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Impact of ENSO-related rainfall variability on soybean yield in the state of Rio Grande do Sul, Brazil

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ABSTRACT

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 climate effects, with special focus on rainfall during 25 soybean-growing seasons. Eleven sites were clustered according to soybean yield. 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 Ninã in 36% and 32%, respectively. No season presented difference of rainfall among Clusters under Neutral conditions. The limit of 800 mm rainfall for significant yield increments 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 a water cost from -3.7 to -15.2 kg mm^{-1} ha^{-1}.

Introduction

Brazil is the main soybean producer worldwide, producing 137.3 million tons from 38.9 million hectares in the 2020/21 season (Conab, 2021). The southernmost State of Brazil, Rio Grande do Sul (RS) ranks second among soybean-producer states, with 15.1% of Brazilian production (Conab, 2021). 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, the average on-farm soybean yields of the last ten crop seasons ranged from 1.55 to 3.43 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).

Despite a continuous increase in average on-farm soybean yield during last decades, soybean production is heavily controlled by within-season rainfall variability linked to El Niño South Oscillation (ENSO) presents itself as a limiting factor to obtain the potential yield of the crop. Studies have demonstrated a likelihood of rainfall increase above the climatological mean to be significantly higher during El Niño events. The opposite was observed during the cold ENSO phase (La Niña) events (Berlato & Fontana, 2003; Grimm, 2004; Britto et al., 2008; Grimm & Tedeschi, 2009; Gelcer et al., 2013; Tedeschi et al., 2015; Matzenauer et al., 2017).

The need for high efficiency in soybean production has sparked more attention to better understand and quantify ENSO-rainfall variability effects on agriculture in Rio Grande do Sul (Berlato & Fontana, 1999; Matzenauer et al., 2018; Arsego et al., 2018). Most of these results described the cause-effect relationship. More recent studies (Battisti & Sentelhas, 2017; Nóia Júnior et al., 2020), with higher detail on the production system, are helping to choose bests sowing times, cultivars and soil management practices.

Even though, the impact of ENSO on local climate and crop production is not completely understood. Based on the knowledge state, our research seeks consider the main aspects of regional agricultural production systems of RS. Considering soil and crop features we intend to provide better knowledge regional ENSO-related rainfall variability on soybean yield. More specifically, we intend to catch the ENSO phenomenon intensity impact on soybean production, some aspect fundamentally related to agricultural policies and food security.

So, the specific objectives of this study were to combine the effects of soil and climate on crop yields based on actual yield data and water deficit in each region of RS.

Materials and Methods

Sites, climate and soil conditions

For eleven sites from Rio Grande do Sul (Figure 1) data about yield and climate, 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 climate 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 is subtropical humid (Alvares et al., 2013)

We used time series datasets of daily rainfall and air temperature. These datasets were quality controlled, checked for homogeneity, and gap-filled to address missing data and possible outliers. The quality controlled analyses were based on three classes of consistency tests: range test (Shafer et al., 2000; AEMET, 2008), step test (WMO, 2008) and internal consistency test (Reek et al., 1992; Feng et al., 2004). We also applied three homogeneity tests, the Pettitt, Standard Normal Homogeneity Test (SNHT) and Buishand to explore homogeneity in rainfall time series. The tests were applied at 5% significance level. According to the results the monthly rainfall are homogeneous times series, as also previous described by Buriol et al. (2012) for partly dataset.

Rainfall missing data were replaced by data from the closest weather station from database of Agência Nacional de Águas, Brazil (ANA, 2020). Air temperature missing data was replaced from linear relationships between the values from nearby stations.

Based on climatic regions of the State of Rio Grande do Sul (Maluf & Caiaffo, 2001) and the homogeneous climate zones provided by van Wart et al. (2013), the weather network density used provided a properly coverage for the State of Rio Grande do Sul.

ENSO conditions were defined by sea surface temperature (SST) variations and their persistence along the equatorial Pacific Ocean. Dataset defines El Niño and La Niña events based on a threshold temperature anomaly of ±0.5°C on the Oceanic Niño Index (ONI) as the 3-month running mean of SST anomalies across the Niño 3.4 region. As the soybean crop season in RS occurs between October and May we considered SST anomalies from October-November-December (OND) to March-April-May (MAM) of each year (NOAA, 2018).

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

Figure 1. Distribution of sites considered in the analyzes within the Rio Grande do Sul.

