

Article

Soil—Plant Relationships in Soybean Cultivated under Conventional Tillage and Long-Term No-Tillage

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Abstract: Soybeans [*Glycine max* (L.) Merrill] have great economic prominence in the world, and soil management systems can directly interfere with their yield through changes in soil physical-hydric properties. Thus, the aim of this research was to verify the relationship between yield components, physiological traits, root development, and soil physical-hydric properties in soybean yields grown under conventional tillage and no-tillage systems. The experiment was carried out in Botucatu, SP, Brazil, with two treatments: soybeans grown under conventional tillage and no tillage. It is a long-term experiment, conducted since 1986. The main variables that influenced soybean yield were plant height, relative leaf water content, root dry matter, soil penetration resistance, and soil accumulated water infiltration. Physiological components of the plant and soil water showed a significant and negative correlation with soybean yield. On the other hand, the root development and soil physical components were positively correlated with soybean yield. However, the yield components were not significant. The no-tillage system resulted in 7.8% more soybean productivity compared to conventional tillage. Soybean yield depends on the physical properties and the water storage capacity of the soil, as well as on the physiological traits and the root development of the plant.

Keywords: conservation management; *Glycine max*; plant physiology; root development; soil physics; soil water



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1. Introduction

Soil management systems directly interfere with the productive response of crops, mainly through changes in the soil physical-hydric properties [1,2].

There is research evaluating the effect of soil management systems, mainly between conventional tillage (CT) and no-tillage (NT); however, these research studies evaluate the effects on the soil or the plant, in isolation [3–6], thus leaving a gap to be filled, on responses of these managements jointly, so as to facilitate the understanding of the soil-plant system.

Areas managed under CT are more vulnerable to plants under water-deficit conditions, due to the lower rate of water infiltration, less storage capacity, and plant water availability [7,8]. However, there is less compaction in the surface layer once the soil is turned, which can favor root development, and consequently, a greater absorption of water and nutrients, due to greater root exploration, resulting in increased yields [9,10]. Nevertheless, it is worth mentioning that the effects on soil physical-hydric properties in CT are temporary, requiring annual operations [11].

NT-cultivated areas generally have the most compacted surface layers due to the traffic of agricultural machinery and implements: however, no soil disturbance provides greater continuity of the pores, making the porosity more efficient in the movement of solutions and gases [6,12,13]. In NT, there is also a greater volume of mesopores, contributing to greater water retention [11]. Thus, it is characterized as a system with greater water stability, offering less risk to production due to drought [1,14].

Water deficiency is a common situation for many crops and is one of the main factors affecting agricultural production, influencing all the aspects related to plant development [15]. In water deficit situations in the soil, plants develop defense mechanisms to reduce the effects of stress and anticipate the senescence of plant tissues [16]. Such strategies consist in dehydration avoidance and dehydration tolerance [17].

Dehydration avoidance characteristics act in maintaining the relative water content in tissues. Plants with dehydration tolerance strategies tend to keep stomata open for as long as possible, even at the cost of reducing water potential or dehydrating tissues [18].

In addition to knowing the strategies of the physiological adaptations of plants, it is important to know the interaction of these factors with soil management systems, so as to enable the reduction of the effect of water stress and the correct planning of agricultural activities [19]. Whereas soybeans are one of the main agricultural commodities and are susceptible to climatic conditions [20] and soil management [5], the hypothesis of this study is that management systems can affect the soil physical-hydric structure, and consequently, soybeans' development and yield. Thus, the aim of this research was to verify how the soil physical and hydric properties, as well as the production, physiological, and root-development variables affect the yield of soybeans grown under conventional tillage and no-tillage systems.

2. Materials and Methods

2.1. Site Description

The field experiment was conducted during the 2017/18 season in Botucatu, SP, Brazil (22°49' S; 48°25' W, at an altitude of 780 m), on a Typical Rhodudalf soil [21], classified as a clayey-textured. The main soil chemical [22] and textural [23] properties are presented in Table 1.

Table 1. Chemical and granulometric analysis of soil managed under conventional tillage (CT) and long-term no-tillage (NT).

Management System	pH	P	S	H + Al	Ca	Mg	K	Sand	Silt	Clay
	CaCl ₂	mg dm ⁻³			mmol _c dm ⁻³					
CT	5.0	61.2	3.6	36.3	39.5	12.7	4.7	147	239	614
NT	5.4	84.4	4.4	29.6	43.5	14.8	3.3			

The climate, according to the Köppen classification, is Cwa type, which means mesothermal climate with dry winter, with mean annual rainfall of 1450 mm [24]. Means of temperature and rainfall between the years 1985 and 2018 and during 2017/18 season are shown in Figures 1 and 2, respectively.

