Vol. 21(2), pp. 102-111, February, 2025
DOI: 10.5897/AJAR2024.16797
Article Number: 2C2CDBA72986
ISSN: 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Soil quality role for enhanced soybean resilience under hydric stress season

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Received 18 October, 2024; Accepted 9 January, 2025

This study investigates how soil organic matter and the physical and microbiological attributes affect soybean yield in two distinct crop environments (high and low productivity) in southern Brazil, during a crop season with the occurrence of a severe hydric restriction. Soil samples stratified by depth were collected to evaluate the chemical (organic matter), physical (root penetration resistance and growth), and microbiological (enzymatic activity) attributes. Soil organic matter was higher in the high productivity environment, both in shallow and deep soil profiles. The resistance to soil penetration was higher in the low productivity environment after 0.15 m, with values exceeding 2.5 MPa (critical value). For root growth (volume, surface area, and dry mass), these values were higher in the high productivity environment at depths of 0-0.10 and 0.20-0.30 m. The activity of beta-glucosidase and arylsulfatase enzymes was also higher in the high productivity environment. The average difference in soybean grain yield was 39% between the environments, at 2188 kg ha^{-1} (high yield) and 1563 kg ha^{-1} (low yield). In this sense, the findings reinforce that surface and deep organic matter stocks will be the best alternative to reduce soybean yield losses in years with severe water.

Key words: Water restriction, production environments, organic matter, compaction, root growth, enzymatic activity.

INTRODUCTION

The growing demand for food is a global challenge (Ray et al., 2013), with Brazil recognized as one of the countries that can play a crucial role in meeting this demand (Fieuzal et al., 2017). However, some business-as-usual agricultural systems should be redesigned to ensure grain production with less disruption to ecosystems (Gavioli et al., 2019) and that allow for climate change adaptation. The study of agricultural practices that improve soil quality in order to increase agricultural resilience is a critical issue in the global food security scenario (Rellán-Álvarez et al., 2016). In view of this concerning fact, in this study, we select, using digital/precision tools, crop systems in southern Brazil that had distinct temporal crop yield performance. Afterward, we select one season with hydric restriction to test the hypothesis that high-yielding crop systems based

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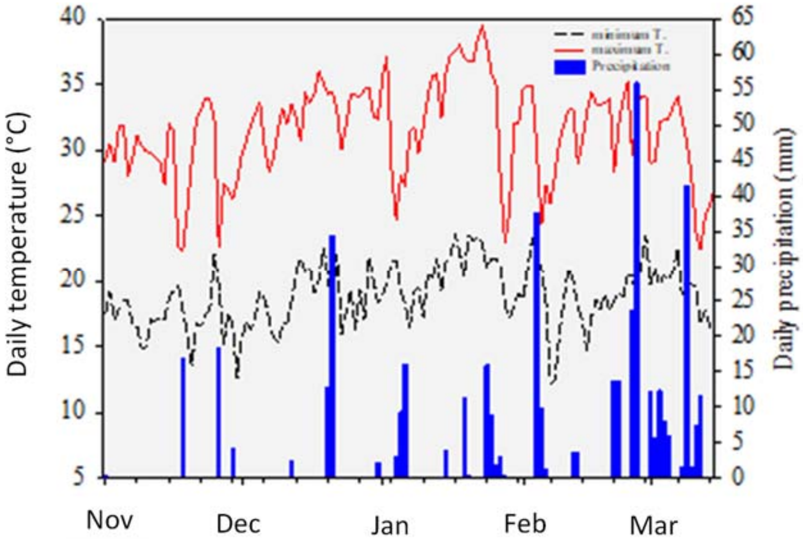

Figure 1. Distribution of rainfall, maximum and minimum daily temperatures, during the research. INMET, Frederico Westphalen - RS, agricultural crop year 2021/2022.
Source: INMET automatic weather station.

on soil quality improvement are able to mitigate, to some extent, the hydric stress. On the other hand, habitual cropping systems that impair soil quality are the systems most vulnerable to plant stress.

Soybeans are the world's leading protein source crop, and it is under threat from climate change, mainly drought and heat waves in several regions of the world (Foyer et al., 2016; Gupta et al., 2020). Soil conservation practices, such as the no-till system (NTS), cover crops, and crop rotation, when fully integrated, can alleviate hydric crop stress, such as leaf stomatal closure, which causes low photosynthetic rates and increased canopy temperature, compromising crop yield (Kelly et al., 2019).

