

# Physiological changes in soybean cultivated with soil remineralizer in the Cerrado under variable water regimes

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**Abstract** – The objective of this work was to evaluate the influence of the soil remineralizer fine-graded mica schist (FMS) on soybean (*Glycine max*) physiology, yield, and grain quality under different water regimes (WRs) in the Brazilian Cerrado. The experiment was conducted under field conditions for two years, using four WRs and three treatments: mica schist, conventional fertilization, and control. In 2017 and 2018, the following WRs were evaluated: WR1, WR2, WR3, and WR4, corresponding to a mean value of 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively. Photosynthesis, stomatal conductance, transpiration, internal CO<sub>2</sub> concentration, effective quantum yield of photosystem II (PSII) ( $F_v'/F_m'$ ), quantum yield (PSII) ( $\Phi_{FSII}$ ), and electron transport rate reduced as a function of the advanced phenological stage of soybean and the reduction in WR. Grain quality was only affected by the WR. The mica schist was statistically similar to conventional fertilization and the control in 2017 and 2018. Yield decreased due to the anticipation of soybean phenological age and WR, but there were no differences between the three treatments in 2017 and 2018. The reduction in soybean yield is attributed to stomatal closure, loss of photoprotective capacity, and damage to the photosynthetic machinery caused by drought.

**Index terms:** *Glycine max*, line source, mica schist, photosynthesis, water stress.

## Alterações fisiológicas de soja cultivada com remineralizador de solo no Cerrado sob regimes hídricos variáveis

**Resumo** – O objetivo deste trabalho foi avaliar a influência do remineralizador de solo finos de mica xisto (FMS) na fisiologia, na produtividade e na qualidade de grãos de soja (*Glycine max*) em diferentes regimes hídricos (RHs), no Cerrado brasileiro. O experimento foi conduzido em condições de campo durante dois anos, tendo-se utilizado quatro RHs e três tratamentos: mica xisto, adubação convencional e controle. Em 2017 e 2018, foram avaliados os seguintes RHs: RH1, RH2, RH3 e RH4, que correspondiam ao valor médio de 100, 65, 44 e 28% da reposição da evapotranspiração da cultura, respectivamente. A fotossíntese, a condutância estomática, a transpiração, a concentração interna de CO<sub>2</sub>, o rendimento quântico efetivo do fotossistema II (FSII) ( $F_v'/F_m'$ ), o rendimento quântico (FSII) ( $\Phi_{FSII}$ ) e a taxa de transporte de elétrons reduziram em função do avanço da fase fenológica da soja e da redução do RH. A qualidade dos grãos foi afetada apenas pelo RH. O mica xisto foi estatisticamente semelhante à adubação convencional e ao controle em 2017 e 2018. A produtividade reduziu devido à antecipação

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da idade fenológica da soja e do RH, mas não houve diferenças entre os três tratamentos em 2017 e 2018. A redução da produtividade da soja é atribuída ao fechamento estomático, à perda da capacidade fotoprotetora e aos danos ao maquinário fotossintético causados pela seca.

**Termos para indexação:** *Glycine max*, linha de aspersores, mica xisto, fotossíntese, estresse hídrico.

## Introduction

In 2020, Brazil produced more than 124 million tons of soybean [*Glycine max* (L.) Merr.] and became the world's largest producer of this grain (Acompanhamento..., 2020). However, the expansion of soybean production to the Midwest of the country has caused some challenges, including rainfall scarcity and concentration (Cattelan & Dall'Agnol, 2018). Although the crop is planted in the rainy season, dry spells may limit its productivity (Bornhofen et al., 2015).

Drought limits plant growth through reductions in cell expansion, but also severely interferes with carbon metabolism, particularly affecting photosynthesis (Baker, 2008). Under water deficit, plants suffer from severe photosynthetic limitation due to stomatal closure, which reduces the entry of CO<sub>2</sub>. Besides this reduction in carbon fixation, under drought excess, light energy that is not used by the Calvin cycle may induce the formation of reactive oxygen species that may, in turn, degrade important cell constituents such as membranes, proteins, and nucleic acids (Kar, 2011; Choudhury et al., 2017). Furthermore,

drought may also influence the total duration of the crop cycle, shortening its vegetative and reproductive stages, directly affecting productivity. Even modest reductions in water availability can cause major impacts, including a soil water potential of -0.8 MPa and reductions in soybean leaf area and dry matter of 60 and 65%, respectively, ultimately leading to decreased productivity (Board & Kahlon, 2011).

For these reasons, new agricultural practices for retaining soil water that could benefit plant metabolism under stress conditions are being sought and evaluated. Among these practices, the use of rock powder has been shown to increase plant growth, leaf area index, and yield in maize (*Zea mays* L.) (Malekian et al., 2012) and also to improve nutrient supply and the complexation of heavy metals (Zhang, 2017).

The water retention capacity of a soil is directly linked to its clay content, which is responsible for the expansion and contraction effect in soils under hydric stress (Novák & Hlaváčiková, 2019). Rock powder may decrease this stress by increasing resilience to drought in agricultural landscapes, specifically by improving soil moisture retention through high surface area minerals as zeolite and smectite, increasing the availability of drought protective elements to the plant through basalts, smectites, and zeolites added to soil water (Pratt et al., 2020). Therefore, in the presence of water, soils supplied with clay minerals from rocks may undergo changes in their physical properties, such as density, porosity, hydraulic conductivity, and water retention capacity (Winiwarter & Blum, 2008). These changes may lead to physiological alterations in plants, including gas exchange and chlorophyll *a* fluorescence (Baker, 2008; Marschner, 2012).

