March (Alvares et al., 2013; Teixeira et al., 2019).

On the other hand, the extreme south and east border of the Brazilian soybean production were the region with the lowest yields and the highest coefficient of variations. In the extreme south, the climate is humid subtropical without dry seasons and classified as Cfa (with hot summer) according to Köppen´s classification (Alvares et al., 2013). Despite the absence of a normal dry season, this region has a strong rainfall interannual variability during the soybean growing season, which is influenced by El Niño South Oscillation (ENSO) phenomenon, which promote dry spells

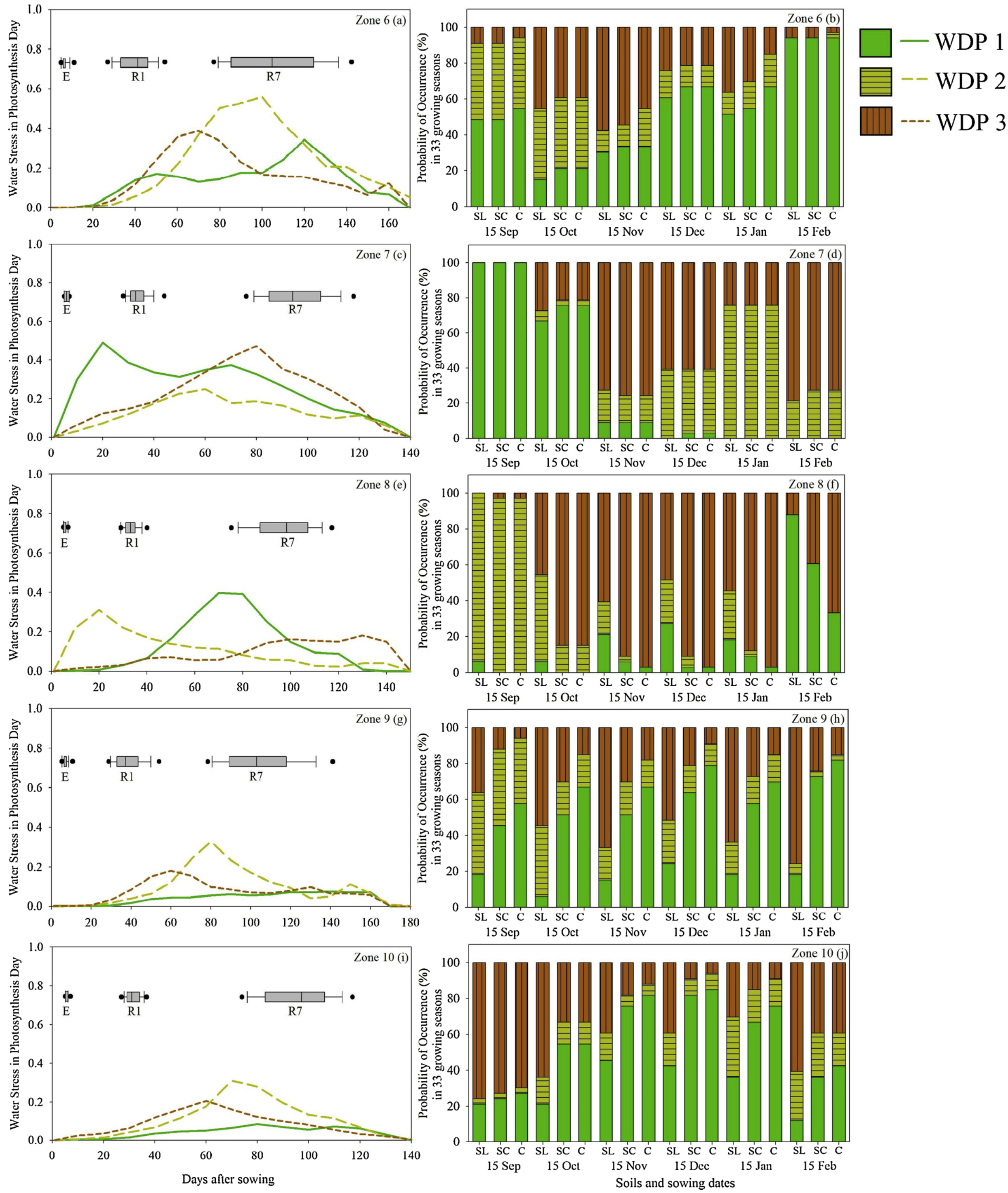

Fig. 8. Three water deficit patterns (WDP) based on water stress for daily photosynthesis (WSDP) (a, c, e, g and i) and their probability of occurrence for 33 growing seasons per sowing date and soil type (b, d, f, h and j) in the environmental zones 6 (a and b), 7 (c and d), 8 (e and f), 9 (g and h) and 10 (i and j). The horizontal bars in Fig. 8a, c, e, g, and i indicates the percentiles (5, 10, 25, 50, 75, 90, 95%) for days after sowing for the occurrence of emergence (E), beginning of flowering (R1), and maturation (R7) across zones and sowing dates. In the right-hand figures the column 100% represent the 33 growing seasons and the probability of occurrence of each WDP by sowing date and for sandy-loam (SL), sandy-clay (SC) and clayey (C) soil types.

