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Impact of rainfall variability on soybean yields in Southern Brazil

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Abstract

As the third soybean-producer state in Brazil, Rio Grande do Sul (RS) presents a known year-on-year unevenness for soybean production, mainly due to water availability. This study aimed to assess the weather effects, with special focus on rainfall during 25 soybean growing seasons and 11 producing regions around the State. Sites were divided into three Clusters according to soybean yield and the effect of El Niño Southern Oscillation (ENSO) was considered in association with soil water balance. Neutral ENSO phases occurred in 32% of the years, while El Niño and La Niña occurring in 36% and 32% of the years, respectively. Seasons under El Niño normally present higher accumulated rainfall, whereas those under La Niña present a reduction. Data from neutral-year sites of Clusters B and C seems to be more disturbed. No season had statistical difference of rainfall among Clusters under Neutral conditions. In addition, thermal gradient in RS from October to January benefited sites of Cluster A. Interaction of soils with higher water-storage capacity and cooler temperature reduces the water consumption by soybeans, causing lower values of water deficiency. A boundary function relating soybean yield and rainfall displays the limit of 800 mm for significant yield increments, and such amounts of rainfall were only achieved in El Niño seasons. The combined effect of rainfall and soil type on soybean yield, represented by the actual soybean yields-water deficit relationship, led to water propitiate from -3.7 to -15.2 kg mm⁻¹ ha⁻¹. Decision-making on public policies and investments on the soybean industry can be supported from our results, either to better planning the investments on the soybean farming systems depending on the ENSO phase predictions, either to reduce the production risks in the region inherent to local weather.

Introduction

Brazil is the second main soybean producer worldwide, producing 119.3 million tons from 35 million hectares in the 2017/18 season (Conab 2018). The southernmost State of Brazil, Rio Grande do Sul (RS) ranks third among soybean-producer states, with 14.4% of Brazilian production

(Conab 2018). Although RS offers climate suitability for soybean crop, the state presents significant inter-annual production variability (Cunha et al. 1998; Battisti et al. 2013).

According to Brazilian National Supply Company (Conab, 2019), the average on-farm soybean yields of the last ten crop seasons ranged from 1.55 to 3.32 Mg ha⁻¹. Considering all Brazilian historical dataset, since 1976/77, the soybean yield variability is even higher, reaching values below 1.0 Mg ha⁻¹ in three seasons, 0.91 Mg ha⁻¹ (1978/79), 0.72 Mg ha⁻¹ (1990/91) and 0.69 Mg ha⁻¹ (2004/05).

In such region soybean yield is heavily controlled by farming systems technology but it is also well-known that the irregular distribution of rainfall during the soybean growing season presents itself as a limiting factor to the potential yield of the crop (Berlato & Fontana, 1999; Sentelhas et al., 2015; Zanon et al., 2016).

Several studies have demonstrated the teleconnections between ENSO and anomalies in the seasonal rainfall patterns in subtropical southeastern South America (Grimm, 2004; Grimm and Tedeschi, 2009; Tedeschi et al., 2015), influencing the spring-summer harvest in RS, especially soybean crop. ENSO is a coupled ocean-atmosphere phenomenon characterized by sea surface temperature anomalies in the equatorial Pacific Ocean (Philander, 1983). Its warm phase called El Niño is associated to some positive precipitation anomalies observed in RS, while the ENSO cold phase is called La Niña, which triggers negative anomalies in the state (Grimm, 2000; Berlato & Fontana, 2003; Grimm, 2004; Gelcer et al., 2013; Tedeschi et al. 2015; Nóia Júnior et al. 2020).

Based on long-term data of 28 weather stations in RS, Matzenauer et al. (2017) offers a recent analysis about ENSO influence on weather of RS. The average annual rainfall for El Niño (EL) years as equal to 1,858mm (occurring in 26.8% of the years), and being 1,529 mm (49.2% of the years) and 1,480 mm (24% of the years) for Neutral and La Niña averages, respectively. Certainly ENSO's influence is geographically different within the state (Gelcer et al., 2013), depending directly on the ENSO intensity/type (Grimm, 2000; Grimm, 2004), and such spatial variability makes the overall impacts of ENSO on soybean yields still uncertain in such region (Berlato & Fontana, 1999; Matzenauer et al. 2018).

To better understand the relationship between climatic variability and agricultural productivity (Berlato and Fontana, 2003; Arsego et al. 2018) and provide some support, analyzes based on drought or seasonal water indexes (Gelcer et al., 2013; Cordeiro et al., 2018), crop modelling (Fraisie et al., 2008; Nóia Júnior and Sentelhas, 2019; Nóia Júnior et al., 2020) or boundary functions derived from field-year observation (van Ittersum et al. 2013) can help to provide assessments of water-limited yield potential (Yw) and also to inform about technology adoption effect (Grassini et al. 2014; Zanon et al. 2016).

To our knowledge, the relationship between weather variability to soybean yields in the region is not yet well defined. To fill the gap in the knowledge about the effect of ENSO and weather variability on soybean yield in RS State, and provide some forecast insights for decision-makers and growers, we analyzed a long-term weather database containing data from 11 weather stations together with the ENSO phases. Specific objectives were: (i) to split the effects of soil and weather on crop yields based on crop modeling simulations and actual yield data (ii) to assess the soybean potential yields and yield gaps for different rainfall levels and regions and (iii) to evaluate soybean crop yield loss due to water deficit in each region of RS.