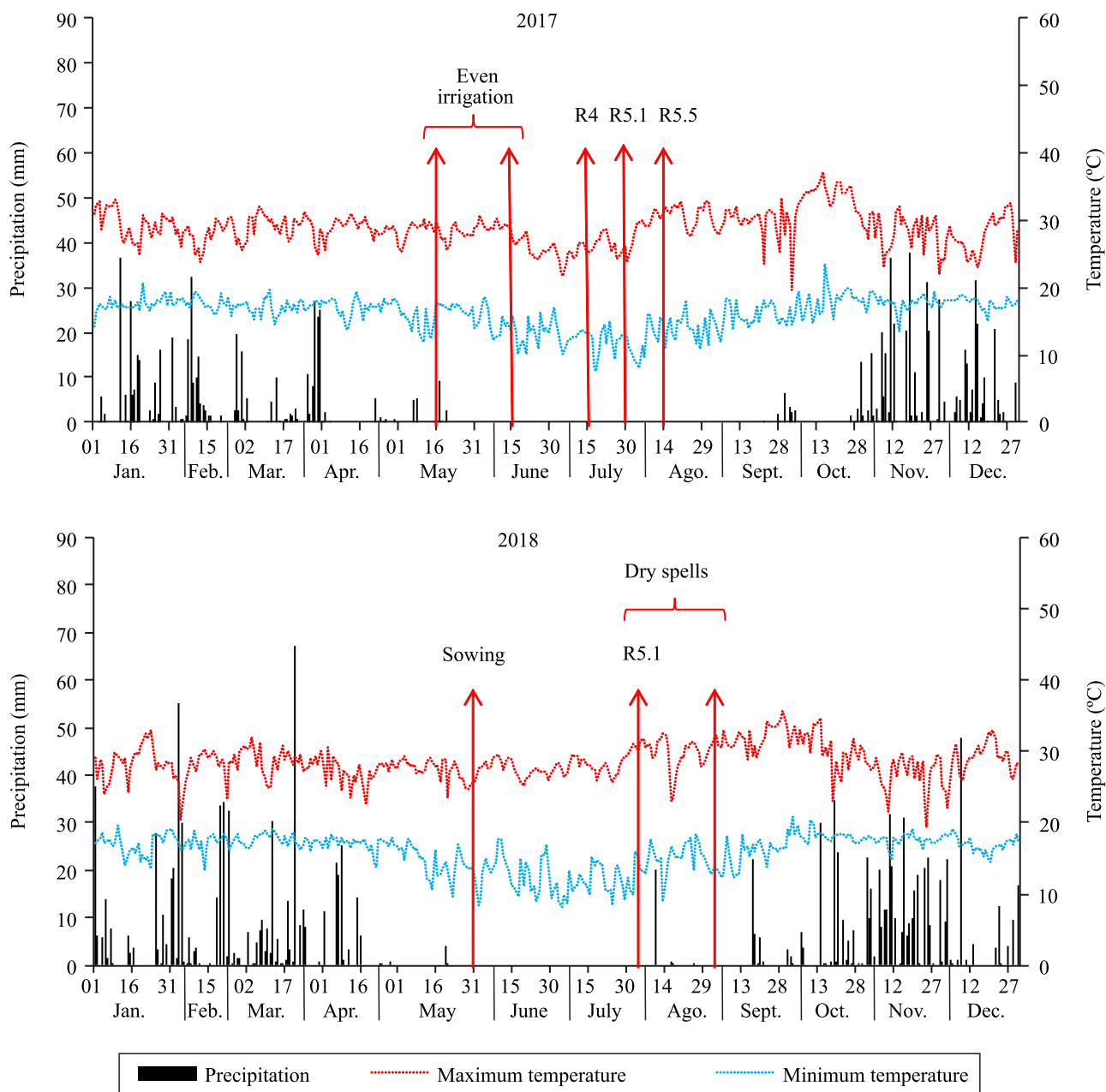
The addition of rock powder to Brazilian soils has been studied as a potential source of mineral phases and potassium using alkaline volcanic breccia, biotite shale, phlogopite, and ultramafic alkaline rocks (Theodoro et al., 2006; Martins et al., 2010; Ribeiro et al., 2010; Souza et al., 2016). However, only the impact on plant nutrition has been evaluated, indicating the need for further researches on conditioning effects due to the retention of water by clay minerals.

The objective of this work was to evaluate the influence of the soil remineralizer fine-graded mica schist (FMS) on soybean physiology, productivity, and grain quality under different water regimes (WRs) in the Brazilian Cerrado.

## Materials and Methods

Two experiments were carried out in a no-tillage system under field conditions at Embrapa Cerrados, in Planaltina, Distrito Federal, Brazil (15°35'30"S, 47°42'30"W), from July to November 2017 and from June to October 2018. The region has an average annual rainfall of 1,500±500 mm, and its prevailing climate is Aw, according to Köppen's classification, tropical, hot,

and humid (Alvares et al., 2013), with two well-defined seasons: dry from May to September and humid from October to April. The climatic conditions during the two years of soybean cultivation are shown in Figure 1. Soybean was planted in the winter because there is no rainfall during this period, allowing a better control of the applied water levels. The used cultivar was NA 5909 RG from the super-early maturity group.



**Figure 1.** Precipitation and minimum and maximum temperatures in the experimental area in 2017 and 2018. R4, R5.1, and R5.5 represent soybean (*Glycine max*) phenological stages.

According to the Brazilian Soil Classification System (Santos et al., 2018), the soil of the region is classified as a Latossolo Vermelho distrófico, i.e., a typical Oxisol (Burt, 2014). Soil analysis was performed in the 0–20 cm layer before the installation of the experiment in 2017 and in early 2019, in order to ensure that proper fertilization and water were the only limiting factors (Table 1). The experimental design was randomized complete blocks with four replicates in a split-plot arrangement, in which the main plot was composed of three treatments – fine-graded mica schist (FMS) as the soil remineralizer, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O fertilization, and control – and the subplots, of four water regimes (WRs). Each plot consisted of two central lines of 5 m, eliminating 1.0 m of the border.

The used FMS is a biotite schist from the Neoproterozoic Araxá group in the state of Goiás, Brazil (Pimentel, 2016). According to Souza et al. (2016, 2017), the geochemical and mineralogical characterization of the biotite rock are: 70% plagioclase, 17% biotite, 7% garnet, 4% micro lithium, and quartz and calcite as accessory minerals. The geochemical composition is: 50.9% SiO<sub>2</sub>, 13.0% Al<sub>2</sub>O<sub>3</sub>, 8.6% Fe<sub>2</sub>O<sub>3</sub>, 9.8% MgO, 7.9% CaO, 3.0% Na<sub>2</sub>O, 2.2% K<sub>2</sub>O, 0.1% P<sub>2</sub>O<sub>5</sub>, 0.2% MnO, 3.2% volatile compounds (CO<sub>2</sub> + SO<sub>3</sub> + H<sub>2</sub>O), 0.5% total carbon, and 0.1% sulfur.