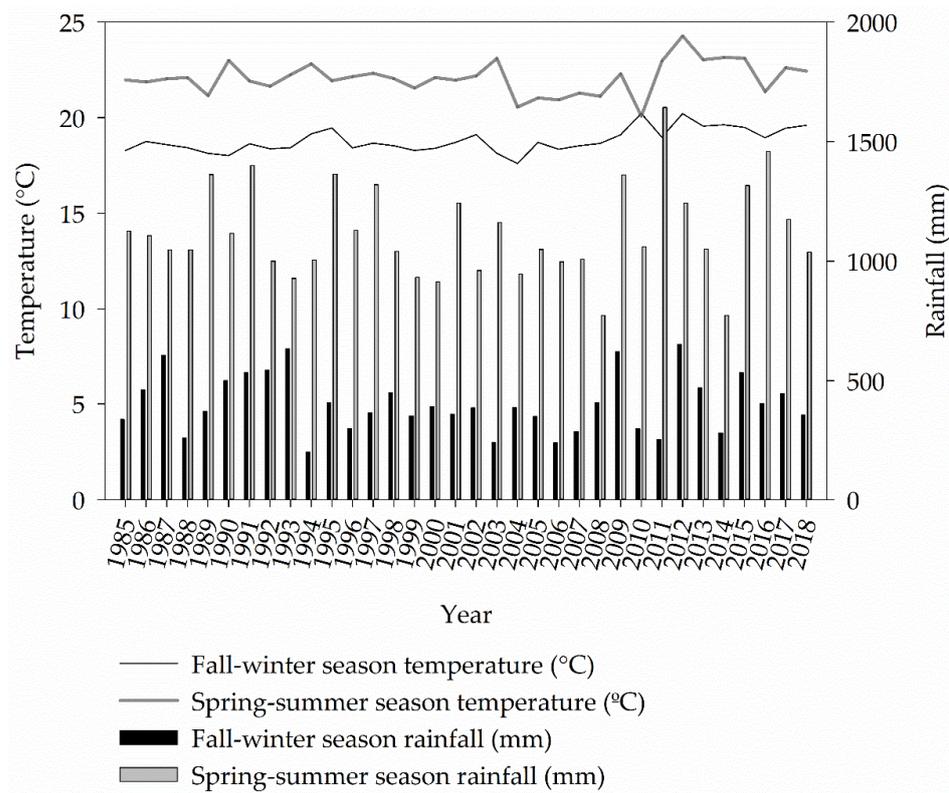


Figure 1. Means of temperature and rainfall in fall–winter and spring–summer seasons since experiment implementation (1985–2018).