Site	Lat (°)	Long (°)	Height (m)
Ibirubá	-28.61	-53.11	433.0
Julio de Castilhos	-28.20	-53.65	440.0
Lagoa Vermelha	-28.41	-51.58	772.0
Passo Fundo	-28.25	-52.40	639.0
Cruz Alta	-28.63	-53.60	429.0
Iraí	-27.18	-53.23	262.0
Santa Rosa	-27.85	-54.47	308.0
Bagé	-31.33	-54.10	215.0
Encruzilhada do Sul	-30.53	-52.52	427.7
Santa Maria	-29.67	-53.80	191.0
São Luiz Gonzaga	-28.42	-54.96	245.0

Table 1. Site, cluster, 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	Cluster	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[1,2]	A	0.560	0.240	0.200	1,110	1.00	0.341	0.219	134.0
Julio de Castilhos[1,3]	A	0.330	0.200	0.470	1,480	0.80	0.238	0.152	102.0
Lagoa Vermelha[1]	A	0.736	0.210	0.046	1,080	1.20	0.396	0.260	177.0
Passo Fundo[1,4]	A	0.450	0.310	0.240	1,430	1.20	0.326	0.206	206.0
Cruz Alta[1,5,6,7,8]	B	0.477	0.173	0.350	1,240	1.00	0.284	0.184	124.0
Iraí[9]	B	0.200	0.420	0.372	1,500	0.40	0.273	0.167	63.0
Santa Rosa[10]	B	0.641	0.312	0.047	1,430	1.00	0.399	0.255	206.0
Bagé[11,12]	C	0.120	0.420	0.510	1,370	0.40	0.242	0.134	59.0
Encruzilhada do Sul[12;13]	C	0.298	0.260	0.441	1,490	0.50	0.249	0.157	69.0
Santa Maria[12,14]	C	0.140	0.300	0.560	1,400	0.55	0.204	0.125	61.0
São Luiz Gonzaga[1]	C	0.580	0.370	0.050	1,430	0.80	0.398	0.252	167.0

Information sources: [1]Divisão de Pedologia e Fertilidade do Solo. Ministério da Agricultura (1962); [2]Pötter (1980); [3]Zalamena (2008); [4]Vieira & Klein (2007); [5]Secco et al. (1997); [6]Secco et al. (2004); [7]Nunes & Cassol (2008); [8]Genro Junior et al. (2009); [9]Cunha et al. (2010); [10]Nicoloso et al. (2008);[11]Macedo (1984); [12]Giarola et al. (2002); [13]Cunha et al. (2005); [14]Reinert et al. (2008)

soybean root system depth (Z) to 1.2m, maximum water availability (θ_{AW}) was calculated through a pedotransfer functions (Reichert et al., 2009).

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

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

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

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), 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) the classes were: **Cluster A** – high yield, **Cluster B** – medium yield and **Cluster C** - low yield.

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 climate data considering the El Niño, La Niña or Neutral 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 (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 (Battisti, 2013).

For each site (Figure 1), three crop water balances were simulated 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 & Samani, 1985, Eq 4) by the crop coefficient (Kc). The Kc followed the soybean development (Martorano, 2007) (Eq.5):

$$\text{ETo} = 0.0023\left(\frac{\text{Qo}}{2.45}\right)(\text{T}_{max} - \text{T}_{min})^{0.5}(T_{avg} + 17.8) \quad (4)$$

where Qo/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.

$$\text{Kc} = -0.0001(\text{DAE})^2 + 0.0168(\text{DAE}) + 0.4269 \quad (5)$$

where DAE means days after plant emergency.

Soybean yield and statistical analyses

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 climate. So, soybean yield was detrended using linear regression (Goldblum, 2009). The same rate was applied to all sites.

Rainfall, water deficit and soybean yield mean comparison statistical analyses were performed using the Tukey test at 5% of error probability.

Results and Discussion

Regarding rainfall in RS, about the 25 crop seasons considered (Table 2), eight were classified as Neutral, nine as El Niño and eight as La Ninã phases. For El Niño anomaly, two seasons stood out with strong events: 1997/1998 (1.9°C) and 2015/16 (2.1°C), when the cumulative rainfall exceeded 1,000 mm in the crop season, without different ($p > 0.05$) among Clusters. Under influence of a weak El Niño, 1994/95 season was the only one to have 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 2). No season presented difference of rainfall among Clusters A, B and C (Table 2) under Neutral conditions.

Rainfall was statistical different ($p<0.05$) when considered the ENSO phases. For La Niña, it was almost 11% lower than in Neutral conditions despite the statistical equality between data, and 28.6% lower than the average for El Niño (Table 3).

Table 2. Tropical Pacific Ocean surface temperature anomaly from October-November-December (OND) to March-April-May (MAM), average surface temperature anomaly (Tavg), climate condition and average rainfall during soybean crop for each Cluster (A, B and C).

Harvest	Sea Temperature Anomaly (°C)						Avg. sea temp. season anomaly	Weather Condition	Rainfall (mm)		
	OND	NDJ	DJF	JFM	FMA	MAM	(ΔTavg; °C)		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.

Results for Cluster B presented the same statistical description as Cluster A (Table 3), with average rainfall along the soybean season very similar for each climate condition. For Cluster C statistical analyses showed El Niño rainfall upper and distinct from the other two climate conditions (Table 3).