In the first year, FMS was added to soil surface at a rate of 5 Mg ha<sup>-1</sup>, whereas, in the second, it was applied at 10 Mg ha<sup>-1</sup> in the same plots. For the N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O (02-28-14) treatment, the applied fertilization rates were 6 kg ha<sup>-1</sup> N, 80 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>, and 42 kg ha<sup>-1</sup> K<sub>2</sub>O. In the control, no fertilization was performed.

In the second year, the FMS and N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O treatments received maintenance fertilization with P (80 kg ha<sup>-1</sup> P<sub>2</sub>O<sub>5</sub>) as simple superphosphate (20% P<sub>2</sub>O<sub>5</sub>),

since the K contents were adequate. In both years, soybean seeds were inoculated with *Bradyrhizobium japonicum* (Kirchner 1896) Jordan 1982 (1x10<sup>9</sup> CFU g<sup>-1</sup> inoculant) at 200 g per 50 kg seeds. From November 2017 to May 2018, millet (*Pennisetum glaucum* R.Br.) was used as a cover crop, with residual soybean fertilization.

In 2017 and 2018, irrigation was carried out during the morning, homogeneously for 35 days after emergence (DAE), using sprinklers with the same flow rate to determine irrigation time. After this period, the line source methodology was adopted (Hanks et al., 1976), modified by introducing an irrigation line (Jayme-Oliveira et al., 2017) with sprinklers with a decreasing flow from the middle to edge of the line, in order to produce a water deficit gradient. The WRs were obtained through the 36/42 irrigation sprinkler line, 20 m wide on each side, connected to the self-propelled irrigation equipment, TurboMaq 75/GB (IrrigaBrasil, Pinhais, PR, Brazil), with adjustable speed according to the water depth to be applied.

The highest level of irrigation to be applied was determined according to the irrigation monitoring program of Embrapa Cerrados, based on the replacement of evapotranspiration (Embrapa, 2011), soil type, agrometeorological indicator of the region, and date of plant emergence, as well as time of irrigation and speed of the line, depending on water depth. Four irrigation levels were spread along the line, with different lengths from the initial portion of the system, representing the four WRs. During the uniform irrigation phase from July 27 to August 30, 2017, and from June 8 to July 13, 2018, approximately 160 mm water were supplied. The depths accumulated during the plant cycle from the central area to the edge of the

**Table 1.** Soil analysis after two years of implementation of the experiment at a depth of 0–20 cm in 2017 and 2019.

Depth	pH (H <sub>2</sub> O)	OM (g kg <sup>-1</sup> )	Ca	Mg	Al	H+Al	K	P	CEC <sub>total</sub>	CEC <sub>effective</sub>	SB	V (%)
			----- (cmol <sub>c</sub> dm <sup>-3</sup> ) -----				(mg L <sup>-1</sup> )		----- (cmol <sub>c</sub> dm <sup>-3</sup> ) -----			
2017												
0–20	5.74	22.46	2.317	1.146	0.069	5.461	0.232	9.868	9.225	3.834	3.765	40.8
2019												
WR1 <sup>(1)</sup>	6.3	49.00	5.73	2.36	0.0	3.9	1.55	44.86	13.58	9.64	9.64	66
WR2	6.3	47.20	5.83	2.40	0.0	3.8	1.51	43.70	13.58	9.74	9.74	68
WR3	6.3	42.66	5.16	2.20	0.0	3.8	1.49	41.00	12.65	8.85	8.85	71
WR4	6.4	44.56	5.16	2.33	0.0	3.8	2.07	31.36	13.36	9.56	9.56	70

<sup>(1)</sup>WR, water regime (WR1, WR2, WR3, and WR4 are equivalent to 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively). OM, organic matter; CEC, cation exchange capacity; SB, sum of bases; and V, base saturation.

line, corresponding to WR1, WR2, WR3, and WR4, respectively, were: 634.35 mm (4 m), 420.55 mm (10 m), 274.68 mm (13 m), and 160.01 mm (16 m) in 2017; and 531.43 mm (4 m), 343.15 mm (10 m), 237.45 mm (13 m), and 164.79 mm (16 m) in 2018; the numbers between parentheses represent the distance of each WR from the center to the edge of the irrigation line, and each WR was formed by overlapping sprinklers. Irrigation was performed according to the evapotranspiration of the crop, and WR1, WR2, WR3, and WR4 in 2017 and 2018 corresponded to a mean value of 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively.

In the experiment conducted in 2017, at 52, 62, and 76 DAE, leaf gas exchange and chlorophyll *a* fluorescence were evaluated in the R4, R5.1, and R5.5 phenological stages, respectively. In the experiment carried out in 2018, assessments were made from 63 DAE in the R5.1 phenological stage. Leaf gas exchange, fluorescence, and vegetation indexes were obtained. From 63 DAE onwards, the simulation of a 15-day dry spell started. In the sixteenth and seventeenth days, irrigation was performed to replace the water lost by evapotranspiration. Gas exchange analysis was carried out on the first, eighth, fifteenth, and seventeenth day after irrigation suppression (DAIS). The operating efficiency of photosystem II (PSII) ( $F_q'/F_m'$ ) was measured using the light-induced fluorescence transient (LIFT) methodology (Pieruschka et al., 2014) through the LIFT-REM fluorometer (Soliense Inc., Shoreham, NY, USA), and vegetation indices were assessed using a spectrometer included in the same equipment to measure fluorescence. These evaluations were carried out during the initial ten days of the dry spell experiment.