during its cold phase (La Niña). Otherwise, the east border region is located in a transition among three climate zones: tropical zone with dry winter (Aw); tropical zone with dry summer (As); and tropical semi-arid zone (BSh), which promotes very irregular rainfall distribution, limiting soybean yield (Alvares et al., 2013).

Based on the soybean yields (average and variability) obtained across the country, ten environmental zones (Fig. 3) were identified for soybean production with three water deficit patterns for each one (Fig. 7 e 8). These zones followed the attainable yields and their variation across the regions, which was associated with climate, conditioned by sowing date, soil type, and crop phases. For example, water deficit can occur at the beginning (sowing in 15 Sep) or at the end (sowing in 12 Feb) of the cycle (Fig. 7c and 7d) in region 2, where, rainfall season starts in middle of October and ends in April (Sentelhas et al., 2015), doing sowing window from 15 Oct to 15 Jan the preferential for this region. Region 3 had water deficit pattern similar to

Table 1
Potential and attainable yield and relative water stress index (RWSI[1]) for each water deficit pattern for ten environmental zones in Brazil. Values between brackets represent the standard deviation from three soil types, six sowing dates and a variable number of growing seasons based on water deficit pattern frequency.

Zone	Water deficit pattern						
	1	2	3	Zone	1	2	3
	Potential Yield (kg ha^{-1})				Potential Yield (kg ha^{-1})		
1	2493 (±458)	2974 (±441)	3239 (±267)	6	3542 (±618)	2732 (±1047)	3704 (±754)
2	3521 (±586)	2738 (±545)	3906 (±255)	7	3389 (±723)	3234 (±585)	3772 (±581)
3	2669 (±782)	3464 (±740)	3803 (±494)	8	3169 (±826)	3641 (±662)	3972 (±345)
4	2499 (±256)	2867 (±164)	2880 (±177)	9	2949 (±985)	3027 (±1037)	3385 (±701)
5	2816 (±396)	3192 (±306)	3219 (±298)	10	3481 (±880)	3507 (±776)	3162 (±853)
Zone	Attainable Yield (kg ha^{-1})			Zone	Attainable Yield (kg ha^{-1})		
1	2266 (±562)	2947 (±443)	2912 (±515)	6	683 (±468)	1381 (±789)	1127 (±749)
2	3379 (±642)	1971 (±787)	3221 (±640)	7	790 (±721)	1404 (±890)	767 (±792)
3	1601 (±835)	3029 (±872)	2714 (±891)	8	1169 (±779)	2383 (±982)	2039 (±1019)
4	2416 (±305)	1870 (±767)	1011 (±811)	9	2380 (±981)	1695 (±924)	1598 (±841)
5	2106 (±697)	926 (±761)	379 (±440)	10	1875 (±967)	2783 (±938)	1566 (±935)
Zone	RWSI			Zone	RWSI		
1	0.09 (±0.15)	0.01 (±0.04)	0.10 (±0.14)	6	0.80 (±0.13)	0.45 (±0.27)	0.70 (±0.19)
2	0.04 (±0.09)	0.29 (±0.23)	0.17 (±0.17)	7	0.75 (±0.24)	0.55 (±0.29)	0.81 (±0.20)
3	0.40 (±0.24)	0.12 (±0.18)	0.28 (±0.22)	8	0.63 (±0.22)	0.34 (±0.25)	0.49 (±0.26)
4	0.03 (±0.09)	0.35 (±0.27)	0.65 (±0.28)	9	0.18 (±0.21)	0.44 (±0.23)	0.52 (±0.24)
5	0.24 (±0.26)	0.71 (±0.23)	0.88 (±0.13)	10	0.46 (±0.25)	0.20 (±0.22)	0.50 (±0.26)

[1]RWSI = (Potential yield - Attainable yield)/Potential yield.

region 2, but showed a lower attainable yield, which was caused by the higher water deficit during grain filling period, the most sensitive phase of the crop to water shortage (Fig. 7e). This condition highlights the importance to adjust crop cycle duration and sowing date as a function of water deficit pattern in the region (Battisti and Sentelhas, 2014).