It was observed that the simplification of production systems has caused serious problems in the chemical, physical, and microbiological soil attributes, which reduce plant soil water availability and, consequently, nutrient uptake, compromising crop yield, mainly in tropical regions where water restriction combined with high temperatures is frequent (Da Costa et al., 2018). In usual production systems with poor soil quality, soybean root growth is confined to shallow layers as a result of soil compaction, low organic matter, low oxygen flux, decreased microbiological activity, and increased resistance to soil penetration (Müller et al., 2021).

High crop yields have been observed with management practices that promote deeper soybean root systems, such as low soil resistance to penetration, increased calcium content, decreased aluminum content, and increased soil organic matter throughout the soil profile (CESB, 2016; Sako et al., 2016; Battisti and Sentelhas, 2017; Dantas, 2018; Pott et al., 2020; Bossolani et al., 2021, 2022; Passinato et al., 2021).

Studies using digital/precision tools, such as yield maps and NDVI images to identify distinct crop environments based on crop yield performance within the same agro-ecological region and season, are still scarce. Once investigated, these studies can serve as a basis to redesign crop systems in order to enhance soil water storage and deep root growth, both key strategies to improve crop resilience. This study investigates the role of soil organic matter and the physical and microbiological attributes in mitigating hydric stress and heat waves in southern Brazil.

MATERIALS AND METHODS

Study location

The research was carried out in the agricultural year 2021/2022, in the municipality of Frederico Westphalen, Rio Grande do Sul, Brazil (27º 23' 51" S and 53º 35' 19" W, 490 m altitude), with average annual precipitation of 1,881 mm, average temperature of 19.1°C, and a humid, subtropical climate "Cfa" according to the Köppen classification. Figure 1 shows the average daily maximum and minimum temperature and precipitation, with data from the National Institute of Meteorology (INMET) Meteorological Station at the Federal University of Santa Maria, Frederico Westphalen Campus. Note that in agricultural crop 2021/2022 there was a severe drought in the South of Brazil during different crop stages of the soybean cycle, with total rainfall of only 341 mm, and two weeks of high temperatures (heat waves) in January and February, reaching air temperature close to 40°C.

Plant and growth condition in bold

The soil is classified as Dystrophic Red Latosol (Oxisol), deep and well-drained (Santos et al., 2018), with a texture in the 0-0.10 m

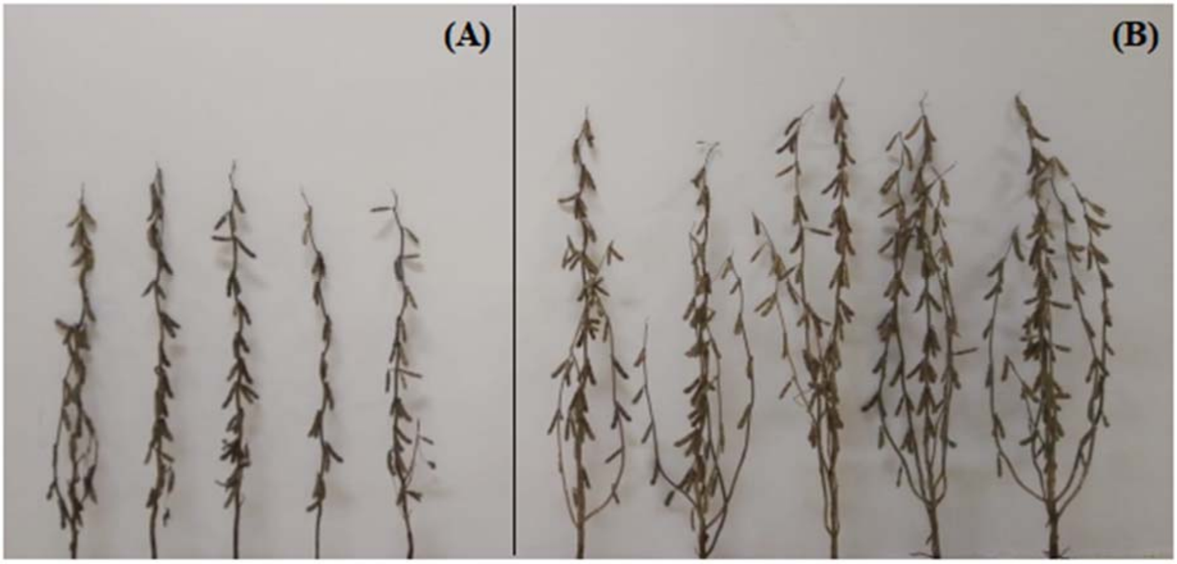

Figure 2. Plant pattern for two production environments: (A) a low productivity environment, and (B) a high productivity environment. Frederico Westphalen - RS, agricultural crop 2021/2022.
Source: Sangiovo (2022).

layer of 480 g kg^{-1} sand, 210 g kg^{-1} silt, and 310 g kg^{-1} clay. The study area was approximately 8 ha, conducted under a no-till system with crop rotation over the last five autumn-winter/summer harvests. In 2017/2018, the crops were wheat (*Triticum* species)/soybeans (*Glycine max* L.); in 2018/2019, radish oil (*Raphanus sativus* L.) + black oats (*Avena strigosa* S.)/soybeans; in 2019/2020, black oats + radish oil + common vetch (*Vicia sativa* L.)/soybeans; in 2020/2021, black oats + radish oil/corn (*Zea mays* L.); and in 2021/2022, pearl millet (*Pennisetum glaucum* L.)/wheat/soybeans.