The net assimilation of CO<sub>2</sub> (*A*), stomatal conductance (*g<sub>s</sub>*), and transpiration rate (*E*) were evaluated from 9:00 a.m. to 1:00 p.m., under an irradiance of 1,200 μmol photons m<sup>-2</sup> s<sup>-1</sup> and external CO<sub>2</sub> concentration of 400 μmol mol<sup>-1</sup> air. In 2017, the LI-6400XT portable open-flow gas exchange system (LI-COR Inc., Lincoln, NE, USA) was used; in 2018, the same variables were evaluated, but using another portable open-flow gas exchange system, the LCproSD (ADC Bioscientific Ltd., Herts, United Kingdom).

In 2017, chlorophyll *a* fluorescence analyzes were performed using the fluorescence chamber coupled to the CO<sub>2</sub> assimilation chamber of the LI-6400XT

infrared gas analyzer. In each plot, to quantify gas exchange and chlorophyll *a* fluorescence, three evaluations were carried out on the central leaf of the fully-expanded trifolium of physiologically mature soybean light-adapted leaves.

The effective quantum efficiency of photosystem II (Genty et al., 1989) was calculated using the formula:  $F_v'/F_m' = (F_m' - F_0')/F_m'$ . The electron transport ratio (ETR) (Baker, 2008) was obtained by:  $ETR = \Phi PSII \times DFF \times (0.84) \times (0.5)$ , where DFF is the photon flow density or the amount of light absorbed (μm photons m<sup>-2</sup> s<sup>-1</sup>) (Baker, 2008).

The STS-VIS spectrometer (Ocean Optics, Inc., Largo, FL, USA), installed in the LIFT equipment with a spectral range of 400–800 nm, was used to determine the vegetation indices photochemical reflectance index (PRI) and normalized difference vegetation index (NDVI). These spectral indices were calculated as follows:  $NDVI = (R_{800} - R_{640})/(R_{800} + R_{640})$ , and  $PRI = (R_{531} - R_{570})/(R_{531} + R_{570})$ . Poor signal-to-noise ratio data were eliminated.

Yield was determined after correction of grain humidity to 13% (w/w). In 2017, grain quality (protein and oil contents) was analyzed, together with plant height, number of pods, number of internodes, stem diameter, and thousand-grain weight (TGW).

All data were subjected to Shapiro-Wilk's normality test. The analysis of variance was performed, and means were compared by Tukey's test, at 5% probability, using the SAS statistical software, version 9.1.2 (SAS Institute, Inc., Cary, NC, USA). The statistical model was adjusted with SAS PROC MIXED, using the method of restricted maximum likelihood.

## Results and Discussion

In 2017, there were no statistical differences for physiological evaluations and yield between the FMS, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and control treatments within each WR for each soybean phenological stage (Tables 2 and 3). In the first year of remineralizer application, it was anticipated that, due to the short time allowed for reaction and to the chemical attack by microorganisms and the rhizosphere, there would be no effect (Harley & Gilkes, 2000). Indeed, only the effects of WR and phenological stage were observed, as all the studied variables presented significant alterations, with greater effects as the WR was reduced and when the

crop progressed in its phenological stage, especially in R5.5 and under severe water stress (Table 3). Furthermore, during the first year of the experiment, significant reductions in  $A$ ,  $g_s$ , and  $E$  occurred in function of the WR and phenological stage. Therefore, in addition to limiting  $\text{CO}_2$  entry, stomatal closure led to a state of over excitation of the thylakoid membranes in the chloroplasts (Baker, 2008). Therefore, with an increased time of exposure to drought, the damage becomes more severe, as shown by the reductions in  $F_v'/F_m'$ ,  $\phi_{\text{FSII}}$ , and ETR, limiting the photosynthetic potential of soybean (Baker, 2008).

Drought accelerates the production of abscisic acid and ethylene, which are directly related to abortion, early senescence of leaves, and reduction of gas exchange, culminating in the early maturation of grains and reduced productivity (Kar, 2011), symptoms which were also detected in the present study. The influence of drought on the photosynthetic metabolism of soybean was very clear, since the early effect of the WR was already significant in the R4 stage in WR4 (Table 3). In the other stages, such as R5.1 and R5.4, the reductions in  $F_v'/F_m'$ ,  $\phi_{\text{FSII}}$ , and ETR were drastic. Under severe drought, the super excitation in the thylakoid membranes leads to damage to plant tissues, much of which is irreversible, which may explain the reduction in  $A$  (Table 3), as also observed by DaMatta et al. (2018). Such damage to plant metabolism is even more harmful during the reproductive stage (Board & Kahlon, 2011), as soybean depends on photoassimilate production for maximum productivity. Therefore, progressive drought also caused a progressive

reduction in gas exchange during the R4, R5.1, and R5.5 stages (Figure 2) due to photosynthetic machinery damage and plant metabolism effects. These results are in agreement with the reduction in productivity in the 2017 harvest, which shows the cause-and-effect relationship of the influence of drought on soybean physiological parameters, justifying reductions in crop yield (Table 2).

It was anticipated that the FMS treatment might alleviate the deleterious effects of drought on plant physiology during the second year of application considering the potential benefits of the rainy period during the summer. However, in 2018, there were no statistically significant differences between the FMS, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and control treatments for  $A$ ,  $g_s$ , and  $E$  (Table 4).

When comparing different WRs, the treatments that received most water (WR1 and WR2) were statistically similar, while the least irrigated (WR3 and WR4) had significantly lower values for the evaluated parameters, with WR4 presenting the lowest values for all days after irrigation suppression. On the eighth DAIS, the symptoms of the dry spells were identified in almost all WRs except in WR1, and, on the fifteenth DAIS, there were no statistical differences between the WRs. However, after irrigation on the seventeenth DAIS, WR1 and WR2 showed higher values for  $A$ ,  $g_s$ , and  $E$  (Table 4). Therefore, the assessed physiological variables decline rapidly according to the duration of the drought period when there was a simulation of dry spells, and, on the fifteenth DAIS, reductions of up to 60% were observed.

**Table 2.** Productivity of soybean (*Glycine max*) in the 2017 and 2018 cropping seasons under four water regimes and three fertilization treatments<sup>(1)</sup>.