Materials and methods

Study area and weather and soil conditions

For eleven sites from Rio Grande do Sul (Figure 1) data about yield and weather, also correlated with ENSO, were used to analyze soybean yield variability. The Brazilian official dataset of soybean yield is supplied since 1990 by the National Institute of Geography and Statistics (IBGE), and the weather data are provided by the National Institute of Meteorology (INMET) and the State Foundation for Agricultural Research (FEPAGRO) from 1991 to 2017. The climate in RS (Figure 1) is subtropical humid with well distributed annual rainfall between 1,220 mm to 1,350 mm.

Figure 1. Location of the State of Rio Grande do Sul - Brazil, and distribution of weather stations considered in the analyzes within the State.

Rainfall missing data were replaced by data from the closest weather station. Air temperature missing data was replaced from linear relationships between the values from nearby stations. Validation methods were applied to identify erroneous data from weather sensors measurements (Estévez et al. 2011). The analyses were based on three classes of consistency tests: range test, step test and internal consistency test (Table 1). The quality of the weather data was examined searching for outliers when compared to other years and to those observed in neighboring stations. By visual inspection, we did not find any outliers after the statistical tests showed in Table 1 were applied to the datasets. Therefore, based on climatic regions of the State of Rio Grande do Sul as defined (Maluf & Caiaffo 2001) and the homogeneous climate zones provided by van Wart et al. (2013), the weather network density used in the present study provided a properly coverage for the State of Rio Grande do Sul.

Table 1. Quality control procedures applied to Rio Grande do Sul weather stations network for daily data.

Validation procedures	Air temperature (°C)	Rainfall (mm)
	$-30 < T_{\max}; T_m; T_{\min} < 50$	$0 \leq P \leq P_{\text{HIGH}}$
Range test	(Shafer et al., 2000) $T_{\text{LOW}} < T_{\max}; T_m; T_{\min} < T_{\text{HIGH}}$ (AEMET, 2008)	
Step test	$T_m - T_{m(d-1)} < 25$ (WMO, 2008)	None
Internal consistency test	$T_{\max(d)} > T_{m(d)} > T_{\min(d)};$ $T_{\max(d)} > T_{m(d-1)};$ $T_{m(d)} \leq T_{\max(d-1)}$ (Reek et al., 1992; Feng et al., 2004)	None

T_m : daily mean temperature (°C); $T_{\max}$: daily maximum temperature (°C); $T_{\min}$: daily minimum temperature (°C); T_{LOW} : minimum temperature value measured in long-term observatory closer or to each station (°C) and T_{HIGH} : maximum temperature value measured in long-term observatory closer or to each station (°C) (Inmet, 2018); P : daily rainfall; P_{HIGH} : maximum daily rainfall value measured in long-term observatory closer or to each station (°C); (d) : day and $(d-1)$: day before day.

Tropical Pacific Ocean's surface-temperature anomalies from October-November-December (OND) to March-April-May (MAM) of each year were taken from NOAA (2018).

Typical soil of each site (Figure 1) was defined based on references, describing soil taxonomy, profile features, granulometry and soil density (Table 2 and Table 3). From sand, silt and clay contents data, soil density, and A and B layers of soil depth - limiting soybean root system

depth (Z) to 1.2m, maximum water availability (θ_{AW}) was calculated through a pedotransfer functions (Reichert et al. 2009) (Equations 1, 2 and 3):

$$\theta_{fc} = 0.037 + 0.38(\text{Clay} + \text{Silt}) \quad (1)$$

$$\theta_{pwp} = 0.236 + 0.045 \text{ Clay} - 0.21 \text{ Sand} \quad (2)$$

$$\theta_{AW} = (\theta_{fc} - \theta_{pwp}) Z SD \quad (3)$$

where θ_{fc} is the soil moisture at field capacity (kg kg^{-1}); θ_{pwp} is the soil moisture at permanent wilting point (kg kg^{-1}); Clay, Silt and Sand content (kg kg^{-1}); SD is the soil density (kg m^{-3}); and θ_{AW} is the maximum available water (mm).

From a cluster analysis performed by Melo et al. (2004) with the Ward method, using the Euclidean distance and data from 210 municipalities of soybean production in RS, the 11 sites (Figure 1) were divided into three classes according to soybean yield (Mg ha^{-1}), soybean production (tons) and percentage of soybean cultivated area data (ratio between soybean area and total area of the municipality) as: A – high yield, B – medium yield and C - low yield (Table 2). For each production region, soils are described in terms of texture and hydraulic parameters in Table 3.

Table 2. Sites, geographical coordinate of weather station, clusters, soil class, and information sources.

Site	Lat (°)	Long (°)	Height (m)	Cluster	Soil Taxonomy	Information sources
Ibirubá	-28.61	-53.11	433.0	A	Typic Sombrihumult / Oxisol	Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962); Pötter (1980)
Julio de Castilhos	-28.20	-53.65	440.0	A	Typic Haplohumult	Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962); Zalameña (2008)
Lagoa Vermelha	-28.41	-51.58	772.0	A	Rhodic Hapludox	Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962)
Passo Fundo	-28.25	-52.40	639.0	A	Rhodic Hapludox	Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962); Vieira and Klein (2007)
Cruz Alta	-28.63	-53.60	429.0	B	Rhodic Hapludox	Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962); Secco et al. (1997); Secco et al. (2004); Nunes and Cassol (2008); Genro Junior et al. (2009)
Iraí	-27.18	-53.23	262.0	B	Rhodic Lithic Hapludalf.	Cunha et al. (2010)
Santa Rosa	-27.85	-54.47	308.0	B	Rhodic Hapludox	Nicoloso et al. (2008)
Bagé	-31.33	-54.10	215.0	C	Endoaqualf	Macedo (1984); Giarola et al. (2002)
Encruzilhada do Sul	-30.53	-52.52	427.7	C	Oxic Paleudult	Giarola et al. (2002); Cunha et al. (2005)
Santa Maria	-29.67	-53.80	191.0	C	Typic Hapludalf	Giarola et al. (2002); Reinert et al. (2008)
São Luiz Gonzaga	-28.42	-54.96	245.0	C	Rhodic Hapludox	Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962)

Table 3. Site, fractions of clay, silt and sand, soil density (SD), maximum exploitable depth of soil (Z), water potential in field capacity (θ_{fc}), water potential in permanent wilting point (θ_{pwp}) and maximum water availability (θ_{AW}).