The soybean cultivar was BMX Zeus IPRO, sown on 08/11/2021, with fertilization at the time of sowing of 150 kg ha^{-1} of triple super phosphate (46% P_2O_5) and 120 kg ha^{-1} of potassium chloride (60% K_2O) broadcast-applied. The final plant density was 277,777 plants ha^{-1}.

The two production environments studied were defined by the plant/plant sensor pattern (Figure 2) in two microregions of the same area during the R5 phenological stage (the beginning of grain swelling), defined as an environment of high and low productivity. In each environment, three random experimental plots/replicates were demarcated, each 20 m in length, with 10 rows spaced at 0.45 m, totaling an area of 90 m^2 for each replicate.

During the soybean phenological stage R5, soil sampling was carried out in each experimental replication for subsequent soil chemical, physical, and microbiological analysis.

Soil organic matter

To investigate the chemical attributes of the soil, soil samples were collected vertically in the soil profile stratified in the following layers (0-0.10, 0.10-0.20, 0.20-0.30, 0.30-0.40 and 0.40-0.50 m), totaling five samples per experimental replicate. The samples were sent to the Soil and Plant Tissue Laboratory of the Regional Integrated University Frederico Westphalen, Rio Grande do Sul, for determination of the soil organic matter (SOM) content, following the methodology described by Tedesco et al. (1995).

Physical attributes of the soil

Resistance to soil penetration (RP) was performed close to field capacity, using a digital penetrometer (PenetroLOG, Falker®, model PLG1020). The readings were taken in the soybean row line, every centimeter up to 0.40 m deep, through a load cell and insertion of the rod at a speed of 0.018 m s^{-1}. A type 2 cone (diameter 12.83 mm) was used at an angle of 30º (ASABE, 2006). Ten evaluations were carried out on each replica.

To evaluate the soybean roots, small trenches were open to collect samples in the following layers: 0-0.10, 0.10-0.20 and 0.20-0.30 m. The roots were collected in an area measuring 0.45 m in length × 0.08 m in width × 0.10 m in depth. These dimensions were determined according to the spacing between rows (0.45 m) and the plant density of 277.777 plants ha^{-1}, which represents the spacing between the plants of the 0.08 m in row, following the methodology proposed by Müller et al. (2021).

The trenches were positioned transversal to the row, so the sowing line was the center of the sample. The roots were soil cleaned by gently washing with running water, using a 0.2 mm mesh sieve avoiding loss of fine roots, and tweezers were used to collect all roots retained on the sieve. After that, the roots were analyzed with Sapphire Software (Embrapa), determining the volume of the root system (m^3.ha^{-1}) and surface area (cm^2). The roots were dried at a constant 65°C until the weight of the samples reached a stable weight, with the dry mass determination value expressed in kg ha^{-1}. The data were expressed per hectare, considering that the volume collected from the soil with roots was 0.0036 m^3.

Microbiological attributes of the soil

The activity of the beta-glucosidase (Carbon cycle) and Arylsulfatase (Sulfur cycle) enzymes was analyzed as biological indicators of soil health (Mendes et al., 2019; Tabatabai, 1994; Passinato et al., 2021). Four soil subsamples were collected in the 0-0.10 m layer, with one in the center of the soybean row, and