Water regime (WR)	Productivity (kg ha <sup>-1</sup> ) – 2017 cropping season			Productivity (kg ha <sup>-1</sup> ) – 2018 cropping season		
	FMS	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	Control	FMS	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	Control
WR1	3,524Aa	3,835Aa	3,852Aa	4,208Aa	4,425Aa	4,514Aa
WR2	4,063Aa	4,136Aa	3,114Ab	3,539Ba	4,034Ba	3,723Ba
WR3	1,544Ba	1,610Ba	1,697Ba	2,741Ca	2,569Ca	2,639Ca
WR4	1,007Ba	1,421Ba	998Ba	1,990Da	1,930Da	1,985Da
CV1 (%)		17.8			10.7	
CV2 (%)		16.1			11.5	

<sup>(1)</sup>Means followed by equal letters, lowercase in the lines comparing treatments (FMS, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and control) and uppercase in the columns comparing WRs, do not differ by Tukey's test, at 5% probability. WR1, WR2, WR3, and WR4, equivalent to 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively. CV1, coefficient of variation related to treatments; and CV2, coefficient of variation related to WRs. FMS, fine-graded mica schist.

After irrigation on the sixteenth and seventeenth DAIS, there was only a significant response for WR1 and WR2, with a tendency to recover plant photosynthetic capacity, with a higher  $A$ ,  $g_s$ , and  $E$  (Table 4). However, in WR3 and WR4, there was no recovery of photosynthetic performance. It is possible that drought, during the reproductive stage, led to an accelerated leaf senescence and a reduced crop cycle, so that, even after re-irrigation, these WRs did

not recover (Menezes-Silva et al., 2017). Therefore, stress due to dry spells causes modifications in the metabolism of plants, leading to the shortening of their cycle. In this case, the use of FMS was unable to ameliorate this response (Baker, 2008). FMS, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and the control behaved similarly in terms of NDVI and PRI, measured using the spectrometer, and  $F_v'/F_m'$ , using the LIFT methodology, in 2018. The imposition of simulated dry spells caused a gradual

**Table 3.** Net photosynthesis ( $A$ ), stomatal conductance ( $g_s$ ), internal CO<sub>2</sub> concentration, and transpiration rate ( $E$ ), as well as effective quantum yield ( $\Phi$ FSII) of photosystem two ( $F_v'/F_m'$ ) and electron transport rate (ETR), in three phenological stages (R4, R5.1, and R5.5) of soybean (*Glycine max*) under four water regimes (WR1, WR2, WR3, and WR4) in three treatments (fine-graded mica schist, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and control), in the winter of 2017<sup>(1)</sup>.

Variable	WR1			WR2			WR3			WR4			CV1 / CV2 (%)
	FMS <sup>(2)</sup>	N-P-K <sup>(3)</sup>	Control	FMS	N-P-K	Control	FMS	N-P-K	Control	FMS	N-P-K	Control	
R4 phenological stage													
$A$	19.33Aa	20.60Aa	19.96Aa	20.26Aa	20.55Aa	20.22Aa	20.18Aa	21.56Aa	19.26Aa	13.81Ba	13.44Ba	14.73Ba	7.8/7.4
$g_s$	0.31Aa	0.32Aa	0.31Aa	0.31Aa	0.33Aa	0.29Aa	0.29Aa	0.31Aa	0.30Aa	0.15Ba	0.14Ba	0.16Ba	14.8/17.6
$C_i$	271Aa	267Aa	267Aa	259Aa	269Aa	258Aa	256Aa	252Aa	252Aa	218Ba	221Ba	223Ba	4.5/6
$E$	4.93Aa	5.56Aa	5.14Aa	5.07Aa	5.39Aa	4.92Aa	4.73Aa	5.15Aa	5.15Aa	3.32Ba	2.91Ba	3.44Ba	9.5/13
$F_v'/F_m'$	0.48Aa	0.49Aa	0.49Aa	0.47Aa	0.49Aa	0.51Aa	0.51Aa	0.51Aa	0.48Aa	0.48Aa	0.51Aa	0.50Aa	5.4/5.4
$\Phi$ FSII	0.24Aa	0.26Aa	0.26Aa	0.27Aa	0.25Aa	0.26	0.25Aa	0.25Aa	0.25Aa	0.21Ba	0.20Ba	0.21Ba	7.4/9.1
ETR	118Aa	134Aa	137Aa	140Aa	133Aa	135Aa	130Aa	131Aa	129Aa	111Ba	98Ba	108Ba	10.6/11.4
R5.1 phenological stage													
$A$	17.40Aa	18.40Aa	17.75Aa	18.16Aa	19.33Aa	17.75Aa	14.51Ba	14.01Ba	14.67Ba	6.77Ca	7.06Ca	8.06Ca	14.9/12.4
$g_s$	0.25Ab	0.33Aa	0.26Ab	0.27Aa	0.25Aa	0.25Aa	0.17Ba	0.17Ba	0.18Ba	0.09Ca	0.09Ca	0.11Ca	16.1/13.7
$C_i$	255Aa	280Aa	261Aa	263ABa	244ABa	255Aba	237Aba	235ABa	243Aba	258Ba	251Ba	249Ba	5.9/5.6
$E$	6.58Aa	7.42Aa	6.73Aa	6.94Aa	6.16Aa	6.76Aa	5.06Ba	5.17Ba	5.18Ba	2.99Ca	3.22Ca	3.86Ca	14.0/10.6
$F_v'/F_m'$	0.53Aa	0.54Aa	0.53Aa	0.54Ab	0.53Ab	0.55Aa	0.53Ab	0.54Ab	0.55Aa	0.43Ab	0.45Ab	0.51Aa	2.4/5.4
$\Phi$ FSII	0.30ABa	0.28Aba	0.31ABa	0.31Aa	0.31Aa	0.32Aa	0.28Ba	0.27Ba	0.27Ba	0.15Ca	0.16Ca	0.16Ca	5.6/9.9
ETR	154ABa	147Aba	161ABa	166Aa	162Aa	169Aa	146Ba	141Ba	143Ba	79Ca	81Ca	99Ca	6.3/11.5
R5.4 phenological stage													
$A$	17.5Aa	17.22Aa	16.56Aa	14.43Ba	14.42Ba	12.58Ba	9.16Ca	10.03Ca	9.67Ca	4.26Da	5.29Da	7.73Da	17.0/18.9
$g_s$	0.25Aa	0.27Aa	0.22Aa	0.18Ba	0.17Ba	0.15Ba	0.12Ca	0.12Ca	0.13Ca	0.09Ca	0.07Ca	0.11Ca	19.7/20.1
$C_i$	255Aab	263Aa	249b	240Aa	237Aab	228Ab	249Aa	235Ab	250Aa	299Aa	267Aab	259Ab	3.0/9.0
$E$	6.07Aa	7.59Aa	6.34Aa	5.34Ba	5.12Ba	4.78Ba	3.63BCa	4.18BCa	4.27BCa	2.97Ca	2.76Ca	3.74Ca	19.5/21.2
$F_v'/F_m'$	0.54Aa	0.54Aa	0.55Aa	0.52ABa	0.53ABa	0.49Aba	0.44Ba	0.47Ba	0.50Ba	0.31Ca	0.35Ca	0.45Ca	9.8/10.8
$\Phi$ FSII	0.28Aa	0.29Aa	0.32Aa	0.28Aa	0.27Aa	0.28Aa	0.18Ba	0.22Ba	0.20Ba	0.09Ca	0.13Ca	0.16Ca	20.9/18.6
ETR	147Aa	156Aa	167Aa	145Aa	142Aa	144Aa	94Ba	115Ba	106Ba	48.39Ca	69.86Ca	83.31Ca	21.7/18.6