Site	Clay (kg kg ⁻¹)	Silt (kg kg ⁻¹)	Sand (kg kg ⁻¹)	SD (kg m ⁻³)	Z (m)	θ_{fc} (kg kg ⁻¹)	θ_{pwp} (kg kg ⁻¹)	θ_{AW} (mm)
Ibirubá	0.560	0.240	0.200	1,110	1.00	0.341	0.219	134.0
Júlio de Castilhos	0.330	0.200	0.470	1,480	0.80	0.238	0.152	102.0
Lagoa Vermelha	0.736	0.210	0.046	1,080	1.20	0.396	0.260	177.0
Passo Fundo	0.450	0.310	0.240	1,430	1.20	0.326	0.206	206.0
Cruz Alta	0.477	0.173	0.350	1,240	1.00	0.284	0.184	124.0
Iraí	0.200	0.420	0.372	1,500	0.40	0.273	0.167	63.0
Santa Rosa	0.641	0.312	0.047	1,430	1.00	0.399	0.255	206.0
Bagé	0.120	0.420	0.510	1,370	0.40	0.242	0.134	59.0
Encruzilhada do Sul	0.298	0.260	0.441	1,490	0.50	0.249	0.157	69.0
Santa Maria	0.140	0.300	0.560	1,400	0.55	0.204	0.125	61.0
São Luiz Gonzaga	0.580	0.370	0.050	1,430	0.80	0.398	0.252	167.0

Boundary function to soybean yield gap analyses

To identify the soybean yield gap, a boundary function (Equation 4) was fitted, relating crop yield and total rainfall through soybean crop (van Ittersum et al. 2013). Zanon et al. (2016) fitted a boundary function for RS from experimental yield and seasonal water supply in rainfed and irrigated soybean crops grown during four growing seasons in RS. This boundary function was adopted and considered as a yield attainable (Y_w) because the soybean yield limit matched the ten most productive cultivars at each harvest and place (2008/09 to 2016/17) reported by the national trial of soybean cultivars (ECR 2017).

$$Y_w = a + b [1 - \exp(-cx)] \quad (4)$$

where x is the seasonal water supply (rainfall, mm) and a , b and c are parameters of the equation model.

Regarding the 11 sites, a previous treatment of the soybean yield data had to be done. Given improvements in genetic and fertilizer applications over the 25 years, which on average caused a yearly increase of 52.9 kg ha⁻¹ in RS (CONAB, 2018), it was necessary to statistically detrend the time-series of crop yield to remove these factors, and isolate the role of weather. So, soybean yield was detrended using linear regression (Goldblum, 2009).

Soybean water balance

Furthermore, as a complementary analysis to define the role of water on soybean crop, relationships between soybean yield and water deficit were fitted, therefore integrating soil and plant features and weather data considering the El Niño, La Niña or Neutral weather condition.

Through this methodology, each unit of water deficit was assessed for different production clusters. To account for the water deficit, water balances (BH) were calculated using the concept of Thornthwaite & Mather (1955). The maximum available water (θ_{AW}) reflected the root system depth simulation (RSD), thus considering the maximum availability of water [θ_{AWr} (%)] for each soybean development sub period (Table 4).

Table 4. Soybean development sub periods (Fehr and Caviness 1977): mean time per sub period (Days) and relative water content in relation to the maximum (θ_{AWr}) for the soybean crop.

Soybean sub periods	Days ¹	θ_{AWr} (%) ¹
Establishment (S-V1)	15	30
Vegetative (V2-R1)	40	75
Flowering/Grain filling (R1-R5.5)	35	90
Maturation (R6-R8)	30	100

¹Battisti (2013)

For each site (Figure 1), three crop water balances were calculated on a daily scale considering the following sowing data: October 15, November 15 and December 15, recommended by MAPA (2018). To represent cultivars from the relative maturity group 5-6 recommended to soybean macro-region 1 (micro regions 101, 102 and 103), a cycle of 120 days was fixed (Alliprandini et al. 2009, MAPA, 2018).

Soybean evapotranspiration (ETc) was calculated by multiplying the reference evapotranspiration (ETo) (Hargreaves and Samani 1985, Eq 5) by the crop coefficient (Kc). The Kc followed the soybean development (Martorano 2007) (Eq.6):

$$ETo = 0.0023 \left(\frac{Q_0}{2.45} \right) (T_{max} - T_{min})^{-0.5} (T_{avg} + 17.8) \quad (5)$$

where $Q_0/2.45$ is the extraterrestrial solar radiation (mm day⁻¹); T_{max} is the maximum air temperature (°C); T_{min} is the minimum air temperature (°C); T_{avg} is the average air temperature.

$$Kc = -0.0001(DAE)^2 + 0.0168(DAE) + 0.4269 \quad (6)$$

where DAE means days after plant emergency.

Mean comparison statistical analyses were performed using the Tukey test at 5% of error probability.

Results and discussion

Air temperature data was not analyzed for associations with El Niño, La Niña or neutral events (Table 5, Figure 2). A simple and comparative analysis presents the thermal nuances among

the sites in order to identify its influence on soybean evapotranspiration and consequently on the water balance results and crop yield.