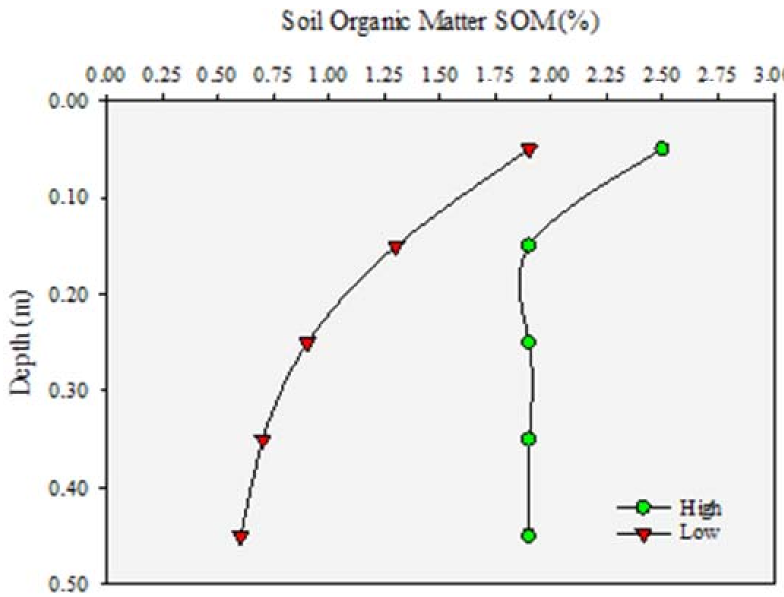

Figure 3. Distribution of soil organic matter in different layers (0-0.10; 0.10-0.20; 0.20-0.30; 0.30-0.0 and 0.40-0.50 m) of soil profile in two production environments.

three on each side of the line as a subsample that later were homogenized to get a composite sample (300 g) in each replica and for each environment. The laboratory analysis of the activity of the enzymes β-glucosidase and arylsulfatase followed the methodology of Tabatabai (1994).

Soybean grain yield

Soybean grain yield was determined by manual harvesting of the plants from an area of 13.5 m^2 in each replica. Afterwards, the samples were threshed, weighed, and the grain moisture adjusted to 13%.

Statistical analysis

Data on soil penetration resistance (PR), root growth and soybean grain yield were submitted to variance analysis (ANOVA), compared by the Tukey test ($p < 0.05$), performed with the statistical program Sisvar, version 5.3.

RESULTS

Soil organic matter (SOM)

The mean SOM content in the 0-0.20 m layer in both crop environments were classified as low (Figure 3). The SOM was 2.02% in the high productivity environment, and 1.08% in the low productivity environment. The highest values were observed in the shallow layer (0-0.10 m) for both environments, high productivity (2.5%) and low (1.9%). The SOM stratification in the profile was notable. In the low productivity environment, there was a significant reduction of 31, 52, 63 and 68% in the layers of 0.10-0.20, 0.20-0.30, 0.30-0.40 and 0.40-0.50 m, respectively, compared with 0-0.10 m layer. In the high productivity environment, the SOM stratification was attenuated where the 0.10-0.20 m to 0.40-0.50 m layers had average content of 1.9%.

Physical attributes of the soil

In general, no significant differences in RP between the two productivity environments were observed up to a depth of 0.15 m (Figure 4). However, at depths greater than 0.20 m, the environments showed significant differences, with the high productivity environment exhibiting lower RP values (ranging from 2.0 to 2.5 MPa). The RP in the low productivity environment was higher at these same depths, ranging from 3.0 to 4.2 MPa.

In the comparison of the two environments, the average RP in the layer between 0.20 and 0.40 m was 2.07 MPa for the high productivity environment and 3.34 MPa for the low productivity environment. This represents an increase of up to 61.4% in RP in the low yield environment compared to the high productivity environment, consequently restricting deep root growth, as seen in Figure 5.

The soybean root system volume (RSV) showed differences among the layers evaluated and between the production environments. The RSV was higher in the shallow layer (0-0.10 m), decreasing by 86% at a depth of 0.10-0.20 m and by 90% at 0.20-0.30 m, regardless of the production environment (Figure 6A). The RSV was

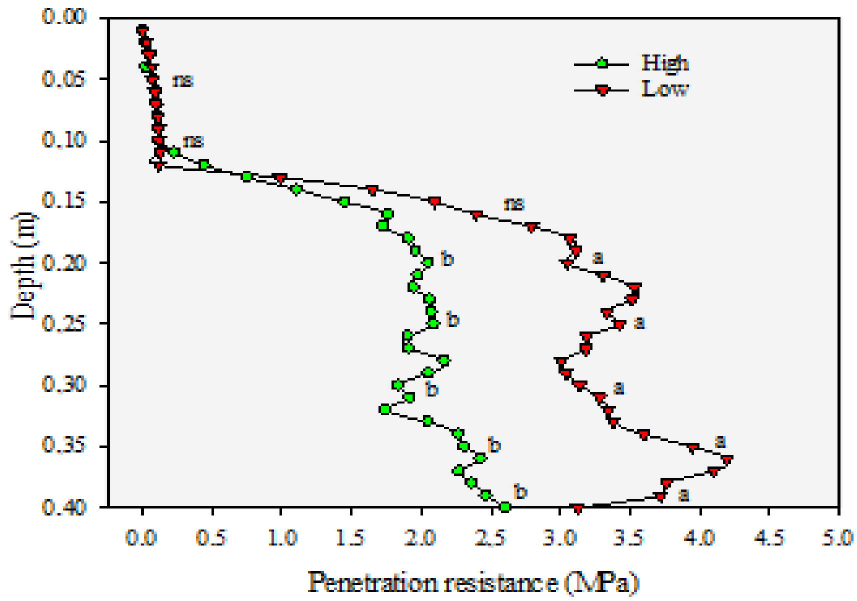

Figure 4. Soil penetration resistance in two production environments. Different letters at the same depth indicate a significant difference according to the Tukey test ($p < 0.05$). nsNot significant.