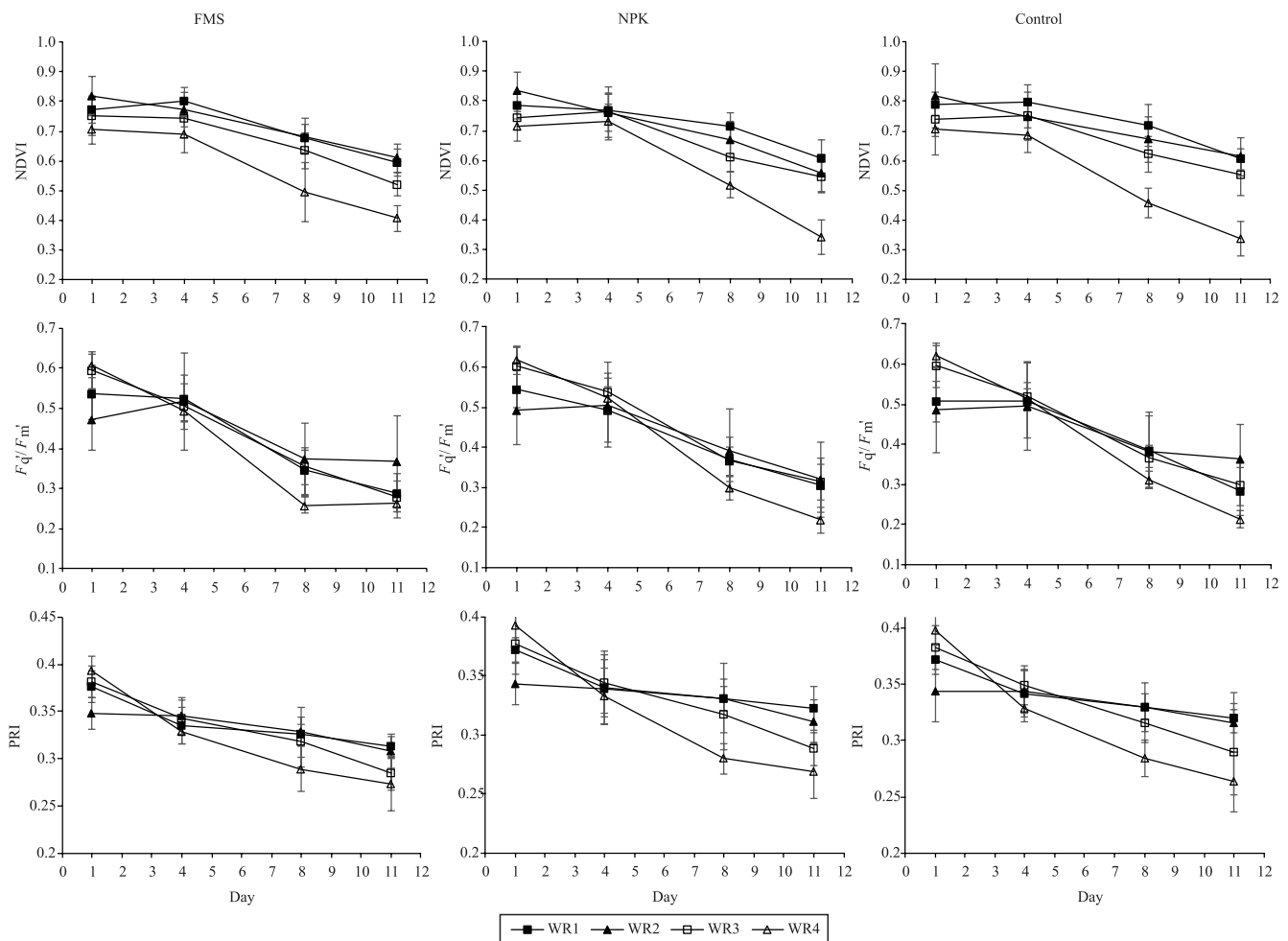
<sup>(1)</sup>Means followed by equal letters, lowercase in the lines comparing treatments within each WR and uppercase comparing each conditioner in the WRs within each phenological stage, do not differ by Tukey's test, at 5% probability. <sup>(2)</sup>Fine-graded mica schist. <sup>(3)</sup>N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O fertilization. WR1, WR2, WR3, and WR4, equivalent to 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively. CV1, coefficient of variation related to treatments; and CV2, coefficient of variation related to water regimes.

reduction in these variables; however, the greatest differences were observed only in WR4 on the last day of evaluation (Figure 2).

NDVI measurements showed that drought accelerated pigment degradation processes, such as those of chlorophylls, and reduced vegetation density, which was more intense under severe water deficit (Figure 2) as found by Babar et al. (2006). A reduction in  $F_q'/F_m'$  was observed during drought imposition for all WRs. These results are indicative that all WRs were affected by the dry spells, such that the functioning of the photosystem reaction centers was impaired and ultimately biomass accumulation was reduced, as shown by the

reductions in productivity (Cabrera-Bosquet et al., 2012; Pieruschka et al., 2014).