Regarding the average rainfall data, which show a negative influence of La Niña on rainfall (Table 3), rainfall was lower than those thresholds in several El Niño and Neutral seasons (Table 2). About Cluster A (599.0 mm La Niña average, see Table 3), precipitation did not exceed this value in three Neutral seasons (1996/97, 2001/02 and 2005/06) and two times under El Niño (1991/92 and 2004/05) phase (Table 2). In Cluster B, two neutral seasons (2001/02 and 2005/06) and one El Niño season (2004/05) (Table 2) did not reach the 556.3 mm La Niña average (Table 3). In Cluster C only one neutral (2005/06) and one El Niño (2004/05) season (Table 2) did not match the 510.3 mm La Niña average (Table 3). 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 rainfall variability in RS emphasizes a differentiated atmospheric circulation dynamics between the north and south portions of RS. 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).

With more suitable climate (Table 2; Table 3) associated with regional soils (Table 1) the influence of the ENSO phenomenon on the rainfall seasons in Clusters A is not revealed when analyzing the water balance and soybean yield (Table 3). These sites (Cluster A) have lower mean water deficit in relation to the sites of Clusters B and C (statistically not defined), and thus have higher soybean yield (Table 3).

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 3). Clusters B and C have greater soil water storage capacity variability (Table 1). This pedological characteristic linked to climatic induces to different water deficit results (Table 3). In these sites, soybean crop seasons under Neutral or La Niña phases have less favorable water availability to crop. However, this is again not revealed when analyzing the soybean average yield, which is equal ($p > 0.05$) among the ENSO phases. Regarding the average soybean yield data for all sites (Table 3) the same was verified by Matzenauer et al. (2018).

The relationship between season rainfall and ΔTavg for each Cluster shows distinct influence of the phenomenon on local climate due to its intensity (Figure 2). 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 data (Figure 2) below 800 mm (Zanon et al., 2016) required to maximize soybean yield based on the full attendance of water requirement.

The climate condition already unfavorable to soybeans in neutral years becomes even worse under the influence of La Niña (Figure 2). Angular coefficients of the linear adjusted graphic 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.

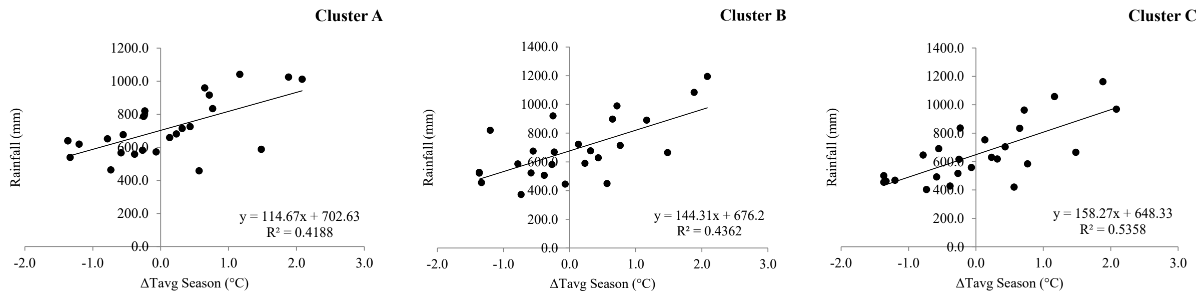
On the other hand, Cluster C sites (±158mm $°C^{-1}$) are the most disturbed, characterizing sites with higher climate risk of soybean yield loss (MAPA, 2018). In Cluster A sites,

Table 3. 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	2.31a
La Niña	556.3b	244.0a	2.19a
El Niño	825.4a	171.2b	2.53a
Cluster C			
Neutro	611.3b	241.5ab	1.87a
La Niña	510.3b	289.4a	1.69a
El Niño	821.1a	192.2b	1.91a

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

Figure 2. Relationship between mean cumulative rainfall (mm) and mean temperature deviation of the Central Equatorial Pacific Ocean Surface (°C) (OND to MAM seasons).



the interaction between soils with greater water storage capacity (Table 1) results in lower soybean water deficiency (Table 3). So, in most soybean crop seasons, even with total rainfall close to Clusters B and C sites especially at neutral condition (Table 3), Cluster A seems to be more suitable and least risk places for the production of soybeans in RS (Figure 2).

Besides soil type (due to maximum water availability - θ_{AW}) (Table 1), an important issue related to the increase/decrease rainfall relative to the ΔTavg (Figure 2) 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 ENSO (El Niño) (Figure 2), often with intense rainfall above normal (Table 2), these areas are more susceptible to damages not only due to water deficiency, but also caused by flooding (Zanon et al., 2015).

So, taking the 800 mm threshold (Zanon et al., 2016), according to linear adjustments (Figure 2) in all sites, this condition is only achieved under the influence of El Niño. So, the 800 mm threshold is only achieved with a ΔTavg of at least +0.85 °C in comparison to Clusters A and B and of +0.95 °C for Cluster C.

Zanon et al. (2016) found no further soybean yield increasing beyond 800-mm of rainfall in Rio Grande do Sul. It can be inferred that 80.8% of site-years cases were water limited (for Neutral 88% and La Niña 94%) (Table 2). The results of 61% about El Niño influence (Table 2) highlights that, even regarding a large-scale phenomenon, generally considered positive for soybean production, climate under ENSO warm phase can often imposes restrictions for soybean crop (Table 2), as also described by Cirino et al. (2015).

