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Long-term effects of four tillage systems and weather conditions on soybean yield and agronomic characteristics in Brazil

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Abstract

Intensive mechanized tillage systems, which are widely adopted by farmers, can cause soil disturbances and compromise the agricultural production sustainability. Despite some divergences, the no-tillage system (NT) has been shown to be more environmental and economically sustainable for farming in southern Brazil. The aim of this study was to assess the long-term effects of four soil management systems on soybean yield and agronomic characteristics, in a 14-cropping-season experiment that was established on an Oxisol in the Rio Grande do Sul state, southern region of Brazil. The experiment was carried out in randomized complete block design with three replications. The treatments consisted of four soil management systems: two conservation systems [no-tillage (NT) and reduced-tillage (RT)] and two conventional tillage [disk plowing + disking (DPD) and moldboard plowing + disking (MPD)]. The parameters of grain yield, thousand-grain weight, plant height, first pod insertion height, plant stand, and soybean yield components (the number of pods per plant, the number of grains per plant, and the grain yield per plant) were evaluated at crop maturity. During the 14 successive crops, conservation systems provided grain yield and plant agronomic characteristics that were similar or significantly better than to those of conventional tillage in the majority of the cropping seasons. These findings demonstrate that NT and RT are suitable methods in environmental and economic terms, particularly NT, because it has lower production costs by reducing some mechanized operations. The main variations in soybean yield were due to changes in weather conditions that occurred during the study period (172 months), particularly with respect to the impact of water stress on plant development.

Keywords: no-tillage, reduced-tillage, conventional tillage, yield components, *Glycine max*.
Abbreviations: NT_no-tillage system; RT_reduced-tillage; DPD_disk plowing + disking; MPD_moldboard plowing + disking; SMS_soil management systems.

Introduction

Agriculture in the Rio Grande do Sul state, southern region of Brazil, is characterized by soybean and corn crops in the summer and wheat in winter. Farmers from this region sow approximately four million hectares (approximately 70 % of the agricultural area) of soybeans each year, with an average yield of 2160 kg ha^{-1} over the last 10 years (Conab, 2014), making soybean the main cash crop in the region. Mechanized tillage techniques, which are available to farmers, have been recently adopted due to better methods of chemical weed control, seeding systems and lower costs. However, mechanized soil preparation by the intensive use of disk or moldboard plowing at the soil surface, successively at the same depth, disrupts the topsoil, resulting in two layers within the soil profile: one that is superficial and fragmented and the other that is a subsurface compacted layer (Bertol et al., 2000; Gabriel Filho et al., 2000). These impacts on the soil reduce the water infiltration rate and increase the soil and nutrient losses by erosion, negatively affecting root growth and crop productivity. Tillage systems that are compatible with the soil and climatic characteristics of southern Brazil are essential to cease the current land degradation process and maintain the sustainability and competitiveness of the agricultural sector (Santos et al., 2000). In this context, it is possible to highlight the adoption of conservation systems, i.e., those that require less soil disruption, such as no-tillage and reduced-tillage, which are able to maintain or increase the grain yield over successive crops, especially when associated with the crop rotation in the same area. The no-tillage system recommends minimizing soil disruption, having soil rupture only in the seed row, which is more efficient for soil and water conservation (Spera et al., 2011; Silva et al., 2012). Reduced-tillage with a chisel plough also does not revolve the arable layer. However, changes in the soil physical properties have been observed under these conservation tillage systems when such systems are adopted for long periods. Some of these changes have been reported by Spera et al. (2009), who found increases in the soil bulk density and microporosity and decreases in the total porosity at the 0.10-0.15 m depth in an Oxisol that was managed for 10 years with no-tillage. However, there is still no consensus on the effects of tillage systems, and corresponding soil changes, on the yield of crops such as soybean. Several short-term experiments (one crop season) evaluated the soybean yield under different tillage systems, and the results are controversial. In some of these experiments, soybean productivity under no-tillage did not differ from that under conventional tillage by plowing, disking or chiseling (Kluthcouski et al., 2000; Al-Kaisi et al., 2005; Secco et al., 2005; Nicoloso et al., 2008; Girardello et al., 2011; Pivetta et al., 2011; Drescher et al., 2012; Girardello et al., 2014), whereas in other studies the productivity was higher (Dickey et al., 1994) or lower (Bertol and Fisher, 1997). In many of these studies, the absence of soybean response to mechanized tillage was attributed to the fact that this oleaginous plant is considered a rustic species that, under favorable weather conditions (good rainfall distribution during the growing season), is not affected by the soil physical limitations that are present in no-tillage areas. Another argument refers to the fact that the soil is easily reconsolidated after some mechanized tillage, such as chiseling (Hamza and Anderson, 2005); therefore, tillage does not promote the expected effects of improving soil physical structure throughout the growing season. Long-term experiments under variable weather conditions, which jointly analyze the effects of tillage systems on soybean yield in several growing seasons, are very scarce; therefore, it has become essential to clarify the controversial results that are reported in experiments of short duration. The aim of this study was to assess the long-terms effects of four tillage systems on soybean yield and agronomic characteristics, in a 14-cropping-season experiment under variable weather conditions in an Oxisol in Passo Fundo, Rio Grande do Sul state, southern region of Brazil.