When the reaction centers of photosystem II remain open and linear electron transport is maintained,  $F_q'/F_m'$  remains high. Otherwise, the reflections of such damage directly affect  $F_q'/F_m'$ ,  $A$ , and, consequently, productivity (Figure 2 and Table 2). Regardless of whether the remineralizer was supplied, there was a strong reduction in absorption capacity and transformation of light energy into carbohydrates, since the reaction centers of photosystem II remained closed, resulting in metabolic damage, especially on the last day of evaluation for the FMS, N- $P_2O_5$ - $K_2O$ , and control treatments (Baker et al., 2008). Moreover,



**Figure 2.** Normalized difference vegetation index (NDVI), effective quantum yield of photosystem two ( $F_q'/F_m'$ ), and reflectance photochemical index (PRI) for the fine-graded mica shist (FMS), N- $P_2O_5$ - $K_2O$ , and control treatments evaluated during ten days of water deficit in the winter of 2018.



**Table 4.** Net photosynthesis (*A*), stomatal conductance (*g<sub>s</sub>*), and transpiration rate (*E*) in four evaluation periods and four water regimes (WRs) for three treatments – fine-graded mica shist (FMS), N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and control – in the winter of 2018<sup>(1)</sup>.

Variable	Treatment	1 DAIS				8 DAIS				15 DAIS				17 DAIS			
		WR1	WR2	WR3	WR4	WR1	WR2	WR3	WR4	WR1	WR2	WR3	WR4	WR1	WR2	WR3	WR4
<i>A</i>	FMS	18.41Aa	17.57Aa	10.89Ba	9.95Ca	16.83Aa	13.43Ba	14.12Ba	8.53Ca	7.49Aa	6.64Aa	7.67Aa	5.88Aa	10.06Aa	9.40Aa	6.01Ba	4.92Ba
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	18.07Aa	17.25Aa	14.24Ba	8.75Ca	17.65Aa	13.21Ba	15.28Ba	7.65Ca	9.05Aa	4.71Aa	6.38Aa	5.67Aa	11.01Aa	9.24Aa	8.17Ba	5.80Ba
	Control	17.68Aa	18.17Aa	15.05Ba	10.27Ca	16.66Aa	13.88Ba	13.43Ba	9.30Ca	6.59Aa	6.99Aa	7.30Aa	6.26Aa	9.92Aa	9.76Aa	6.19Ba	5.03Ba
CV1/CV2 (%)		15.7 / 16.7		19.3 / 15.0		31.5 / 27.6		17.5 / 18.5									
<i>g<sub>s</sub></i>	FMS	0.29Aa	0.26Aa	0.14Ba	0.12Ca	0.25Aa	0.2Ba	0.21Ba	0.09Ca	0.099Aa	0.08Ba	0.08Ba	0.07Ba	0.13Aa	0.13Aa	0.07Ba	0.07Ba
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	0.26Aa	0.24Aa	0.18Ba	0.11Ca	0.27Aa	0.19Ba	0.23Ba	0.09Ca	0.11Aa	0.064Ba	0.07Ba	0.07Ba	0.14Aa	0.13Aa	0.10Ba	0.08Ba
	Control	0.28Aa	0.29Aa	0.21Ba	0.13Ca	0.24Aa	0.20Ba	0.18Ba	0.11Ca	0.09Aa	0.08Ba	0.08Ba	0.08Ba	0.13Aa	0.13Aa	0.08Ba	0.08Ba
CV1/CV2 (%)		15.5 / 19.4		23.6 / 18.1		24.1 / 25.1		20.0 / 18.5									
<i>E</i>	FMS	5.15Aa	4.25Aa	3.62Aa	3.27Ba	3.43Aa	2.85Ba	3.00Ba	1.91Ca	4.26Aa	3.12Ba	3.18Ba	2.98Ba	3.34Aa	3.33Aa	2.41Ba	2.279Ba
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	4.76Aa	4.2Aa	4.49Aa	3.12Ba	3.66Aa	2.73Ba	3.23Ba	1.89Ca	4.57Aa	2.65Ba	2.88Ba	2.84Ba	3.38Aa	3.30Aa	3.03Ba	2.58Ba
	Control	4.76Aa	4.51Aa	4.82Aa	3.56Ba	3.37Aa	2.84Ba	2.83Ba	2.07Ca	3.89Aa	3.33Ba	3.08Ba	3.28Ba	3.18Aa	3.30Aa	2.57Ba	2.62Ba
CV1/CV2 (%)		10.2 / 12.6		14.1 / 15.8		18.7 / 19.7		14.8 / 15.2									

<sup>(1)</sup>Means followed by equal letters, lowercase in the lines comparing treatments within each WR and uppercase comparing each conditioner in the WRs within each evaluated period (day after irrigation suppression – DAIS), do not differ by Tukey's test, at 5% probability. WR1, WR2, WR3, and WR4, equivalent to 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively. CV1, coefficient of variation related to treatments; and CV2, coefficient of variation related to water regimes.

dry spells caused an increase in the ability of soybean to dissipate the excess excitation energy from the thylakoid membranes through the xanthophyll cycle, due to observed reductions in PRI (Figure 2), which may be closely related to the ability to maintain photosynthetic metabolism during drought (Gamon et al., 1997; El-Hendawy et al., 2015; Elsayed & Darwish, 2017).

Productivity was only affected in the control treatment in 2017 in WR2, which did not happen in 2018, since all treatments were statistically similar in this year (Table 2). In the second year, there was no statistical difference between FMS, N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and the control for any of the WRs studied. The production components only differed from WR (Table 5). It should be noted that the entire experimental area had been regularly fertilized overtime to eliminate the influence of nutritional factors so that the soybean plants were only affected by the manipulation of water levels. Therefore, due to the nutritional residue of previous harvests, high yields (Malekian et al., 2012; Li et al., 2014), including for the control treatment, were also observed (Table 2).