As only 28%, 24% and 20% of the soybean seasons in RS, respectively for Clusters A, B and C presented at least 800mm of rain (Table 2), the profitability of this cropping system should be enhanced through management and soybean genotypes. Techniques and inputs should focus on increase water use efficiency (Battisti & Sentelhas, 2017). A very similar condition was also described by Calviño & Sadras (1999) who already indicated that water availability was limiting on farm yield in 54% of the years in the Argentinean Pampas.

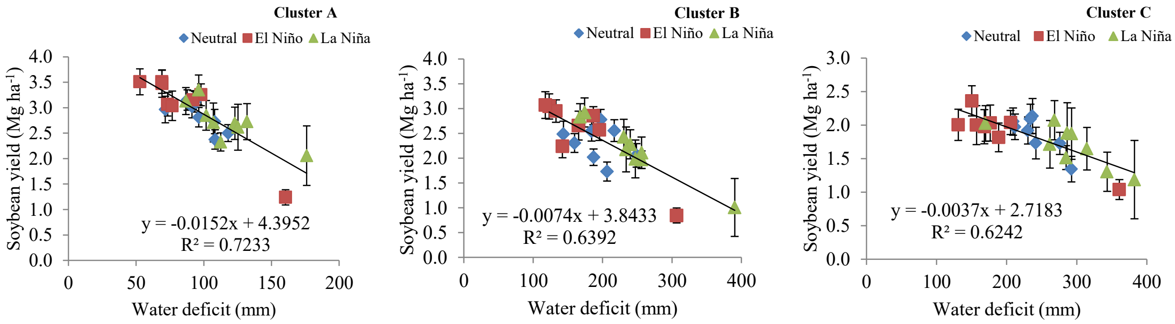
As established by Purcell & Specht (2004) and Nóia Junior & Sentelhas (2019) the water availability to plants depends on not only the amount and temporal distribution of rainfall and its disturbances caused by phenomena such as ENSO (Figure 2). Indisputably it is also depends on soil type - water storage capacity (Table 1), 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 3). Linear adjustments between soybean yield and water deficit can support water valuing from the angular coefficient and project the attainable soybean yield (municipality) performed from the linear one.

Although in Cluster A water deficit was lower than 200 mm (Figure 3), sites less influenced by ENSO phenomena (Figure 2) and with higher soil water retention (Table 1) (Julio de Castilhos, Lagoa Vermelha, Passo Fundo and Ibirubá) presented the highest cost for water (-15.2 kg mm^{-1} ha^{-1}). These sites were included as 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 clear the combination of climate predisposed by ENSO phenomenon (Figure 2), coupled with soils less suitable for soybean cultivation (Table 1), that make the sites less productive and therefore less costly in relation to water deficiency (Figure 3), leading Cluster B to an average loss of -7.4 kg mm^{-1} ha^{-1} and Cluster C -3.7 kg mm^{-1} ha^{-1}.

From the correlation between soybean yield and water deficit (Figure 3), identifying the climatic condition of

Figure 3. Relationship between soybean yield and water deficit (mm) for different ENSO phases (Neutral, El Niño and La Niña) for Clusters A, B and C.



each crop season (Neutral, La Niña or El Niño), it is El Niño that leads to a minimum water deficit and maximum yield gains, as observed in 2002/03 and 2014/15 (Table 3; Figure 3). These ENSO seasons (2002/03 and 2014/15) represented extreme events by increasing rainfall (Table 2) exceeding the 800mm required to maximize soybean yield.

Also, the results (Figure 3) presented similarity between the soybean yield and water deficit relationships for neutrality and La Niña conditions, and a crop failure in El Niño condition (2004/05) (Table 2). The 2004/05 crop season (Table 2), with a weak El Niño condition (ΔTavg = 0.6°C), leaded to the minimum soybean yield level of the entire data series analyzed. This El Niño season (2004/05) was classified as an El Niño Modoki (Tedeschi et al., 2013; Andreoli et al., 2016), condition that may not trigger precipitation increase in the La Plata Basin, including RS state.

Results such as those obtained by us help to understand the relationship between interannual climate and soybean, complementing with existing studies. Although the results corroborate the relationship between the ENSO phases and the accumulated rainfall in the soybean production season, there was no significant difference in the average yield of soybeans (1991/92 to 2015/16). Regarding it, we can compile that: (*i*) it is established, in relation to the average data, the increase (El Niño) and decrease (La Niña) of accumulated rainfall in the soybean production season in RS (Table 2), (*ii*) correlated with the intensity of the phenomenon (Figure 2), (*iii*) revealing the influence of ENSO also through the accumulated water deficit (Table 3). (*iv*) In fact, even in soybean crop seasons with 800mm of accumulated rainfall there are crop failures (Figure 3), since ENSO does not affect rainfall (increase/decrease) in a homogeneous way during all soybean crop season. (*v*) Therefore, it is emphasized that the maximum available water in the soil (Table 2) and agronomic managements related to better water availability are essential to the temporal stability of soybean production, in order to avoid the financial losses caused by the climatic condition (Figure 3).