Results and Discussion

Yield and agronomic characteristics of soybean as influenced by weather conditions

The weather conditions were indispensable for the appropriate season-to-season evaluation of soybean yield and agronomic characteristics variations in this study in the Passo Fundo humid subtropical region. There were no significant changes in the mean annual temperature and real evapotranspiration during the experimental period (Fig 1). However, the accumulated precipitation in each season (November to March) varied significantly among the crops, and there was wide variability of rainfall distribution and water deficit or surplus over a given period of time among the months of each crop season. Consequently, the average grain yield also varied significantly among the 14 seasons (Fig 2). A lower soybean yield (794 kg ha^{-1}) was obtained at the 2004/2005 harvest, which had the lowest cumulative rainfall (408 mm) and the highest water deficit (-62 mm) (Fig 1). This pronounced water deficit had a positive impact on the thousand-grain weight (219 g), which was 29 % higher in this crop season than the average for all other of the crops. These results could be considered a plant survival mechanism because the thousand-grain weight is one of the important scales in seed quality that influence germination, seed vigor, seedling establishment and yield (Moshatati and Gharineh, 2012). However, plant height, the height of the insertion of the first pod, plant stand, and other agronomic characteristics of soybean were lower in this driest season, specifically the yield components: the number of pods per plant, the number of grains per plant, and the grain yield per plant, which decreased by 43, 47 and 35 %, respectively (Fig 2 and 3).

The soybean yield from the 2003/2004 crop season, despite receiving good accumulated rainfall (807 mm), had the second lowest average grain yield (1793 kg ha^{-1}) (Fig 2), which can be attributed to the strong irregularity of rainfall distribution, with a coefficient of variation of 86 % among the crop months, when the highest water surplus (297 mm) occurred in December 2003, and the water deficit (-15 mm) expressed during the grain-filling period (March 2004) (Fig 1); consequently, these water stresses have significantly damaged the soybean yield. In turn, higher grain yields were recorded in the 2000/2001 (3324 kg ha^{-1}) and 2010/2011 (3279 kg ha^{-1}) crop seasons, which were benefited by good cumulative rainfall (844 mm in both seasons) and excellent rainfall distribution during the vegetative and reproductive development stages. The 1997/1998 crop season received the highest accumulated precipitation (1394 mm), which was well distributed throughout the five crop months (Fig 1). However, this pattern did not generate a higher yield because the productivity (2763 kg ha^{-1}) of this season was equivalent to only 83 % of the highest productivity that was recorded in the 2000/2001 crop, which may be attributed to periods of excess moisture in the clayey soil of this experiment. Saturated soil may be detrimental to many plant process, disturbing root growth, nutrient and water uptake, photosynthesis, and hormonal balances due to a lack of oxygen in the soil (Armstrong and Drew, 2002). Despite the use of different cultivars over 14 crops, we can conclude from the results of this study that soybean has a cumulative water demand of approximately 840 mm, associated with good rainfall distribution, which are relevant factors in obtaining higher yields at the site of this experiment. Watts and Torbert (2011) obtained similar results in a long-term (nine growing seasons) soybean experiment in northeastern Alabama (USA), which has a subtropical climate with no pronounced dry season. These authors found that the soybean yield was effectively influenced by the large rainfall variation, obtaining a grain yield of 1800-3400 kg ha^{-1}. In their study, the best soybean yield was achieved with 800 mm of accumulated rainfall during the crop season (April-September 1995). Similar to the present study, these authors found that the crop with higher precipitation (1075 mm, 1997) did not result in a higher grain yield, attributing the effect to the poor distribution of rainfall that was concentrated in the initial stage of crop season. According to the authors, the lowest soybean crop yields were obtained in seasons with rainfall below the average precipitation that was registered in their experiment, and they stated that the periods of water stress were crucial to grain yield decreases.