From October to January while soybean crops are predominantly in vegetative development stages, besides the thermal differences among sites basically due to the relief, the Rio Grande do Sul also presents a temporal distinction increase of air temperature from spring to summer among sites from low to high altitude (Table 5 and Figure 2). Cluster A sites (Ibirubá, Júlio de Castilhos, Lagoa Vermelha and Passo Fundo), the highest altitude and colder soybean crop areas in RS also show less thermal increase. So, these areas seems to be not thermally suitable for soybean, considering the optimum temperature range for soybean growth is between 20 and 30°C (Silva et al., 2015). However, there is an apparent inconsistency since these are the most soybean yieldness sites of RS.

This issue was evaluated by Melo et al. (2004) emphasizing that in sites of Cluster A the thermal condition could restrict the development of soybeans by reducing the growing season of the crop. According to them the air temperature seems to have a greater influence on crop cycle than on the final grain yield. Therefore, in these sites the sowing date must be well adjusted in order to take advantage of the weather, using early varieties adapted to the thermal conditions. This was presented by Melo et al. (2004) and Nóia Júnior et al. (2020) who also point out the risk for the occurrence of low temperature and late freeze events increase during the vegetative phase due to a possible anticipation of sowing to September.

In addition, about the ENSO effects on air temperature in Rio Grande do Sul, Puchalsky (2000), Berlato and Althaus (2010) and Cordeiro et al. (2016) describe that there is a greater influence of La Niña, when the lowest average minimum temperature values are recorded. This ENSO disturbance is quite important for higher altitude sites (Cluster A) due to the increased risks of late freeze for the soybean crop. El Niño, on the other hand, increasing cloudness and rainfall (Fontana and Berlato, 1997; Berlato and Fontana, 2003; Custódio et al., 2009) interfering with the long waves balance, reducing losses, therefore, raising the minimum temperature.

Table 5. Minimum (T_{LOW} , °C), maximum (T_{HIGH} , °C) and daily mean air temperatures (T_m , °C) values measured in long-term observatory of each site.

Site	Cluster	T_{LOW} (°C)	T_{HIGH} (°C)	T_m (°C)
Ibirubá	A	-4.0	40.6	18.7
Júlio de Castilhos	A	-5.8	38.4	18.5
Lagoa Vermelha	A	-5.3	34.2	17.3
Passo Fundo	A	-3.5	36.3	18.0
Cruz Alta	B	-3.0	37.5	18.8
Irai	B	-5.3	39.2	20.4
Santa Rosa	B	-4.6	40.1	20.8
Bagé	C	-3.9	39.9	17.7

Encruzilhada Do Sul	C	-4.0	40.6	17.3
Santa Maria	C	-2.9	40.2	19.4
São Luiz Gonzaga	C	-1.8	39.9	20.9

Data recording times: Santa Rosa (1922-1949); Julio de Catilhos (1915-1949), others sites (1981-2010).

Figure 2. Vertical thermal gradient ($^{\circ}\text{C } 100\text{m}^{-1}$) from October to May among all weather stations.

In the northern region of RS, where most of the soybean production area of the state is, such as Cluster A, there are predominantly clayey soils, with deep horizons A and B with at least 0.8m, resulting in maximum water availability ranging from 102 to 206mm (Table 3). In sites of Clusters B, the soils are clayey and deeper too, excepted Iraí (Table 3).

Sites of clusters A and B differ mainly by altitude and air temperature (Table 2). As previous set (Table 5, Figure 2) sites in A (higher altitude) have lower temperature than sites in B, an important issue regarding to soybean evapotranspiration, which is minimized, reducing occurrences of water deficiency and thus favoring production (Pilau et al., 2018).

Sites of cluster C are in less clayey and also shallower soils areas, with lower water holding capacity (Table 3). In addition, they represent the areas of low altitude and higher temperatures (T_{HIGH}) of Rio Grande do Sul (Figure 2). In these sites, as an sample of how ENSO can influence, based on monthly mean temperature along the soybean crop season, the literature shows that in the Central region of the State (Santa Maria, see Fig. 1) the pan class A evaporative rate (ECA) and air humidity (RH) are strongly dependent on ENSO (Streck et al., 2008). These authors found lower ECA values and higher RH values during El Niño years, and higher ECA values and lower RH values during La Niña years.

Although the results can contradict the thermal aspects described by Puchalsky (2000) about ENSO influence, these results are also connected to cloudiness and number of rainy days, both with

positive deviations in El Niño years in relation to normality, which usually results in yield gain under El Niño and yield losses under La Niña (Berlato and Fontana, 1999).

Also, Gelcer et al. (2013) through the Agricultural Reference Index for Drought (ARID) and Cordeiro et al (2018) using the relative evapotranspiration (actual/potential evapotranspiration rate) described the influence of ENSO for Rio Grande do Sul, showing El Niño events determining lower water stress, and the opposite for La Niña events. They also showed that in the Southern part of the state (represented by Bagé and Encruzilhada do Sul in Figure 1), there was a higher frequency of water stress events, mainly from November to January during La Niña. These results corroborates the lack of water availability in the Southern part of the state for rainfed spring-summer crops, which can be used to support crop management decisions based on forecasts of El Niño or La Niña.

In summary, our results together with the literature shows that ENSO phenomenon can also have influence on the thermal atmosphere condition, particularly influencing the water consumption of rainfed spring-summer crops in the State (Table 5; Figure 2). Still, considering that the average rainfall during the spring and summer in the State of Rio Grande do Sul is generally insufficient to meet the soybean water requirements (Ávila et al. 1996) the evapotranspiration rates reduction mainly observed in El Niño seasons (Gelcer et al., 2013; Cordeiro et al., 2018) can favor the crop.