Conclusions

In this paper we explore the role of weather, ENSO and soils on soybean yield in Southern Brazil. Comparing sites in neutral years, Clusters B and C have less rainfall (on average -49 mm and -75 mm 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. The relationship between soybean water deficiency and yield reinforces the lower quality of some soil sites and the negative effects even more pronounced in years of Neutral and La Niña phenomenon.

Author contributions

F.G. PILAU performed conceptualization, data collection and analysis, writing, and editing. D.A.V. GRUBERT, F.R. MARIN, G.A. DALMAGO and T.L. ROMANELLI performed data analysis, writing, and editing.

References

AEMET - Resumen de extremos climatológicos en España, 2008. Disponível em: <http://www.aemet.es/documentos/es/divulgacion/resumen_efemerides/Resumen_extremos.pdf. Acesso em: 02 mar. 2019

ALVARES, C. A.; STAPE, J. L.; SENTELHAS, P. C.; GONÇALVES, J. L. DE M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v. 22, n. 6, p. 711-728, 2013. DOI 10.1127/0941-2948/2013/0507

ALLIPRANDINI, L. F.; ABATTI, C.; BERTAGNOLLI, P. F.; CAVASSIM, J. E.; GABE, H. L.; KUREK, A.; MATSUMOTO, M. N.; OLIVEIRA, M. A. R. de; PITOL, C.; PRADO, C.; STECKLING, C. Understanding soybean maturity groups in Brazil: environment, cultivar classification, and stability. **Crop Science,** v. 49, p. 801-808, 2009. doi: 10.2135/cropsci2008.07.0390

ANA - Agência Nacional da Águas, 2020. Disponível em: https://www.ana.gov.br/gestao-da-agua/sistema-de-gerenciamento-de-recursos-hidricos/agencias-de-agua. Acesso em 02 March 2019

ANDREOLI, R. V.; OLIVEIRA, S. S.; KAYANO, M. T.; VIEGAS, J.; SOUZA, R. A. F.; CANDIDO, L. A. The influence of different El Niño types on the South American rainfall. **International Journal of Climatology** (published online) 2016. Doi: 10.1002/joc.4783.

ARSEGO, D. A.; FERRAZ, S. E. T.; STRECK, N. A.; **CARDOSO**, A. de O.; ZANON, A. J. Estudo do impacto de diferentes índices associados ao El Niño Oscilação Sul na produtividade de soja no Rio Grande do Sul. **Ciência e Natura**, v. 40, p. 82-87, 2018. DOI:10.5902/2179460X30684

BATTISTI, R. Épocas de semeadura da cultura da soja com base no risco climático e na rentabilidade líquida para as principais regiões produtoras do Brasil. 2013. 261 p. Dissertação (Mestrado em Ciências) – Escola Superior de Agricultura "Luiz de Queiroz" - Universidade de São Paulo, Piracicaba.

BATTISTI, R.; SENTELHAS, P. C.; PILAU, F. G.; WOLLMANN, C. A. Eficiência climática para as culturas da soja e do trigo no estado do Rio Grande do Sul em diferentes datas de semeadura. **Ciência Rural**, v. 43, p. 390-396, 2013. http://dx.doi.org/10.1590/S84782013000300003-0103

BATTISTI, R.; SENTELHAS, P. C. Improvement of soybean resilience to drought through deep root system in Brazil. **Agronomy Journal**, v. 109, n. 4, p. 1612-1622, 2017. https://doi.org/10.2134/agronj2017.01.0023

BERLATO, M. A.; FONTANA, D. C. Variabilidade interanual da precipitação pluvial e rendimento da soja no Estado do Rio Grande do Sul. **Revista Brasileira de Agrometeorologia**, v. 7, n. 1, p. 119-125, 1999.

BERLATO, M.A.; FONTANA, D.C. **El Niño e La Niña: Impactos no clima, na vegetação e na agricultura do Rio Grande do Sul: Aplicações de previsões climáticas na agricultura**. UFRGS (ed), 2003. 110p.

BRITTO, F. P.; BARLETTA, R.; MENDONÇA, M. Variabilidade espacial e temporal da precipitação pluvial no Rio Grande do Sul: Influência do fenômeno El Niño Oscilação Sul. **Revista Brasileira de Climatologia**, v. 3, p. 1-12, 2008.

BURIOL, G. A.; ESTAFANEL, V.; OLIVEIRA, J. S. DE; LANZER, L. M.; SOUZA, C. M. de. Homogeneidade dos totais mensais de precipitação pluvial no Estado do Rio Grande do Sul. **Pequisa Agropecuária Gaúcha**, v. 18, n. 2, p. 120-127, 2012.