Soybean yield as affected by the soil management systems

The soybean yield in two crop seasons (1999/2000 and 2000/2001) was 13 % higher in conservation soil management systems (NT and RT) compared with conventional tillage systems (DPD and MPD) and was similar to that of other seven crops (1997/1998, 1998/1999, 2002/2003, 2004/2005, 2005/2006, 2009/2010 and 2010/2011) (Fig 2). Comparing jointly the 14 crops, we found that conservation soil management systems produced on average 3.2 % more than conventional tillage systems according to the following numerical order: RT (2624 kg ha^{-1}) > NT (2579 kg ha^{-1}) > DPD (2536 kg ha^{-1}) > MPD (2505 kg ha^{-1}). Similar findings were obtained by Franchini et al. (2012) in a long term experiment (23 years) in a clayey Oxisol (Rhodic Eutrudox in the USA classification) in Londrina (Paraná State, Brazil), whose soybean yields

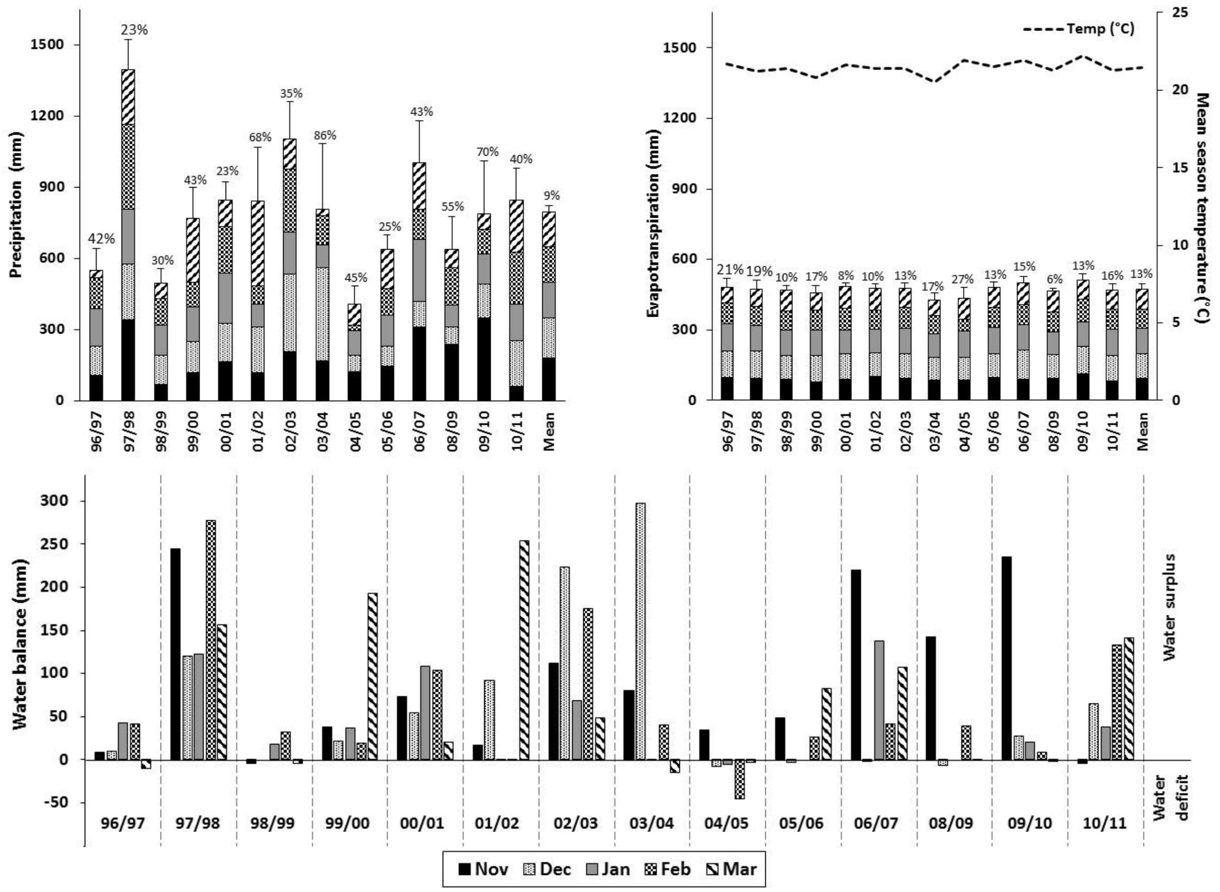

Fig 1. Precipitation, real evapotranspiration, mean season temperature (November-March) and water balance (Thornthwaite & Mather, 1955) in the crop seasons from 1996/1997 to 2010/2011, in Passo Fundo, Brazil. The vertical bars and percentage values above the columns represent, respectively, the standard deviation and the coefficient of variation of monthly rainfall and evapotranspiration during each soybean crop season.

averaged 36 % higher in the NT compared with the DPD in 15 crop seasons but did not differ significantly in eight other crops. Comparing these 23 crops, these authors found that the soybean yield in NT was 23 % higher compared with the DPD. Pedersen and Lauer (2003), in a long-term experiment (seven crop seasons) on a Typic Argiudoll (silt loam soil) in Arlington (Wisconsin, USA), obtained an average soybean yield that was 8 % higher in NT compared to conventional tillage (chisel plow in fall and two passes of field cultivation in spring before planting) for the last five crop seasons, with no significant difference between treatments in the first two crops after the experiment establishment. Archer and Reicosky (2009) did not obtain significant differences in the grain yield between NT and other mechanized tillage systems