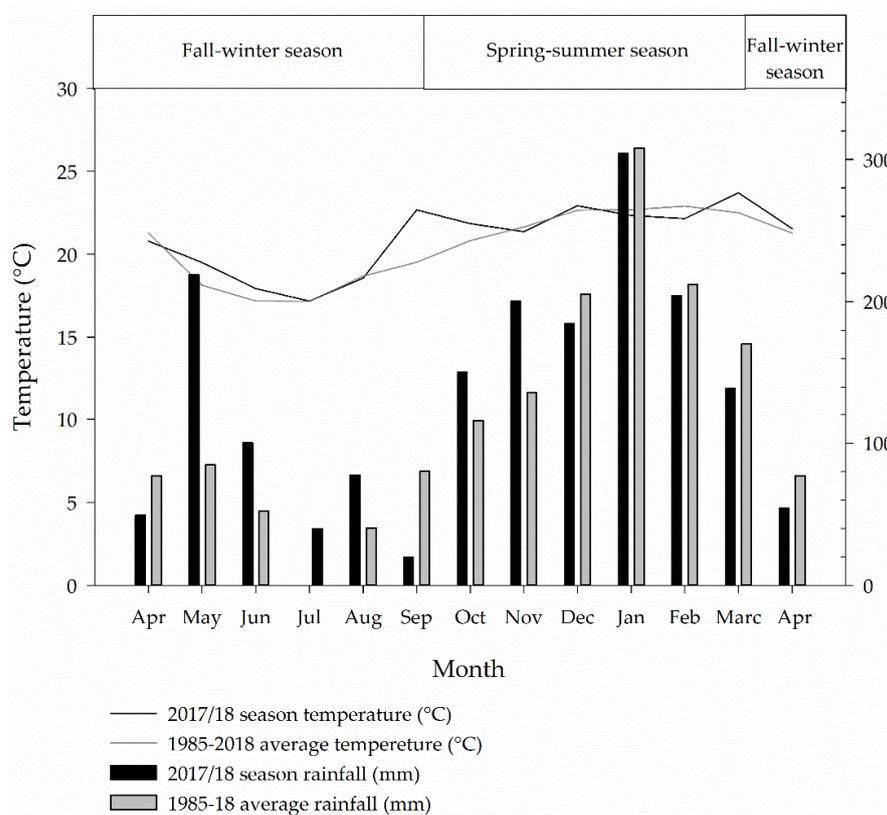


Figure 2. Means of monthly temperature and rainfall between the years 1985 and 2018 and during the 2017/18 season.

2.2. History and Experimental Design

The experiment has been carried out under conventional tillage (CT) and no-tillage (NT) since 1985, and the management history is shown in Table 2.

Table 2. Soil management systems and crop succession used since 1985, highlighting management and species cultivated in the fall–winter and spring–summer seasons of each agricultural year.

Year	Management System				Season Fall-Winter/ Spring-Summer
	Conventional Tillage		No-Tillage		
	Fall	Spring	Fall	Spring	
1985/86	Plowing + harrowing	Plowing + harrowing	Plowing + harrowing	No-tillage	Wheat/soybean
1986/87 to 1994/95	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Wheat/soybean
1995/96 to 1998/99	Without soil mobilization	Without soil mobilization	No-tillage	No-tillage	Fallow/fallow
1999/00	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Black oat/maize
2000/01 and 2001/02	Without soil mobilization	Without soil mobilization	No-tillage	No-tillage	Fallow/fallow
2002/03 and 2003/04	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Black oat/millet-bean
2004/05 and 2005/06	Plowing + harrowing	Plowing + harrowing	No-tillage	No-tillage	Black oat/maize
2006/07	Without soil mobilization	Without soil mobilization	No-tillage	No-tillage	Fallow/soybean
2007/08	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Yellow oat/bean
2008/09	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Yellow oat/bean
2009/10 and 2011/12	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Black oat/maize + brachiaria
2012/13	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Brachiaria/soybean
2013/14	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Wheat/soybean
2014/15	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Safflower/soybean
2015/16	Without soil mobilization	Plowing + harrowing	No-tillage	No-tillage	Safflower/maize
2016/17	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Black oat/maize
2017/18	Plowing + harrowing	Without soil mobilization	No-tillage	No-tillage	Black oat/soybean

The experimental design was randomized in blocks with four replications and two soil management systems, those being conventional tillage (CT) and no-tillage (NT).

2.3. Management and Analysis in Soybean Plant

The soybean cultivar used was TMG 7062 IPRO; sowing was carried out on 8 December 2017, with 0.45 m spacing between lines, aiming at a density of 300,000 plants ha⁻¹, using seeds treated with fungicide Carboxin + Thiran, insecticide Tiametoxam, inoculant *Bradyrhizobium* sp., and micronutrients Co and Mo. The sowing fertilization was conducted with 60 kg ha⁻¹ of K₂O and 60 kg ha⁻¹ of P₂O₅, using KCl and single superphosphate, respectively. The harvest was carried out 111 days after sowing.

2.3.1. Physiological Traits

In full bloom stage (R2), the SPAD index was evaluated using the SPAD-502 chlorophyll meter (Minolta Corp., Ransey, NJ, USA), in five plants per plot. The SPAD index is an indirect measure used to quantify chlorophyll by emitting a beam of light. The device quantifies the intensity of green in the leaf blade, thereby correlating with the amount of chlorophyll in the leaf tissue. Reading the value of the SPAD unit indicates the leaf pigment content, and it is equivalent to the amount of light transmitted by the leaf in two wavelength bands, in which the absorption by chlorophyll is different [25]. In this case, the value is proportional to the amount of chlorophyll present in the leaf.

To determine the leaf area index (LAI), all plants' leaves were collected in 0.5 m and then analyzed in a bench leaf area integrator (LICOR, model LI-3100C, Lincoln, NE, USA).