CALVIÑO, P. A.; SADRAS, V. O. Interannual variation in soybean yield: Interaction among rainfall, soil depth and crop management. **Field Crops Research**, v. 63, p. 237-246, 1999. http://dx.doi.org/10.1016/S0378-4290(99)00040-4

CIRINO, P. H.; FÉRES, J. G.; BRAGA, M. J.; REIS, E. Assessing the Impacts of ENSO-related weather effects on the Brazilian Agriculture. **Procedia Economics and Finance**, v. 24, p. 146-155, 2015. https://doi.org/10.1016/S2212-5671(15)00635-8

CONAB - Companhia Nacional de Abastecimento. **Safra 2017/18 - Décimo segundo levantamento**, Brasília, 1-148, ISSN 2318-6852

CONAB - Companhia Nacional de Abastecimento. **Série Histórica das safras**. Disponível em: <conab.gov.br>. Acesso em 12 de dezembro de 2021.

CUNHA, G. R.; HAAS, J. C.; DALMAGO, G. A.; PASINATO, A. Perda de rendimento potencial em soja no Rio Grande do Sul por deficiência hídrica. **Revista Brasileira de Agrometeorologia**, v. 6, n. 1, p. 111-119, 1998.

CUNHA, G. R.; HAAS, J. C.; MALUF, J. R. T.; CARAMORI, P. H.; ASSAD, E. D.; BRAGA, H. J.; JULLO J.; LAZZAROTTO, C.; GONÇALVES, S.; WREGE, M.; BRUNETTA, D.; DOTTO, S. R.; PINTO, H. S.; BRUNINI, O.; THOMÉ, V. M. R.; ZAMPIERI, S. L.; PASINATO, A.; PIMENTEL, M. B. M.; PANDOLFO, C. Zoneamento agrícola e época de semeadura para trigo no Brasil. **Revista Brasileira de Agrometeorologia**, v. 9, p. 400-414, 2001.

CUNHA, N.G. DA; SILVEIRA, R.J. DA C.; KOESTER, E.; OLIVEIRA, L.D. DE; ALBA, J.M.F.; COSTA, F.A. DA; TERRES, V.C.; LOPES, R.T. **Estudos de Solos do Município de Iraí. RS.** Circular Técnica 104. Embrapa (ed) ISSN 1516-8832, 2010.

CUNHA, N.G. DA; SILVEIRA, R.J. DA C.; SEVERO, C.R.S.; PINTO, L.F.S.; MENDES, R.G.; SILVA, J.B. DA; DUARTE, L.R.; SCHUMACHER, R.L. **Estudo de Solos do Município de Encruzilhada do Sul – RS.** Circular Técnica 45. Embrapa (ed). ISSN 1516-8832, 2005.

DIVISÃO DE PEDOLOGIA E FERTILIDADE DO SOLO. MINISTÉRIO DA AGRICULTURA. Levantamento de reconhecimento dos solos do estado do Rio Grande do Sul. Primeira etapa. Planalto Rio-grandense. **Pesquisa Agropecuária Brasileira**, v.2, p.71-209, 1962.

FENG, S.; HU, Q.; QIAN, Q. Quality control of daily meteorological data in China, 1951–2000: a new dataset. **International Journal of Climatology**, v. 24, p. 853-870, 2004.

GELCER, E.; FRAISSE, C.; DZOTSI, K.; HU, Z.; MENDES, R.; ZOTARELLI, L. Effects of El Niño Southern Oscillation on the space–time variability of Agricultural Reference Index for Drought in midlatitudes. **Agricultural and Forest Meteorology**, v. 174-175, p. 110-128, 2013. http://dx.doi.org/10.1016/j.agrformet.2013.02.006

GENRO JUNIOR, A. S.; REINERT, D. J.; REICHERT, J. M.; ALBUQUERQUE, J. A. Atributos físicos de um Latossolo Vermelho e produtividade de culturas cultivadas em sucessão e rotação. **Ciência Rural**, v. 39, n. 1, p. 65-73, 2009. http://dx.doi.org/10.1590/S0103-84782009000100011

GIAROLA, N. F. B.; SILVA, A. P.; IMHOFF, S. Relações entre propriedades físicas e características de solos da região Sul do Brasil. **Revista Brasileira de Ciência do Solo**, v. 26, p. 885-893, 2002.

GOLDBLUM, D. Sensitivity of corn and soybean yield in Illinois to air temperature and precipitation: the potential impact of future climate change. **Physical Geography**, v. 30, n. 1, p. 27-42, 2009.

GRIMM, A. M. How do La Niña events disturb the summer monsoon system in Brazil? **Climate Dynamics**, v. 22, p. 123-138, 2004.

GRIMM, A. M.; TEDESCHI, R. G. ENSO and Extreme Rainfall Events in South America. **Journal of Climate**, v. 22, p. 1589-1609, 2009.

HARGREAVES, G. H.; SAMANI, Z. A. Reference crop evapotranspiration from temperature. **Applied Engineering in Agriculture**, v. 1, n. 2, p. 96-99, 1985.

MACEDO, W. **Levantamento de reconhecimento dos solos do Município de Bagé.** Documentos. 1. EMBRAPA-UEPAE (ed), 1984.

MALUF, J.R.T.; CAIAFFO, M.R.R. Regiões ecoclimáticas do Estado do Rio Grande do Sul. **Anais**: Congresso Brasileiro de Agrometeorologia, 12. / Reunião Latino-Americana de Agrometeorologia, 3. Fortaleza. Água e agrometeorologia no novo milênio 151-152, 2001.