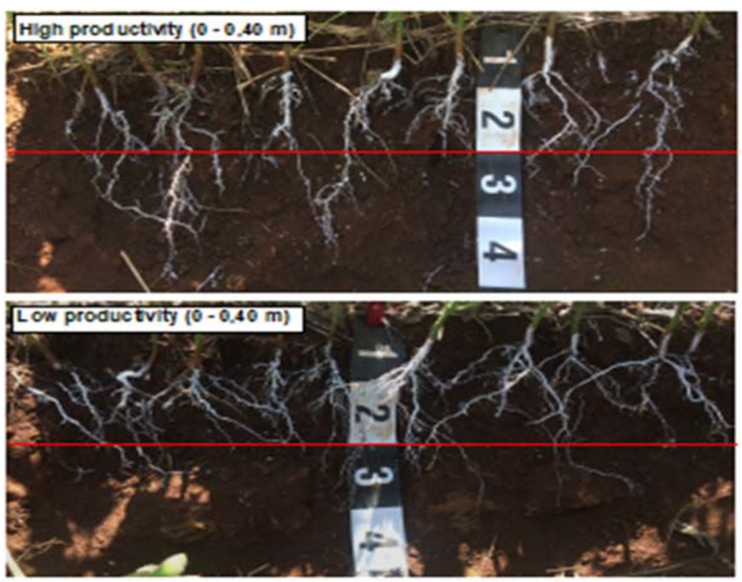

Figure 5. Soybean root development for two production environments. Frederico Westphalen - RS, agricultural harvest 2021/2022.
Source: Sangiovo (2022).

8.24% higher at the 0-0.10 m depth and 32% higher at the 0.20-0.30 m depth in the high productivity environment compared with the low productivity environment.

The root system surface area (RSSA) was higher in the high productivity environment in the 0-0.10 m and 0.20-0.30 m layers, with increases of 9.83% and 55.6%, respectively, compared with the low productivity environment (Figure 6B). Regarding the isolated effect of the layers, a reduction in RSSA was observed by 68% at 0.10-0.20 m and by 73% at 0.20-0.30 m, compared with the 0-0.10 m layer.