Regarding rainfall in RS, influences of the ENSO phenomenon mainly coincide with the soybean season in the state (Table 6). The first time of interference of the warm phase, El Niño, is at the end of the year of the phenomenon, especially during OND with a peak at the end of autumn of the following year (+) (MAM). For La Niña years, there are two events coinciding with those of the warm phase (Matzenauer et al. 2017). The first one, from October to November (OND) coinciding with sowing and vegetative development of soybeans, which may affect sowing and delaying the establishment of the crop. The second one is related to the increase in the frequency and intensity of rainfall from April to June (MAM), which could favor or harm the yield and harvest progress according to sowing date and soybean cultivar cycle.

Regarding the 25 seasons considered in our study (Table 6), eight were classified as Neutral, nine as El Niño and eight as La Niña phases. For El Niño anomaly, two years/harvests stood out: 1997/1998 (1.9°C) and 2015/16 (2.1°C). The cumulative rainfall exceeded 1,000 mm in the crop cycle, which was not different ($p > 0.05$) among Clusters. Under influence of a weak El Niño, 1994/95 season was the only one to show statistical difference of cumulative rainfall among Clusters, while retaining similarity between Clusters A and B with higher accumulated rainfall, but not differing B from C.

For La Niña, only two cases were different ($p < 0.05$) between Clusters. In 2008/09 (weak La Niña), Cluster C had lower rainfall than Cluster A. In 2010/11 (moderate La Niña) again the sites of Cluster C stood out negatively, however differing from Cluster B instead of A (Table 6). No season had statistical difference of rainfall among Clusters A, B and C (Table 5) under Neutral conditions.

Results (Table 6) agree with Matzenauer et al. (2017) data, identifying higher rainfall volumes in the north and northwest RS, where Clusters A and B are set, especially in the spring months. Similarly, the center-southern of RS (Cluster C) under the influence of La Niña had lower rainfall for the same period of the year as well (Grimm et al. 1998; Grimm et al. 2000).

Recent data show that different types of ENSO influence the atmospheric fields differently. Southern Brazil has positive rainfall anomalies during East El Niño (EEN) what do not happen with Central El Niño (CEN) (Tedeschi et al. 2015). Besides, the ENSO-related changes in the frequency of extreme rainfall events are generally coherent with changes in total monthly rainfall quantities. However, significant changes in extremes are much more extensive than the corresponding changes in monthly rainfall because the highest sensitivity to ENSO seems to be in the extreme range of daily rainfall, specially affecting basins with predominance of agricultural areas (Chagas and Chaffe 2018).

About La Niña phase, Grimm et al. (2000) reinforces the previously reported, detaching the dryness weather prevailing in November over south Brazil, triggering water deficit in the sowing period of soybean, while in December and January the rainfall is near normal. The negative anomalies return in February (Grimm and Tedeschi 2008), this time matching with flowering/formation pod and soybean grains stages.

Table 6. Tropical Pacific Ocean surface temperature anomaly from October-November-December (OND) to March-April-May (MAM), average surface temperature anomaly (Tavg), weather condition and average rainfall during soybean crop for each Cluster (A, B and C).

Harvest	Sea Temperature Anomaly (°C)						Avg. sea temp. season anomaly (ΔT_{avg} ; °C)	Weather Condition	Rainfall (mm)		
	OND	NDJ	DJF	JFM	FMA	MAM			Cluster A	Cluster B	Cluster C
1991/92	1.2	1.6	1.7	1.6	1.5	1.3	1.5	El Niño	587.35a	663.78a	664.88a
1992/93	-0.3	0.1	0.1	0.3	0.5	0.7	0.2	Neutral	680.55a	589.69a	629.37a
1993/94	0.0	0.1	0.1	0.1	0.2	0.3	0.1	Neutral	658.92a	722.64a	752.25a
1994/95	1.0	1.1	1.0	0.7	0.5	0.3	0.8	El Niño	833.42a	713.99ab	583.37b
1995/96	-1.0	-1.0	-0.9	-0.8	-0.6	-0.4	-0.8	La Niña	650.73a	585.33a	644.99a
1996/97	-0.4	-0.5	-0.5	-0.4	-0.1	0.3	-0.3	Neutral	581.91a	581.46a	516.10a
1997/98	2.4	2.4	2.2	1.9	1.4	1.0	1.9	El Niño	1024.15a	1083.12a	1161.51a
1998/99	-1.5	-1.6	-1.5	-1.3	-1.1	-1.0	-1.3	La Niña	538.69a	454.99a	461.59a
1999/00	-1.5	-1.7	-1.7	-1.4	-1.1	-0.8	-1.4	La Niña	639.15a	521.01a	499.52a