MAPA - Ministério da Agricultura, Pecuária e Abastecimento. **Portarias de zoneamento agrícola de risco climático**. 2018. Disponível em: <http://www.agricultura.gov.br/assuntos/riscos-seguro/risco-agropecuario/portarias/safra-vigente/rio-grande-do-sul>. Acesso em: 15 ago.2018

MARTORANO, L.G. **Padrões de resposta da soja a condições hídrica do campo sistema solo-planta-atmosfera observados no campo e simulados no sistema de suporte à decisão DSSAT.** 2007. 151p. Tese (Doutorado em Agronomia), Universidade Federal do Rio Grande do Sul, Porto Alegre.

MATZENAUER, R.; RADIN, B.; CARGNELUTTI FILHO, A. Rendimento de grãos de soja e de milho, no Rio Grande do Sul, não difere entre eventos El Niño Oscilação Sul. **Agrometeoros**, v. 26, n. 1, p. 123-129, 2018. DOI: http://dx.doi.org/10.31062/agrom.v26i1.26376

MATZENAUER, R.; RADIN, B.; MALUF, J. R. T. O fenômeno ENSO e o regime de chuvas no Rio Grande do Sul. **Agrometeoros**, v. 25, n. 2, p. 323-331, 2017.

MELO, R. W. DE; FONTANA, D. C.; BERLATO, M. A. Indicadores de produção de soja no Rio Grande do Sul comparados ao zoneamento agrícola. **Pesquisa Agropecuária Brasileira**, v. 39, n. 12, p. 1167-1175, 2004.

NICOLOSO, R. da S.; AMADO, T. J. C.; SCHNEIDER, S.; LANZANOVA, M. E.; GIRARDELLO, V. C.; BRAGAGNOLO, J. E. Eficiência da escarificação mecânica e biológica na melhoria dos atributos físicos de um latossolo muito argiloso e no incremento do rendimento de soja. **Revista Brasileira de Ciência do Solo**, v. 32, p. 1723-1734, 2008. http://dx.doi.org/10.1590/S0100-06832008000400037

NOAA - National Weather Service. **Cold & warm episodes by season**. Disponível em: <origin.pcp.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php>. Acesso em: 26 abr. 2018

NÓIA JÚNIOR, R. de S.; SENTELHAS, P. C. Soybean-maize off-season double crop system in Brazil as affected by El Niño Southern Oscillation phases. **Agricultural Systems**, v. 173, p. 254-267, 2019. https://doi.org/10.1016/j.agsy.2019.03.012

NÓIA JÚNIOR, R. de S.; FRAISSE, C. W.; KARREI, M. A. S.; CERBARO, V. A.; PERONDI, D. Effects of the El Niño Southern Oscillation phenomenon and sowing dates on soybean yield and on the occurrence of extreme weather events in southern Brazil. **Agricultural and Forest Meteorology**, v. 290, p. 108038, 2020. https://doi.org/10.1016/j.agrformet.2020.108038

NUNES, M. C. M.; CASSOL, E. A. Estimativa da erodibilidade em entressulcos de latossolos do Rio Grande do Sul. **Revista Brasileira de Ciência do Solo**, v. 32, p. 2839-2845, 2008. http://dx.doi.org/10.1590/S0100-06832008000700030

PÖTTER, R.O.; HOCHMÜLLER, D.P. **Levantamento detalhado de área piloto para conservação de solos no município de Ibirubá. RS.** Rio de Janeiro. Boletim Técnico. 68. EMBRAPA/SNLCS (ed), 1980.

PURCELL, L.C.; SPECHT, J.E. Physiological traits for ameliorating drought stress. **In**: Boerma HR, Specht JE (eds), Soybeans: Improvement, production, and uses, 3rd ed. Agron. Monogr. 16. ASA, CSSA, and SSSA, Madison, WI. 2004. pp 569-620. http://dx.doi.org/10.2134/agronmonogr16.3ed.c12

REEK, T.; DOTY, S. R.; OWEN, T. W. A deterministic approach to the validation of historical daily temperature and precipitation data from the Cooperative Network. **Bulletin of the American Meteorological Society**, v. 73, p. 753-762, 1992.

REICHERT, J. M.; ALBUQUERQUE, J. A.; KAISER, D. R.; REINERT, D. J.; URACH, F. L.; CARLESSO, R. Estimation of water retention and availability in soil of Rio Grande do Sul. **Revista Brasileira de Ciência do Solo**, v. 33, p. 1547-1560, 2009. http://dx.doi.org/10.1590/S0100-06832009000600004

REINERT, D. J.; ALBUQUERQUE, J. **Á.**; REICHERT, J. M.; AITA, C.; ANDRADA, M. M. C. Limites críticos de densidade do solo para o crescimento de raízes de plantas de cobertura em Argissolo Vermelho. **Revista Brasileira de Ciência do Solo**, v. 32, p. 1805-1816, 2008. http://dx.doi.org/10.1590/S0100-06832008000500002