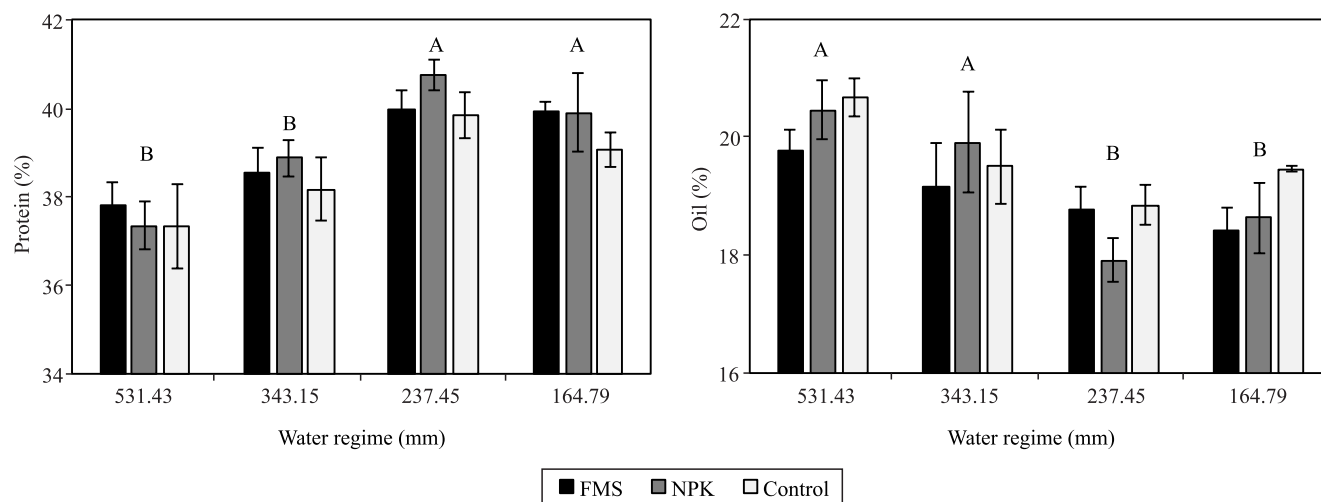
Protein and oil contents in the grains were not affected by the treatments and only responded to the applied WR (Figure 3). Protein content was higher in the less irrigated WRs, i.e., in WR3 and WR4, and oil percentage was lower. This is a commonly observed effect of drought as the greater amount of water in the irrigated treatments stimulates oil production and dilutes the protein content of grains (Ghassemi-Golezani & Lotfi, 2013). Therefore, there is an antagonistic relationship between protein and oil content regarding drought since this stress has negative effects on plant primary metabolism and, consequently, on lipid biosynthesis, which can lead to lower lipidic levels in drought situations (Figure 3).

Since the experiments were carried out over two harvests (2017 and 2018) and also without incorporation into the soil profile, the obtained results do not rule out a potential positive impact of the soil remineralizer throughout a longer period. Therefore, further long-term experiments with more years and remineralizer incorporation will be needed to test the hypothesis that this product retains water in the soil. Physical, chemical, and biological impacts may have occurred but have not yet been sufficient to impact productivity over the two experimental years.

**Table 5.** Height (H), pod number (PN), number of internodes (NI), diameter (D), thousand-grain weight (TGW), and productivity of soybean (*Glycine max*) subjected to water deficit under the control, fine-graded mica schist (FMS), and N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O treatments in 2017.

Variable	Treatment	WR1	WR2	WR3	WR4	CV1 / CV2 (%)
H	FMS	64.00Ab	70.87Ba	58.85Ba	51.17Cb	5.84 / 3.74
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	69.97Aa	69.52Aa	57.87Ba	57.11Ba	
	Control	66.30Aab	68Aa	59.52Ba	51.62Cb	
PN	FMS	40.55Aa	39.12Aa	27.15Ba	20.01Ba	23.61 / 21.02
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	36.20Aa	38.17Aa	27.45Ba	20.04Ba	
	Control	43.8Aa	37.97Aa	30.02Ba	18.75Ba	
NI	FMS	14.62Aa	15.00ABa	13.7Ba	11.98Ca	6.24 / 5.37
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	14.45Aa	14.8ABa	13.2Ba	12.20Ca	
	Control	14.70Aa	14.60ABa	13.85Ba	11.85Ca	
D	FMS	5.95Aa	6.58ABa	5.72Ba	5.53Ba	6.97 / 5.55
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	5.86Aa	6.30ABa	5.66Ba	5.68Ba	
	Control	6.06Aa	6.07ABa	5.92Ba	5.46Ba	
TGW	FMS	11.89Aa	11.36Ba	9.05Ca	8.13Da	3.62 / 5.57
	N-P <sub>2</sub> O <sub>5</sub> -K <sub>2</sub> O	12.37Aa	10.98Ba	8.60Ca	7.85Da	
	Control	12.02Aa	11.43Ba	9.12Ca	8.06Da	

<sup>1)</sup>Means followed by equal letters, lowercase in the lines comparing water regimes (WRs) and uppercase in the columns comparing treatments, do not differ by Tukey's test, at 5% probability. WR1, WR2, WR3, and WR4, equivalent to 100, 65, 44, and 28% of crop evapotranspiration replacement, respectively. CV1, coefficient of variation related to treatments; and CV2, coefficient of variation related to water regimes.



**Figure 3.** Protein and oil abundance for fine-graded mica schist (FMS), N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, and control treatments applied to soybean (*Glycine max*) subjected to water deficit. Means followed by equal letters do not differ statistically by Tukey's test, at 5% probability.

## Conclusions

1. The presence of soil remineralizer does not affect most physiological parameters of soybean (*Glycine max*) in the water levels evaluated in the experiments carried out in 2017 and 2018.

2. The effect of water levels on soybean plant physiology and grain quality is clear in the two experimental years, and drought reduces plant cycle independently of the N-P<sub>2</sub>O<sub>5</sub>-K<sub>2</sub>O, soil remineralizer, or control treatments.

3. The deleterious effects of the simulated dry spells on soybean metabolism were not alleviated by the soil remineralizer after two years of application.

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