The soybean dry root mass (DRM) was also affected

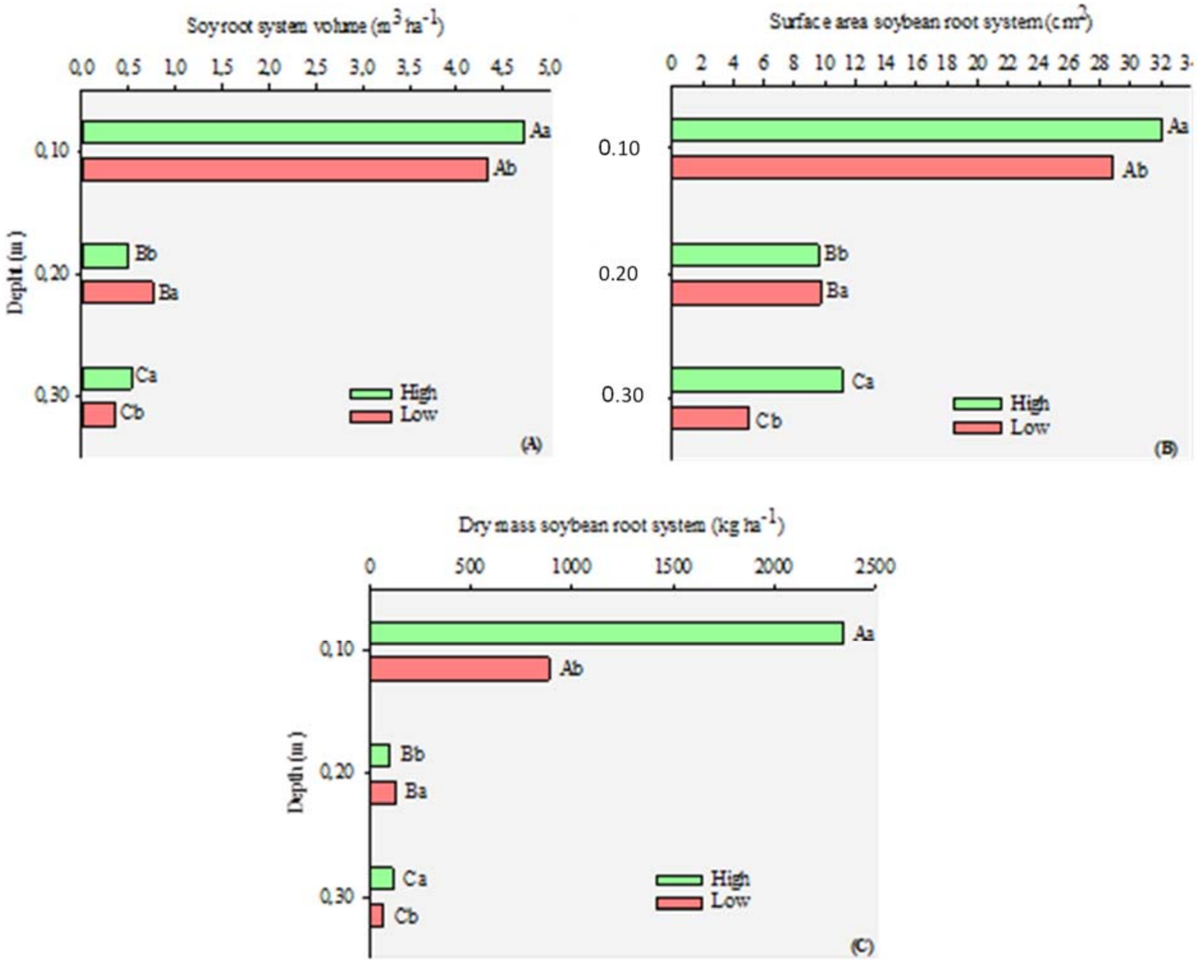

Figure 6. Root system volume (RSV) (m^3 ha^{-1}) (A), root system surface area (RSSA) (cm^2) (B), and dry root mass (DRM) (kg ha^{-1}) (C), in two production environments, at depths of (0-0.10; 0.10-0.20 and 0.20-0.30 m). Uppercase letters compare evaluation depths, lowercase letters compare the environments at each depth. Significant differences Tukey test ($p < 0.05$).

by the soil layer and productivity environment investigated. The high productivity environment presented an average of 853 kg ha^{-1} of DRM, which was 57.7% higher than in the low productivity environment for all layers (Figure 6C). The DRM was also impacted by the soil layer, with a decline of 92.8% at 0.10-0.20 m and 94.3% at 0.20-0.30 m, compared with the topsoil layer of 0-0.10 m.

Soil microbiological assessed by enzymes activity

The activity of the arylsulfatase (sulfur cycle) and beta-glucosidase (carbon cycle) enzymes was higher in the high productivity environment (Figure 7). For these enzymes, there was a reduction of up to 38% in arylsulfatase activity and 14.1% for beta-glucosidase in the low productivity environment compared to high environment.

Soybean grain yield

Soybean grain yield, under hydric stress, differed between the environments. In the high productivity environment, the average grain yield was 2188 kg ha^{-1}, and in the low productivity environment, it was 1563 kg ha^{-1} (Figure 8), which represents around 40% higher yield in the high productivity environment than low environment.

DISCUSSION

The MOS content was a sensitive indicator of productivity environments, although in these environments the MOS values were below the ideal levels for the region, which would be > 3.5% (CQFS, 2016). In the high productivity environment, there was a more uniform distribution of SOM content throughout the soil profile compared to the low productivity environment. As SOM plays many vital