SECCO, D.; DA ROS, C.O.; FIORIN, J .E.; PAUTZ, C. V.; PASA, L. Efeito de sistemas de manejo nas propriedades físicas de um latossolo vermelho-escuro. **Ciência Rural**, v. 27, n. 1, p. 57-60, 1997. http://dx.doi.org/10.1590/S0103-84781997000100011

SECCO, D.; REINERT, D. J.; REICHERT, J. M.; DA ROS C. O. Produtividade de soja e propriedades físicas de um latossolo submetido a sistemas de manejo e compactação. **Revista Brasileira de Ciência do Solo**, v. 28, p. 797-804, 2004. http://dx.doi.org/10.1590/S0100-06832004000500001

SHAFER, M. A.; FIEBRICH, C. A.; ARNDT, D. S.; FREDRICKSON, S. E.; HUGHES, T. W. Quality assurance procedures in the Oklahoma Mesonetwork. **Journal of Atmospheric and Oceanic Technology**, v. 17, p. 474-494, 2000.

TEDESCHI, R. G.; CAVALCANTI, I. F. A.; GRIMM, A. M. Influences of two types of ENSO on South American precipitation. **International Journal of Climatology**, v. 33, p. 1382-1400, 2013. doi: 10.1002/joc.3519.

TEDESCHI, R. G.; GRIMM, A. M.; CAVALCANTI, I. F. A. Influence of Central and East ENSO on extreme events of precipitation in South America during austral spring and summer. **International Journal of Climatology**, v. 35, p. 2045-2064, 2015.

THORNTHWAITE, C.W.; MATHER, J.R. **The water balance**. Centerton, NJ: Drexel Institute of Technology - Laboratory of Climatology. Publications in Climatology, vol. VIII, n.1, 1955.

VAN WART, J.; VAN BUSSEL, L. G. J.; WOLF, J.; LICKER, R.; GRASSINI, P.; NELSON, A, BOOGAARD, H., GERBER, J.; MUELLER, N. D.; CLAESSENS, L.; VAN ITTERSUM, M. K.; CASSMAN, K.G. Use of agro-climatic zones to upscale simulated crop yield potential. **Field Crops Research,** v. 143, n. 1, p. 44-55, 2013. https://doi.org/10.1016/j.fcr.2012.11.023

VIEIRA, M.L.; KLEIN, V.A. Propriedades físico-hídricas de um latossolo vermelho submetido a diferentes sistemas de manejo. **Revista Brasileira de Ciência do Solo**, v. 31, p. 1271-1280, 2007. http://dx.doi.org/10.1590/S0100-06832007000600006

WORLD METEOROLOGICAL ORGANIZATION. **Guide to Meteorological Instruments and Methods of Observations**. WMO-No.8, Geneva, Switzerland, 2008.

ZALAMENA, J. **Impacto do uso da terra nos atributos químicos e físicos de solos do rebordo do Planalto – RS.** 2008. 79p. Dissertação (Mestrado em Agronomia). Universidade Federal de Santa Maria. Santa Maria.

ZANON, A. J.; STRECK, N. A.; GRASSINI, P. Climate and management factors influence soybean yield potential in a subtropical environment. **Agronomy Journal**, v. 108, n. 4, p. 1447-1454, 2016. http://dx.doi.org/10.2134/agronj2015.0535

ZANON, A.J.; WINCK, J.E.M.; STRECK, N.A.; RICHTER, G.L.; ROCHA, T.S.M.; CERA, J.C. Development of soybean cultivars as a function of maturation group and growth type in high lands and in lowlands. **Bragantia**, v.74, p.400-411, 2015. doi:10.1590/1678-4499.0043

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Impacto da variabilidade da chuva relacionada ao ENSO na produção da soja no estado do Rio Grande do Sul

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RESUMO

O Rio Grande do Sul (RS) apresenta acentuada variabilidade interanual da produção de soja, devido à disponibilidade hídrica. O estudo avaliou os efeitos climáticos, com foco especial nas chuvas durante 25 safras de soja. Onze locais foram agrupados de acordo com a produtividade da soja. O efeito do El Niño Oscilação Sul (ENSO) foi considerado em associação com o balanço hídrico do solo. Fases neutras de ENOS ocorreram em 32% dos anos, enquanto El Niño e La Ninã em 36% e 32%, respectivamente. Nenhuma estação apresentou diferença de precipitação entre os Clusters em condições neutras. O limite de 800 mm de chuva para incrementos significativos de produtividade só foi alcançado em épocas de El Niño. O efeito combinado da precipitação e do tipo de solo na produtividade da soja, representado pela relação produtividade real da soja-déficit hídrico, levou a um custo de água de -3,7 a -15,2 kg mm^{-1} ha^{-1}.

REFERENCIAÇÃO

PILAU, F. G.; MARIN, F. R.; GRUBERTO, D.A.V.; DLAMAGO, G.A.; ROMANELLI, T.L. Impact of ENSO-related rainfall variability on soybean yield in the state of Rio Grande do Sul, Brazil. **Agrometeoros**, Passo Fundo, v.30, e027115, 2022.