2000/01	-0.7	-0.7	-0.7	-0.5	-0.4	-0.3	-0.6	La Niña	676.08a	674.58a	690.68a
2001/02	-0.3	-0.3	-0.1	0.0	0.1	0.2	-0.1	Neutral	572.11a	445.11a	557.77a
2002/03	1.3	1.1	0.9	0.6	0.4	0.0	0.7	El Niño	915.77a	988.99a	961.49a
2003/04	0.4	0.4	0.4	0.3	0.2	0.2	0.3	Neutral	713.33a	676.21a	617.63a
2004/05	0.7	0.7	0.6	0.6	0.4	0.4	0.6	El Niño	457.39a	448.32a	420.13a
2005/06	-0.6	-0.8	-0.8	0.7	-0.5	-0.3	-0.4	Neutral	557.98a	506.28a	426.94a
2006/07	0.9	0.9	0.7	0.3	0.0	-0.2	0.4	El Niño	724.41a	628.42a	702.76a
2007/08	-1.5	-1.6	-1.6	-1.4	-1.2	-0.9	-1.4	La Niña	638.68a	526.69a	453.82a
2008/09	-0.6	-0.7	-0.8	-0.7	-0.5	-0.2	-0.6	La Niña	566.51a	530.56ab	491.47b
2009/10	1.3	1.6	1.5	1.3	0.9	0.4	1.2	El Niño	1041.19a	809.80a	1093.33a
2010/11	-1.7	-1.6	-1.4	-1.1	-0.8	-0.6	-1.2	La Niña	618.77ab	790.94a	484.73b
2011/12	-1.1	-1.0	-0.8	-0.6	-0.5	-0.4	-0.7	La Niña	463.04a	366.10a	355.87a
2012/13	0.0	-0.4	-0.4	-0.3	-0.2	-0.2	-0.3	Neutral	786.15a	866.18a	667.39a
2013/14	-0.2	-0.3	-0.4	-0.4	-0.2	0.1	-0.2	Neutral	819.71a	654.17a	722.59a
2014/15	0.6	0.7	0.6	0.6	0.6	0.8	0.7	El Niño	959.22a	897.52a	834.05a
2015/16	2.5	2.6	2.5	2.2	1.7	1.0	2.1	El Niño	1011.58a	1194.84a	968.02a

Values in rows followed by the same letter do not differ significantly at 5% probability by Tukey test.

According to average rainfall data of each Cluster (Table 7), regarding to neutrality conditions or ENSO influence, rainfall in Cluster A was statistically different according to the ENSO phase. For La Niña, it was 8% lower than in Neutral conditions despite the statistical equality between data, and 31% lower than the average for El Niño.

Results for Cluster B presented the same statistical description as Cluster A (Table 7), with average rainfall along the soybean cycle very similar for each weather condition. For Cluster C statistical analyses used rainfall data for El Niño upper and distinct seasons from the other two weather conditions.

It is important to note that although the average rainfall is lower during La Nina (Table 7), there were several El Niño and neutral seasons in which rainfall was lower than those thresholds. Regarding cluster A 599,0mm (La Niña average, see Table 7), precipitation did not exceed this value in three neutral season (1996/97, 2001/02 and 2005/06) and two times under El Niño (1991/92 and 2004/05) phase (Table 6). In cluster B, two neutral seasons (2001/02 and 2005/06) and one El Niño season (2004/05) did not reach the 556.3 mm La Niña average (Table 7). In cluster C only one neutral (2005/06) and one El Niño (2004/05) season did not match the average of 510.3mm La Niña average (Table 7). This more pronounce influence of ENSO warm phase on sites as Santa Maria and Bagé, Cluster C, was also presented by Nóia Junior et al. (2020).

The spatial and temporal variability of precipitation in RS emphasize a differentiated atmospheric circulation dynamics in the north compared to the south. In the north of RS, in addition to the influence of frontal systems, this region is subject to the performance of tropical systems in summer, which are more intense. This intensification associated with orography (mainly in the northeast of the state) explains the greater rainfall in the north of the state (Britto et al., 2008).

These results (Tables 6 and 7) also corroborate with the spatial distribution of the effects of ENSO on weather conditions reported by Fontana & Berlato (1997) for RS. In the study the authors highlighting reductions of 80 to 120 mm of rainfall in most of the state under La Niña phase, pointing out the western portion of RS as the most affected by the phenomenon.

The results also showed that the largest rainfall accumulated in El Niño years are in the North and Northwest regions (Cruz Alta, Ibirubá, Lagoa Vermelha, Julio de Castilhos and Passo Fundo) the geographical position of Cluster A. Lower rainfall data exist in areas of the Northeastern and Upper Plateau, part of the Central Depression and the Campaign and to the extreme west in the Low Valley of Uruguay. Even smaller volumes cover an Eastern part of the state on the North Coast passing through the Central Depression region (Santa Maria – Cluster C), the Southeastern region (Encruzilhada do Sul – Cluster C), moving towards the Campaign region (Bagé – Cluster C) (Matzenauer et al. 2017).

From mean rainfall data of each cluster (Table 7) it is defined that under neutral condition total rainfall (within soybean production period) is higher in Cluster A than in B and C (statistically not defined), which under influence of El Niño have much more close values. Therefore, as already emphasized B and C sites seem to be more benefited by the phenomenon (Figure 3). Nória Junior et al (2020) mention that for Santa Maria and Bagé (cluster C) the number of dry periods (seven consecutive days with no rainfall) events was greatly affected by ENSO in most of the tested soybean sowing dates, increasing during La Niña events in both phenological phases and decreased during El Niño years.

Even so, water deficit is lower on Cluster A sites, basically due to soil (water retention) (Table 3) and air temperature (more crop suitable) (Figure 2). Under La Niña events, Clusters B and C sites again appear to be more vulnerable to changes, in those cases with negative signals because the total rainfall in the soybean production time remains below those from Cluster A (Table 7).

Our results agreed with Grimm et al. (2000) who point out Southern Brazil, specially Rio Grande do Sul, as the region with the strongest signal in the El Niño event in Southern South America (Table 6; Table 7). Based on average rainfall values it can be observed that Rio Grande do Sul has higher rainfall at El Niño events and less rainfall at La Niña phase (Table 7) for all clusters. Despite the differences it is essential to highlight the statistical equality between data of the neutrality condition and La Niña.