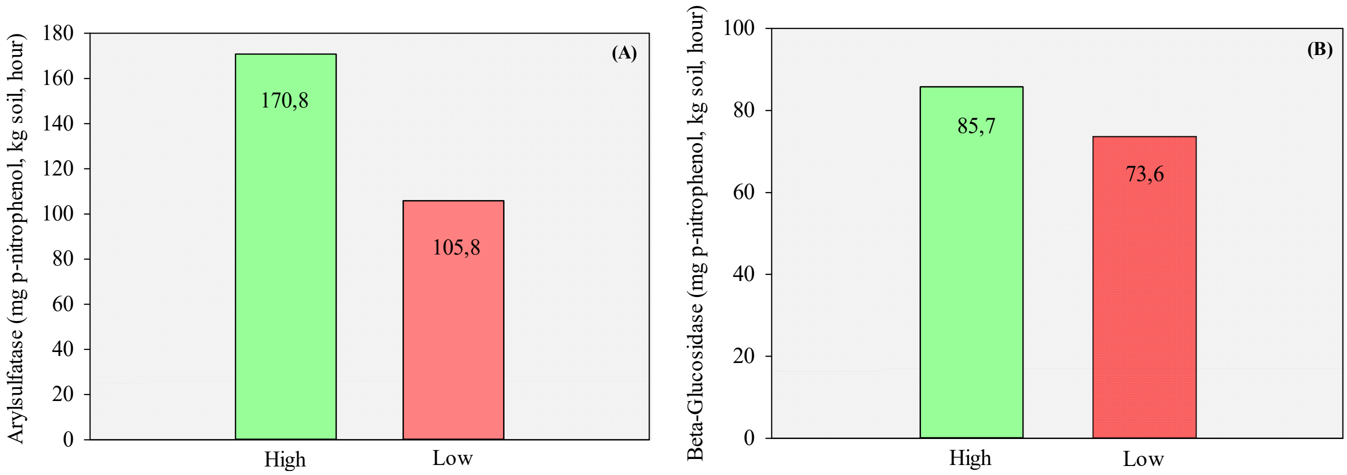

Figure 7. Enzymatic activity of the soil in two production environments, arylsulfatase (A) and beta-glucosidase (B).

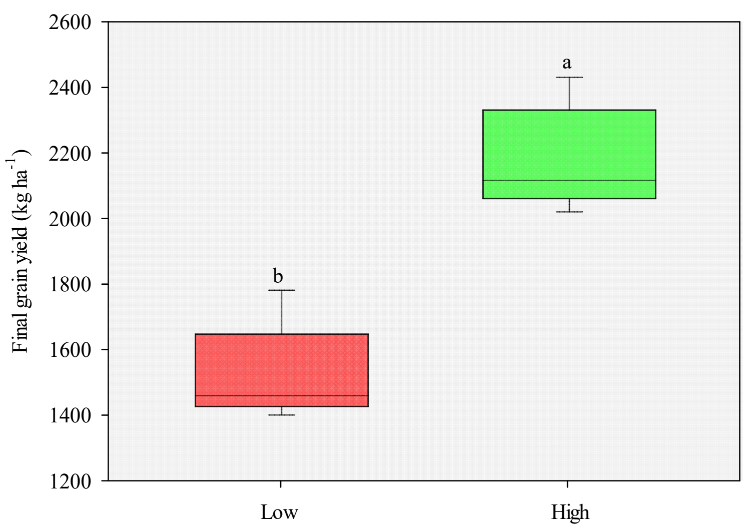

Figure 8. Final yield of soybean grains in two production environments. Different letters indicate significant difference Tukey test (p < 0.05).

soil functions, it is important to restore SOM levels not only in the topsoil but also in the subsoil. In addition to increasing nutrient cycling, MOS forms more stable soil aggregates that are important for water infiltration, aeration, and the deepening of the root system, as well as serving as an energy source for microorganisms (Gmach et al., 2019; Zhou et al., 2020; Magdoff and Van Es, 2021), thus increasing soil resilience to abiotic stress.

Other previous studies evaluating high productivity environments also showed that these environments had a higher SOM content compared to low productivity environments (Santi et al., 2015; Mendes et al., 2018; Pott et al., 2020; Passinato et al., 2021). This allows us to infer that high productivity and resilient production systems necessarily involve strategies for carbon restoration in the soil profile.

For the RP indicator, there was a difference between the two environments, mainly at depths greater than 0.20 m. In previous studies, soils with RP above 2.0 MPa restrict the growth of soybean roots (Tormena et al., 1998). It was observed that the low productivity environment had RP values above the critical level (>2.0 MPa), a factor that can cause changes in root morphology, such as lateral distribution, topsoil concentration, and larger diameter (Lynch, 2019). In response to the increase in soil RP, the plant expends excessive energy, and the decrease in soil oxygen impairs roots and biological activity. In addition, soil compaction causes physiological root stress, hindering the functionality of plant cells in the roots through which water and nutrients are transported from the soil to the conductive vessels of the plant (Taiz et al., 2015).

The root growth parameters indicated that in the high productivity environment, soybeans had a higher volume, surface area, and dry mass in the 0.20-0.30 m layer. Therefore, under the lower RP (Figure 4) and higher SOM content (Figure 3), the plants find better conditions to deepen their root systems with less energy expenditure. This means there is more energy available for the plant's physiological functions, making it more efficient. Other studies in this line also demonstrate that areas of high productivity present greater root development throughout the soil profile (Battisti and Sentelhas, 2017; Dantas, 2018; Lynch, 2019; Bossolani et al., 2021; Bossolani et al., 2022).