The LAI was calculated with the ratio of the total plant leaf areas (m^2) per unit of land ($0.225 m^2$) available for plants [26,27], according to Equation (1):

$$LAI = \text{total leaf area} / \text{soil surface area} \quad (1)$$

To obtain the leaf relative water content (RWC), five plants were analyzed, and two leaf discs (0.69 cm^2 each) were collected from the third trifoliolate leaf (apex to the base) of each plant and the fresh tissue mass (W_f) was determined in analytical balance. After that, the samples were rehydrated in distilled water for 24 h to obtain the turgid mass (W_t), using paper towels to extract the excess water. The dry mass (W_d) was obtained after the discs remained in an oven with forced air circulation at $80 \text{ }^\circ\text{C}$ for 48 h. RWC values were obtained by the equation of [28]:

$$RWC = [W_f - W_d] \times (W_t - W_d)^{-1} \times 100 \quad (2)$$

The leaf water potential (Ψ_w) was obtained using a Scholander chamber (Soil Moisture Equipment, Santa Barbara, CA, USA). The measurements were taken during the hottest period of the day, between 12:00 and 14:00 h, so that the lowest values of leaf water potential would be observed. Ψ_w was determined at the end (tip) of the third trefoil (direction from the apex to the base), where pressure was applied until exudation occurred through a cut made in the leaf petiole.

2.3.2. Root Development

Root analysis was performed at the full bloom stage (R2). Soil samples were collected with an auger hole at the depth of 0.00–0.40 m, with four subsamples per depth to compose a sample.

After collection, the soil portions containing the roots were packed in sealed plastic bags and frozen at $-2 \text{ }^\circ\text{C}$ and then washed, stored in a container containing 30% alcohol and 70% water, and stored in a refrigerated environment. Subsequently, the samples were subjected to an optical reading scanner at a resolution of 250 dpi, and the images obtained were analyzed with the Win Mac Rhizo program to determine the root length density (root cm soil cm^{-3}), root area (root $\text{cm}^2 \text{ soil cm}^{-3}$), and average root diameter (mm). Afterwards, the samples were placed in paper bags and dried in a forced aeration oven at $60 \text{ }^\circ\text{C}$ for 48 h to determine the dry mass.

2.3.3. Yield Components

When the plants reached the phenological R9 stage, the plant height, the height of insertion of the first pod, and the number of pods per plant in 50 plants of each experimental unit were evaluated. Thousand grain weight was also assessed, according to [29].

2.3.4. Yield

The soybean yield estimate was performed after the physiological maturity of the grains (R9), harvesting the plants from the useful fields ($4.5 m^2$), discarding the borders, and the water content of the grains was corrected to 130 g kg^{-1} .

2.4. Soil Analysis

2.4.1. Soil Water Storage

The soil water content was assessed by using tubes for moisture readings using a capacitance probe (model Diviner[®], Sentek Pt Ltd., Stepney, SA, Australia). Water content monitoring was carried out from the surface to 0.40 m in depth (0.10 m range), with readings at 1, 3, 5, 8, and 15 days after rain (DAR); for this evaluation, rains above 10 mm were considered. Stored water values (SW) were the result of the sum of the humidity values up to the depth of 0.40 m in each experimental unit, and for each day of reading, the average of SW was made.

2.4.2. Soil Physical Properties

At the time of root collections, soil penetration resistance tests (PR) were carried out at three points per plot, using the Impact Penetrometer (model IAA/Planalsucar–Stolf, Piracicaba, SP, Brasil).

For the assessment of soil density (Sd), macroporosity (MP), microporosity (mp), total porosity (TP), field capacity (FC), and permanent wilting point (PWP), we collected two samples of soil with undeformed structure at each depth, using volumetric rings, by the trench method [23,30,31]. With the values of FC and PWP, it was possible to calculate the maximum water capacity available (AWC), subtracting from the humidity value in the FC the humidity in the PWP [32].

2.4.3. Infiltration and Rate of Water Infiltration into the Soil

The accumulated water infiltration into the soil (AWI) was evaluated using the concentric ring infiltrometer method [33]. Reading was performed until constant infiltration values were obtained (five similar values). Readings were taken at the following time intervals: five repetitions of one minute; five repetitions of two minutes; five repetitions of five minutes; five repetitions of ten minutes; five repetitions of fifteen minutes; five repetitions of twenty minutes; and finally, intervals of thirty minutes, until the infiltration rate stabilized. Experimental data were adjusted by the infiltration equations according to the mathematical models proposed by Kostiakov–Lewis. To obtain the time of basic infiltration rate (BIR), Equation (3) was used:

$$\text{BIR} = \{[-0.001/[C \times n \times (n - 1)]]\}^{1/(n-2)} \quad (3)$$

where BIR is the basic infiltration rate; n is the line slope, determined on the spot for each type of soil; and C is the constant showing the infiltrated blade in the first minute, in cm.