Although average data (Table 7) point to El Niño's benefits for local soybean production (Figure 4) since rainfall under neutrality indicated climatic risk (Ávila et al. 1996), the observed variability of rainfall (Table 6) indicate that ENSO's impacts on crop yields form a complex pattern, and that the impacts vary among different geographical locations, different crop sowing data and cycles, different ENSO phases, different seasons and different technology adopted

by crop-producing areas (Pscheidt & Grimm 2009; Iizumi et al. 2014; N6ia Junior & Sentelhas, 2019).

Table 7. Mean values of rainfall, water deficit and soybean yield according to ENSO phases and Clusters A, B and C.

ENSO Phase	Rainfall (mm)	Water deficit (mm)	Yield (Mg ha ⁻¹)
Cluster A			
Neutral	671.3ab	96.8a	2.83a
La Niña	599.0b	117.8a	2.72a
El Niño	839.4a	86.4a	3.03a
Cluster B			
Neutral	630.2ab	192.9ab	2.31 ^a
La Niña	556.3b	244.0a	2.19 ^a
El Niño	825.4a	171.2b	2.53 ^a
Cluster C			
Neutro	611.3b	241.5ab	1.87 ^a
La Niña	510.3b	289.4a	1.69 ^a
El Niño	821.1a	192.2b	1.91 ^a

Values in columns followed by the same letter do not differ significantly at 5% probability by Tukey test.

Average precipitation data reveal the difference between the hot and cold phases of ENSO (Table 7). However, the variability observed among years under the same weather condition characterizes the importance of the intensity of the phenomenon (Table 6). The relationship between cumulative rainfall and ΔT_{avg} for each Cluster shows distinct influence of the phenomenon on local weather due to its intensity (Figure 3). Linear coefficients indicate mean rainfall for Neutral weather of 702 mm for Cluster A, 676 mm for Cluster B and 648 mm for Cluster C, all below 800 mm required to maximize soybean yield based on the full attendance of water requirement (Figure 4).

The weather condition already unfavorable to soybeans in neutral years becomes even worse under the influence of La Niña (Figure 3). Angular coefficients of the linear adjusted graphic (Figure 3) distinguished them among Clusters. Cluster A sites confirm to be the least influenced by ENSO, due to higher stability of water availability for the soybean crop. On the other hand, Cluster C sites ($\pm 158 \text{ mm } ^\circ\text{C}^{-1}$) are the most disturbed, characterizing sites with higher climate risk of yield loss (MAPA 2018). In cluster sites A the interaction between soils with greater water storage capacity (Table 3) and colder air temperature (Figure 2) results in lower values of soybean water deficiency (Table 7). So, in most soybean crop years, even with total rainfall close to Clusters B and C sites especially at neutral condition (Table 7), Cluster A seems to be more suitable and least risk places for the production of soybeans in RS (Figure 3).

Besides soil type (due to maximum water availability - θ_{AW}) (Table 3), an important issue related to the increase/decrease rainfall relative to the ΔT_{avg} (Figure 3) is the water drainage capacity (not shown). This last issue is extremely important in Cluster C areas, such as Bagé, Encruzilhada do Sul and Santa Maria, in which soils show limited drainage with superficial water table. As these sites are highly influenced by the positive phase of ENOS (El Niño) (Figure 3), often with intense rainfall above normal (Table 5), these areas are more susceptible to damages not only due to water deficiency, but also caused by flooding (Zanon et al., 2015).

Figure 3. Relationship between mean cumulative rainfall (mm) and mean temperature deviation of the Central Equatorial Pacific Ocean Surface (°C) (OND to MAM seasons).

A boundary function relating soybean yield and rainfall (Figure 4) displays the limit of 800 mm for yield increments. So, taking this threshold, according to linear adjustments (Figure 3) in all sites, this condition is only achieved under the influence of El Niño. So, the 800 mm threshold is only achieved with a ΔT_{avg} of at least +0.85 °C in comparison to Clusters A and B and of +0.95 °C for Cluster C.

Similarly, Zanon et al. (2016) noted no increasing yield beyond 800-mm of rainfall, 6.0 Mg ha⁻¹ being the ceiling point of Ya. This was consolidated by experimental data of soybean field trials (Figure 4), where soybean yield ranged from 0.3 to 6.0 Mg ha⁻¹. For the western U.S. Corn Belt, Grassini et al. (2015) found no further yield increase beyond 650 mm, as this should be sufficient to satisfy crop water requirements for the highest yields at such climate conditions.

The boundary function suggested by Zanon et al. (2016) had a slope (attainable water productivity) of 9.1 kg grain mm⁻¹ ha⁻¹, higher than the 6.1 kg grain mm⁻¹ ha⁻¹ average of municipal soybean yield data (Figure 4). A practically equal difference was observed when analyzing the 9.9 kg mm⁻¹ ha⁻¹ determined by Grassini et al. (2015). Regarding the x-intercept of 183 mm also described by Zanon et al. (2016), the boundary layer fitted indicating higher water consumption as seasonal soil evaporation of 255 mm (about 40% higher). Compared to x-intercept = 73 mm for the western U.S. Corn Belt (Grassini et al. 2015), even Zanon et al. (2016) exposes a much higher average seasonal amount of soil evaporation for RS.

Therefore, according to seasonal water supply (800-mm threshold) and maximum attainable grain yield (~6.0 Mg ha⁻¹), in macro analysis - municipal scale, there would be a soybean yield gap of 1.88 Mg ha⁻¹ in RS, which exposes differences in management and technologies employed in the production of soybean.

Figure 4. Soybean yield plotted against seasonal rainfall, boundary layer for attainable yield (Yw) and soybean yield data from cultivars trials.