Mitigating abiotic stress effects on crops during the growing season is one of the most efficient strategies to preserve crop productivity or minimize yield losses in years of drought (Dantas, 2018). Water storage in the soil and its availability to plants rely on soil characteristics such as texture, SOM, and physical attributes. However, root density and the ability to access deeper layers in the soil profile are critical to maintaining photosynthesis rates, stomatal opening, and carbon assimilation (Zhang et al., 2016; Kelly et al., 2019). Water storage and plant water availability are also affected by site-specific performance of cover crops that create biopores, which serve as preferential pathways for root growth, aeration, water infiltration, and carbon translocation. Williams and Weil (2004) reported that soybean roots tend to grow deeper in the biopores left by the roots of cover crops such as radish oil. Therefore, stimulating the root growth of cover crops in the off-season is a key strategy for building an environment resilient to abiotic stress.

The microbiological analysis shows that the arylsulfatase and beta-glucosidase enzymes were more active in the high productivity environment than in the low productivity environment. However, the cropland is managed under a no-till system, with the same crop rotation plan. The within-field biological activity variability can be explained by the higher cover crop biomass production in the high productivity environment, which is linked to greater root development, the release of exudates, and organic compounds of high molecular weight, such as polysaccharides (mucilage) and proteins (Kamilova et al., 2006), which contribute to the survival of beneficial microorganisms in the soil (Passinato et al., 2021). In addition, a high amount of crop residue kept on the soil surface regulates soil temperature and conserves moisture during the warm summer. These effects are crucial to sustaining a diverse microbial community and balancing the fungus/bacterium ratio in the soil through continuous soil carbon flux (Brockett et al., 2012; FAO, 2020).

Soil quality improvement through conservation practices allows greater production of crop residues to be input into the soil. This carbon and nitrogen supply are key energy sources for microorganisms that mediate SOM buildup. In a long-term experiment, Bonini et al. (2020) reported that NTS, associated with high cover crop residue input and corn rotation with soybean, increased beta-glucosidase enzyme activity by up to 69% at the depth of 0-0.10 m, compared with low residue input and minimal crop diversification systems.

In this study, the low productivity environment had 38% lower arylsulfatase activity and 14.1% lower beta-glucosidase activity, respectively, compared to the enzyme activities in the high productivity environment (Figure 6). A South Brazilian study, similar to this one, investigating enzyme activities, soil DNA, and production environments also reported that less productive environments had lower enzyme activity, with 18% lower beta-glucosidase activity and 19% lower arylsulfatase activity compared to the high productivity environment (Passinato et al., 2021). This result was associated with the low productivity environment's soil physical attributes, which had high soil RP values and restricted soil oxygen diffusion, leading to shallow, confined root systems. In addition, the limited biota diversity resulted in a greater presence of pathogens, such as Fusarium and Macrophomina, which are harmful to root and plant growth (Passinato et al., 2021).

The soybean yield data showed that environments with a higher SOM content in the topsoil and a lower vertical gradient through soil depth (Figure 3), higher enzymatic activity (Figure 7), higher root growth (Figure 6), and lower soil PR (Figure 4) were the most resilient during abiotic stress, as reported in previous studies (Dantas, 2018; Mendes et al., 2020; Pott et al., 2020; Passinato et al., 2021).

In this study, the soybean grain yield difference between the high productivity and low productivity environments was 625 kg ha^{-1}, reflecting poor rainfall distribution and a low amount, with a total precipitation of 341 mm throughout soybean growth, which was much lower than the soybean requirement of 450 to 800 mm (Dantas, 2018). This reinforces the importance of creating environments that are more resilient to abiotic stress associated with climate change. Improving the efficiency of water usage, which regulates a series of physiological and biochemical processes in plants, such as energy balance, respiration, photosynthesis, thermal regulation through cooling, and redistribution of heat, helps to reduce plant stress (Dantas, 2018).

Finally, the redesign of crop systems to mitigate drought involves soil conservation management, such as high crop residue input, soil protection year-round through crop diversity and cover crops, and living roots that release a high number of exudates (continuous carbon supply), sugars, organic acids, and proteins. This management strategy supports microbial activity and the diversity of soil biota that regulates carbon and water cycling (Bonini et al., 2020; Passinato et al., 2021). Overall, the more productive environments based on enhanced soil quality are also the most resilient under abiotic stress.

Conclusions

The most productive soybean environments were associated with higher SOM content on the topsoil and in depth, lower resistance to soil penetration that allows a higher volume, surface area, and dry root mass in subsoil. In addition, activity of beta-glucosidase and arylsulfatase enzymes was also an efficient indicator of high productivity and a resilient environment. Therefore, management practices based on soil protection, soil carbon retention, deepening crop root systems and soil water storage by integrating chemical, physical and biological attributes are necessary to build up productive environments and more resilient systems to drought stress.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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