2.5. Data Analysis

For data analysis, the variables were divided into five groups. The group called Yield components was composed by plant height, height of first pod insertion, number of pods per plant, and weight of 1000 grains; the Physiological group by the variables index SPAD, LAI, RWC, and Ψ_w ; the group Root development by the variables root area, average root diameter, root length density, and root dry matter; the group Soil physics by the variables PR, TP, MP, mp, and Sd; and the group Soil water by AWC, AWI, BIR, and SW in 1, 3, 5, 8, and 15 days after rain.

In each group of variables, it was applied to the principal component analysis (PCA) [34] through the nonlinear iterative partial least squares algorithm (NIPALS).

For each set of variables, the smallest possible number of components was sought that explained at least 70% of the total variability.

The scores of the five groups of variables were then compared with the yield scores and plotted on scatter plots, considering the values of each replication.

From the scores of the principal components selected from each group of variables, the association with each component on the yield of soybean plants was assessed using Pearson's linear correlation coefficient ($p < 0.01$).

3. Results

From the correlation matrix between the pairs of each group of variables (Yield components, Physiological traits, Root development, Soil physics, and Soil water), the eigenvalues and their respective eigenvectors were obtained for the analysis of principal components.

For all groups of variables, the first principal component explained more than 88% of the total variance (Table 3). Therefore, only the first component was considered for the purposes of exploiting the results.

Table 3. Percentage explanation of the first major component of the variables Yield components, Physiological traits, Root development, Soil physics, and Soil water.

Group of Variables	Explanation Percentage (%)
Yield components	97.11
Physiological traits	88.71
Root development	99.99
Soil physics	99.71
Soil water	98.48

Among all the variables analyzed, the number of pods per plant, plant height, relative water content in the leaf, water potential in the leaf, root dry matter, soil penetration resistance, accumulated infiltration, and the basic rate of water infiltration into the soil (Figure 3), were the characteristics that most explained the respective components, with loadings of -0.98 , 0.19 , -0.89 , -0.43 , -1.00 , 0.99 , -0.97 , and -0.22 , respectively.

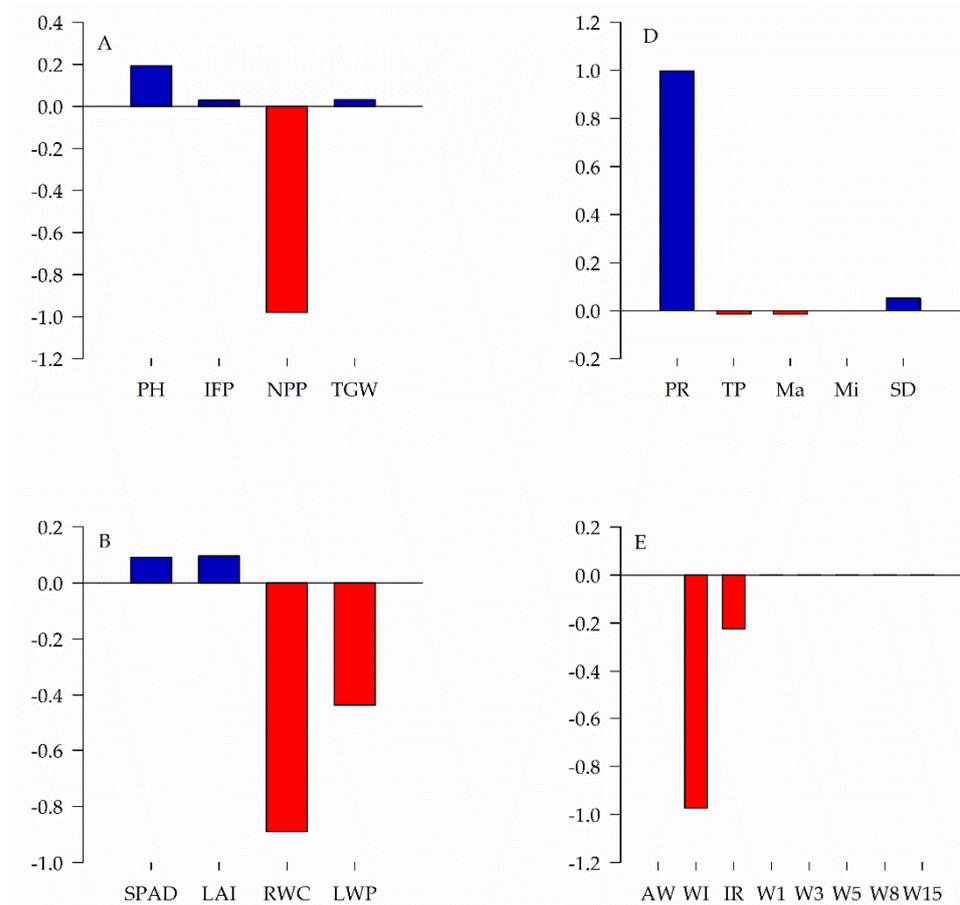


Figure 3. Cont.