Cluster analysis was used to define water deficit patterns based on a 5-day mean water stress in daily photosynthesis, where each region was characterized by three water deficit patterns inherent for that region (Fig. 7 and 8), being not possible to characterize WDP 1, 2 and 3 by a general definition, as used by Heinemann et al. (2016). The water deficit patterns changed considerably according to soil type, due to available water for crop growth, and to the sowing dates by the interaction of local climate with crop phenological phases and their sensitivity to water deficit. The water deficit pattern in each environmental zone and its probability of occurrence by sowing date can give support for further studies to identify the best crop management to reduce the impacts of water deficit on yield (Heinemann et al., 2016; Teixeira et al., 2017).

Kaster and Farias (2011) classified the homogenous regions for soybean production in Brazil, dividing the country into five macro regions with four subdivisions each (total of 20 regions). Even considering that the studies had different purposes, the delimited areas were quite similar with our study. The observed difference were caused by the criteria they used to make the subdivision, which were done according to latitude and altitude. Whereas in the present study yield data and their variability were used to define the soybean regions, the cited authors used sometimes latitude to define the regions in the macro region and other time altitude. For example, in relation to our region 9, they consider subdivision of the region according to high (Cfb Köppen´s climate) and low altitude (Cfa Köppen´s climate). On the other hand, for our region 3, which goes from 8° to 24 °South (Fig. 2), they considered latitude as the criteria to make the subdivisions, whereas in the present study we varied the maturity groups of the cultivars. Another difference between these two studies was that Kaster and Farias (2011) divided Brazil for the new cultivar trial tests, considering latitude, altitude and best sowing dates, while we focused on climate effect on yield considering a long sowings window, different soil types and cultivars, and 33 growing seasons.

We decided to make soybean yield simulations using a long sowing window, from 15 Sept to 15 Feb, to identify the water deficit patterns that affect the crop in the different parts of the country. If from one side it does not give the best yield information, from another allows to identify, in comparative way, which are the differences between regions in terms of yield and WDP variations, making possible to identify the best sowing dates, when the climatic risks are lower. If only the best sowing dates in each region were simulated, similar yields and WDP would be obtained, making the zoning of homogeneous regions impossible. Therefore, the simulations for sowing dates out of the optimum period and for soils with low water availability were responsible for lower simulated yields in comparison with measured ones, not reflecting the reality of the soybean fields in the country (Battisti et al., 2017a; Teixeira et al., 2019).

Further studies should be conducted in order to incorporate the evaluation of different crop managements based on the homogenous regions and soybean sowing dates when WDPs of high intensity and frequency occur, such as in zone 5 where the water deficit is high from the middle to the end of the soybean cycle (WDP 2 and 3) (Fig. 7i). In this case, the strategies to avoid the impact of water deficit on yield should be tested during the early sowings (15 Sep and 15 Oct), using crop models or field experiments. This kind of analysis is important when the production system forces growers to an early soybean sowing in order to grown maize as second crop, as normally observed in the majority of the soybean regions in Brazil (Nóia Jr. and Sentelhas, 2019). Additional strategies can be include to avoid water deficit, such as: physiological traits selection (Sinclair et al., 2010; Gilbert et al., 2011; Battisti et al., 2017b); irrigation (Hatfield and Walthali, 2015; Almeida et al., 2018); deep soil preparation (Battisti and Sentelhas, 2017; Rodrigues et al., 2017); choice of the sowing date based on the ENSO phase (Nóia Jr. and Sentelhas, 2019) and crop cycle and sowing dates interaction (Battisti and Sentelhas, 2014).

5. Conclusion

The soybean-growing areas in Brazil were divided in ten homogenous environmental zones based on the attainable yield, mostly affected by water deficit. Each zone had water deficit pattern clustered in three groups in terms of frequency and type of water deficit observed for the combination of different sowing dates and soil types. There was a clear trend of soybean yield reduction in terms of water deficit intensity; however, with different levels according to environmental zones. The classification of environmental zones helped identify regions with similar attainable yield levels and water deficit patterns, which can be useful to evaluate crop management strategies and to soybean breeding programs for drought tolerance or higher potential yield. Further, homogenous environmental zones showed a strong correlation with measured yield at regional level, indicating that the approach used in this study captured climate tendencies. The main limitation of this study was that homogenous environmental zones were defined exclusively by regional climate and its variability according to interactions between six sowing dates and three soil types. This limitation can change attainable yields if more details about local soil type, maximum root depth, preferential sowing date and cultivar maturity group were provided. Nevertheless, the present approach presented more detailed results for soybean crop in Brazil, which can help elaborate better strategies to improve soybean yield in all assessed regions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fcr.2019.06.007.

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