Based on the 800 mm found out as the threshold (Figure 4), it can be inferred that 80.8% of site-years cases were water limited (for Neutral 88% and La Niña 94%) (Table 6 and Figure 4). The results for El Niño influence (61%) (Table 6) highlights the point that, even in the face of a large-scale phenomenon, generally considered positive for soybean production because it brings punctual increases in rainfall, weather can often imposes restrictions for soybean crop (Table 6; Figure 4) as described by Cirino et al. (2015). Additionally, Calviño and Sadras (1999) already indicated that water availability was limiting on farm yield in 54% of the years in the Argentinean Pampas and also for RS soybean areas, suggesting the profitability of this cropping system can be substantially enhanced with practices and cultivars aimed at increasing available water and water-use efficiency.

As established by Purcell and Specht (2004) and Nóia Junior and Sentelhas (2019) the availability of water to the plant depends not only on the amount and temporal distribution of rainfall and its disturbances caused by phenomena such as ENSO (Figure 3), but indisputably on soil type - water storage capacity (Table 3), as well as crop growth stage and variation in available energy - solar radiation and temperature. All of these show natural variability even in small tracts of land. Considering these variables, water balance can make water deficiency available as an alternative index to be correlated with soybean grain yield (Figure 5).

Through individual analysis of each site, the combined effect of rainfall + soil on soybean yield can be seen in Figure 5, in which linear adjustments between soybean yield and water deficit can support water valuing from the angular coefficient (a) and project the attainable soybean yield (municipality) performed from the linear one (b). Although in Cluster A water deficit was lower than 200 mm (Figure 5), sites less influenced by ENSO phenomena (Figure 3) and with high soil water retention (Table 3) (Julio de Castilhos, Lagoa Vermelha, Passo Fundo and Ibirubá) presented the highest cost for water ($-15.2 \text{ kg mm}^{-1} \text{ ha}^{-1}$). These sites were included with those of higher yields and production in RS (Melo et al. 2004) and were in the preferential zone for soybean crop, when analyzed in relation to loss of yield potential due to water deficits (Cunha et al. 2001).

It is clearly the combination of weather predisposed by ENSO phenomenon (Figure 3), coupled with soils less suitable for soybean cultivation (Table 3), that make the sites less productive and therefore less costly in relation to water deficiency (Figure 5), leading Cluster B to an average loss of $-7.4 \text{ kg mm}^{-1} \text{ ha}^{-1}$ and Cluster C $-3.7 \text{ kg mm}^{-1} \text{ ha}^{-1}$.

From the identification of the harvests corresponding to Neutral, La Niña or El Niño weather conditions (Figure 5), it is El Niño that normally leads to significant yield gains, especially in extreme events by increasing rainfall (Figure 3) and thus reaching the limit to maximize yield (Figure 4). The reason for the positive yield response of the rainfed soybean is that, there is an increase in rainfall compared to Neutral, which is already limiting to meet the crop water needs, and La Nina years, in which there is an even worse condition for soybean in terms of water availability.

Results such as those obtained by us help to understand the relationship between interannual climate and soybean, although as sad to Letson and McCullough (2001) they were not able to attribute the relationship to ENSO or to say that it is economically important.

Figure 5. Relationship between soybean yield and water deficit (mm) for different ENSO phases (Neutral, El Niño and La Niña) for Clusters A, B and C.

Conclusions

In this paper we explore the role of weather, ENSO and soils on soybean yield in Southern Brazil. Eleven assessed sites grouped in three clusters (A, B and C) presented soil distinction, mainly due to water retention capacity, generally higher in Cluster A. Daily rainfall data from 1991 to 2017, relative to months from October to May, help us to understand the action of the ENSO phenomenon in Rio Grande do Sul. Comparing sites in neutral years, Clusters B and C have less rainfall (on average -49mm and -75mm respectively) than Cluster A. In addition, with similar rainfall among cluster under El Niño and distinct (negative deviations) under the opposite ENSO

phase, indicate sites of Clusters B and C as more severely disturbed by the ENSO phenomenon. Relationship between soybean yield and rainfall for each soybean production year (1991 to 2017) and sites pointed the 800-mm rainfall as needed to maximize soybean yield. Differences between soybean attainable (Yw) and average yields of sites quantitatively establish the productive gap of the soybean in RS, and highlighting the variability among producing regions in terms of investment, technology and cropping systems. An inverse relationship between soybean water deficiency and yield reinforces the lower quality of the soil for soybean production and the negative effects even more pronounced in years of Neutral and La Niña phenomenon and its rainfall well below what is required to assure high yield levels. We identified the Cluster A as benefited by the thermal regime positively affecting soybean growth, development and water use. Decision-making on public policies and investments on the soybean industry can be supported from our results, either to reduce temporal production variability in the region and risks inherent to local weather.

Declarations

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Availability of data and material: The weather data that support the findings of this study are openly available in INMET and NOAA websites. Soil data are available in the literature cited. All material is described in the manuscript. More information can be shared upon requested.

Code availability: not applicable

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Figures

Figure 1

Location of the State of Rio Grande do Sul - Brazil, and distribution of weather stations considered in the analyzes within the State.

Figure 2

Vertical thermal gradient (°C 100m-1) from October to May among all weather stations.

Figure 3

Relationship between mean cumulative rainfall (mm) and mean temperature deviation of the Central Equatorial Pacific Ocean Surface (°C) (OND to MAM seasons).

Figure 4

Soybean yield plotted against seasonal rainfall, boundary layer for attainable yield (Y_w) and soybean yield data from cultivars trials.

Figure 5

Relationship between soybean yield and water deficit (mm) for different ENSO phases (Neutral, El Niño and La Niña) for Clusters A, B and C.