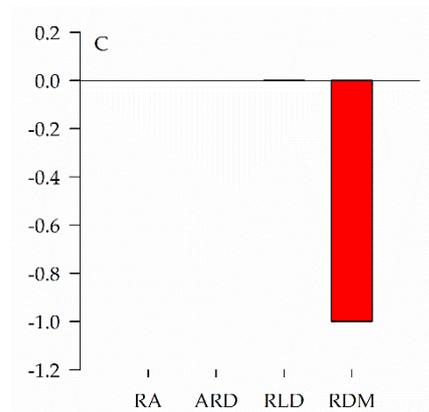


Figure 3. Loadings of variables in Yield components (A), Physiological traits (B), Root development (C), Soil physics (D), and Soil water (E). PH: plant height; IFP: insertion of first pod; NPP: number of pods per plant; TGW: thousand grain weight; SPAD: SPAD index; LAI: leaf area index; RWC: leaf relative water content; LWP: leaf water potential; RA: root area; ARD: average root diameter; RLD: root length density; RDM: root dry matter; PR: soil penetration resistance; TP: soil total porosity; Ma: soil macroporosity; Mi: soil microporosity; SD: soil density; AW: available water capacity; WI: accumulated water infiltration; IR: basic infiltration rate; W1: water stored 1 day after rain; W3: water stored 3 days after rain; W5: water stored 5 days after rain; W8: water stored 8 days after rain; W15: water stored 15 days after rain.

By analyzing two-dimensional dispersion of treatments, it was observed that there was a difference between the soil management systems for all variables groups. Plants grown under the no-tillage system (NT) showed higher yields than under the conventional tillage system (CT) (Figure 4).

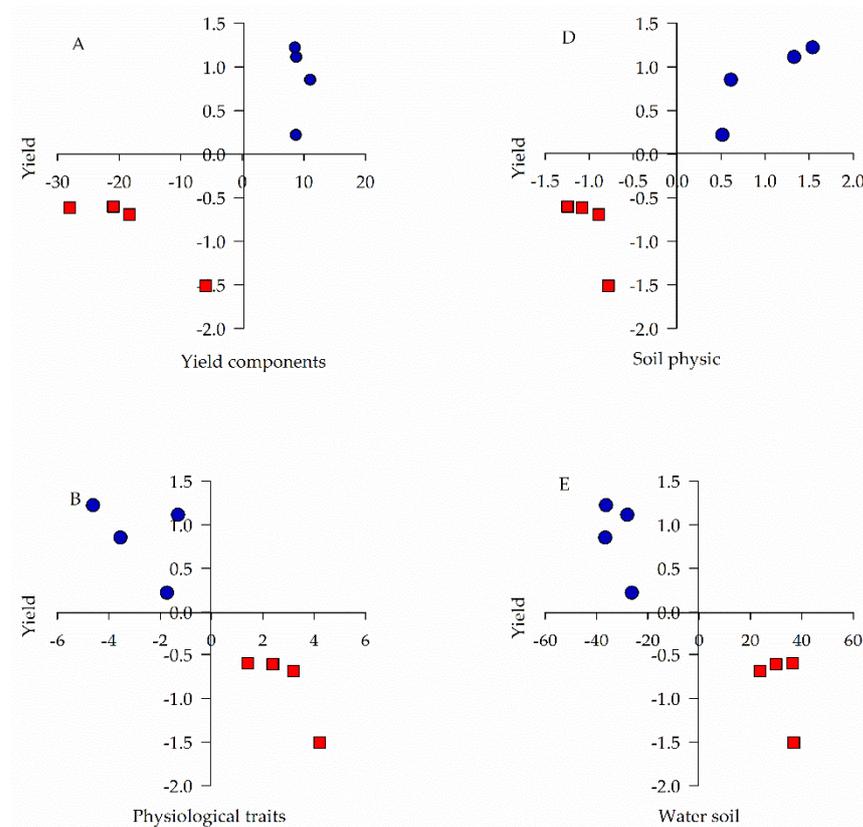


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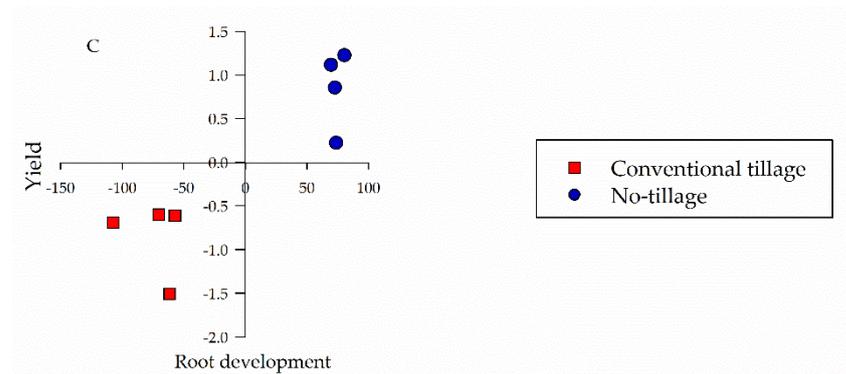


Figure 4. Dispersion of observations in principal component 1 of yield components (A), Physiological traits (B), Root development (C), Soil physics (D), and Water soil (E) variables.

The highest yields observed in NT (4.555 kg ha^{-1}), were associated with the lowest number of pods per plant and root dry matter (Figure 3A,C); however, in contrast, it was also associated with greater height of plant, relative water content, water leaf potential, soil penetration resistance, accumulated infiltration, and basic rate of water infiltration into the soil (Figure 3A,B,D,E).

The lower soybean yield, observed in CT (4.200 kg ha^{-1}), was associated with smaller plants, but with a greater number of pods, lower water content and water potential in the leaf, greater root dry matter and soil penetration resistance, and lower infiltration and basic rate of water infiltration into the soil (Figure 4).

Through Pearson’s correlation analysis (Figure 5), it was observed that physiological components (-0.94), root development (0.88), soil physics (0.91) and soil water (-0.93) showed a significant correlation ($p < 0.01$) with soybean yield; however, the yield components were not significant.

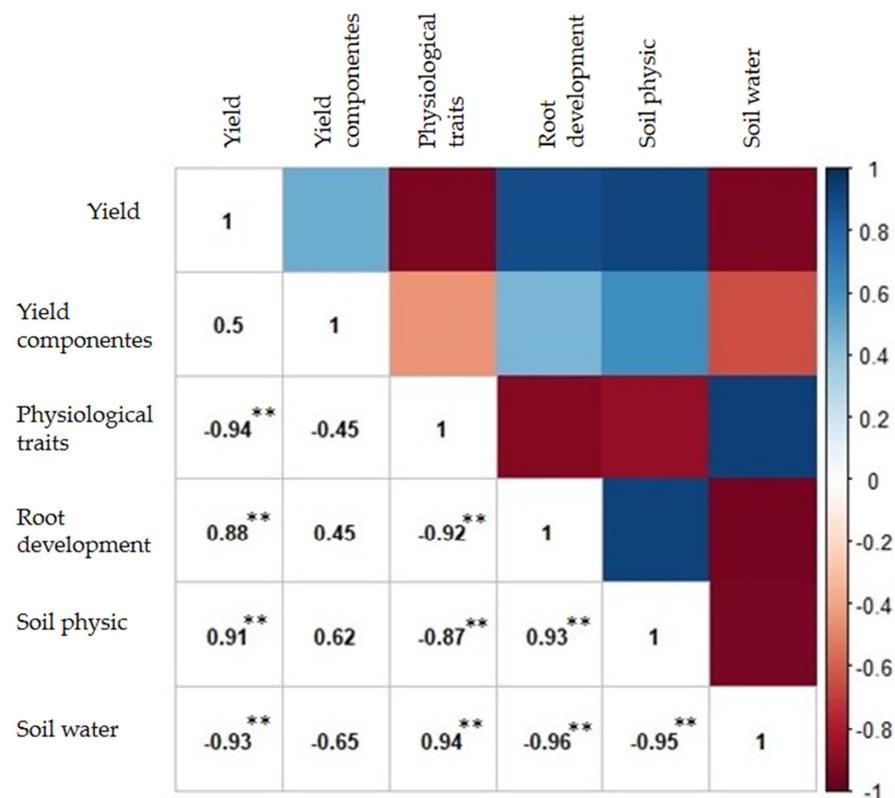


Figure 5. Pearson correlation between first principal component of each variable group. ** significant correlation at $p < 0.01$.

Regardless of the soil management system, it was noticed that yields showed significant correlation with the sets of variables Physiology, Root development, Soil physics, and Soil water. It is noteworthy that the higher water content and water potential in the plant, the better the productive response, and that the lower dry root matter, associated with greater soil penetration resistance, but with greater water infiltration into the soil, also contributed to higher yields (Figures 3 and 5). However, the highest yield was observed in the no-tillage system (Figure 4).

There was also a significant correlation between the Physiological traits component and those of Root development, Soil physics, and Soil water. Root development component was also correlated with Soil physics and Soil water. Also showing a significant correlation was Soil water with Soil physics (Figure 5).

4. Discussion

In the NT system, the higher plant height did not result in a greater number of pods per plant, which is associated with the greater insertion height of the first pod, thus, reducing the plant productive space [35]. However, yield was not affected, since the NT had a higher yield than the CT. This behavior was observed due to the greater weight of 1000 grains in NT, acting as a compensating factor in the grain yield composition [35,36]. Soybean plants grown in CT also presented a compensation factor in relation to plant height since they presented smaller plants, but with a greater number of pods. However, this was not sufficient to result in greater productivity since it produced grains of lower weight, as observed in the TGW variable (Figure 3A).

Based on plant physiological responses, it was noted that soybeans had greater water availability in NT, as they had higher relative water content and water potential in the leaf (Figures 3 and 4). This behavior can also be observed by the direct and significant correlation between the soil water components and physiological traits (Figure 5), indicating that the greater water storage in the soil, the greater water content in the plant.

The lower root production in NT may be associated with greater soil penetration resistance (PR) due to the difficulty of root development in depth and changes in root morphology, leading to a reduction in the rate of root elongation due to the smaller cell division meristem, making the roots less pointed and with larger diameters [10,37,38].

The absence of soil disturbance in conservation systems promotes a higher PR value in superficial soil layers; however, these values tend to decrease in depth [1,5,9]. It is worth mentioning that the PR data presented in this work are from the 0.00–0.40 m layer of soil depth. The higher PR values in the surface layers in NT, generally, do not harm plant development due to the greater continuity of the pores, making the porosity more efficient in liquid and gaseous transport and favoring the growth of the roots [6,12,13].

In general, the higher yields of soybeans in NT can be explained by the association with physiological traits, root development, soil physics, and soil water since the higher PR did not affect the infiltration of water in the soil, thus contributing to the greater water availability to the plants; consequently, the plants did not need to develop deep roots due to the water supply provided by the system, corroborating the better plant water content. Thus, the NT was characterized as a production system less vulnerable to dry spells and drought.

In situations of soil water deficit, plants develop adaptive mechanisms that allow them to survive under these conditions. Stomatal closure is the first line of defense against dehydration [39]. Stress due to drought and consequent stomatal closure leads to the exposure of excess energy in the plant, which, if not safely dissipated, can cause excitation in the center reaction of the PSII photosystem, leading to photoinhibition [16], initiating the production of H₂O₂ which, consequently, leads to the activation of the antioxidative metabolism [40].

In this way, adequate soil management can lead to a greater availability of water, and understanding the dynamics of water in the soil becomes essential for the correct

planning of agricultural activities, with water being the factor that most frequently affects crop yield [15].

It is worth mentioning that there are several factors related to the water storage capacity in the soil and its availability to plants; however, one of the main factors is the soil management system, as it modifies the soil physical properties associated with structure, such as water availability, aeration, and resistance to root growth, directly related to plant development.

In CT, compaction is a recurring problem, due to the heavy traffic of machinery, which is considered the main reason for compaction in agricultural areas [41], thus affecting the infiltration and the water availability for the plants, in addition to contributing to the water erosion of the soil due to the lower rate of water infiltration [1,3]. This behavior can be observed in the results of this research, in which the highest resistance to penetration and soil density in CT (Figures 3D and 4D) and the lowest rate of water infiltration into the soil in this same management system (Figures 3E and 4E) reduced soybean yield.

The positive effect of NT on soil water dynamics is also associated with permanent soil cover, as it reduces the impact of raindrops on the soil surface, decreasing runoff and water evaporation on the surface [4,42]. In addition to these factors, the higher content of organic matter in the superficial layers contributes to greater porosity, favoring a higher rate of infiltration [43].

5. Conclusions

Soybean yields depend on the physical properties and the soil water storage capacity, as well as the physiological traits and the plant root development. The no-tillage system offers plants greater water stability and provides better soybean productivity.

It is recommended to jointly evaluate the variables that affect soybean productivity, the soil physical and hydric properties, as well as production, physiology, and root development, because, in most cases, these factors are correlated with each other. The isolated evaluation of the variables can be insufficient in detecting the limiting factors of productivity, especially when comparing different soil management systems.

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