in a long-term experiment with seven soybean crops near Morris (Minnesota, USA), whose economic analysis showed that the NT was the best alternative due to the lower cost and benefits for soil conservation. The results from Watts and Torbert (2011) showed varying responses of soybean yields in a long-term experiment (nine growing seasons) in a sandy-clayey soil in Crossville (northeastern Alabama, USA), whereas NT achieved higher crop productivity in two seasons (1997 and 2001) and MPD provided higher yield in two others harvests (1992 and 1994), with no difference between the treatments in the other crop seasons. However, contradictory outcomes were obtained by Messiga et al. (2012) in a long-term study (eight crop seasons), in a clay loam soil with low drainage (Dark Gray Gleysol) at the L'Acadie Research Station near Montreal (Quebec, Canada). The findings of these authors showed that the soybean yields in six crop seasons were on average 15 % lower in NT than in MPD. Furthermore, there are no differences between the treatments in the other two crops of their experiment. These foregoing results from long-term experiments confirm the statement of Archer and Reicosky (2009), who report on the influence of the soil type and climatic conditions on the economic performance and yield of soybean under NT. According to these authors, the best NT experimental results were obtained in well-drained soils and warmer climates (Al-Kaisi and Yin, 2004; Yin and Al-Kaisi, 2004; Pendell et al., 2006), and the worst performances were observed in poorly drained soils and colder climates (Chase and Duffy, 1991; Yiridoe et al., 2000; Al-Kaisi and Yin, 2004; Yin and al-Kaisi, 2004). Lal (2007) also argues that NT has the further restrictions under colder weather during the crop season, with sub-optimal soil temperatures, and in poorly drained and heavy soils (with a high clay content). The variability of the results from these studies, in different types of soils and climatic conditions, demonstrates that long-term experiments are essential for assessing the cumulative effects of soil management systems on the soybean yield, as emphasized by Pauletti et al. (2003).

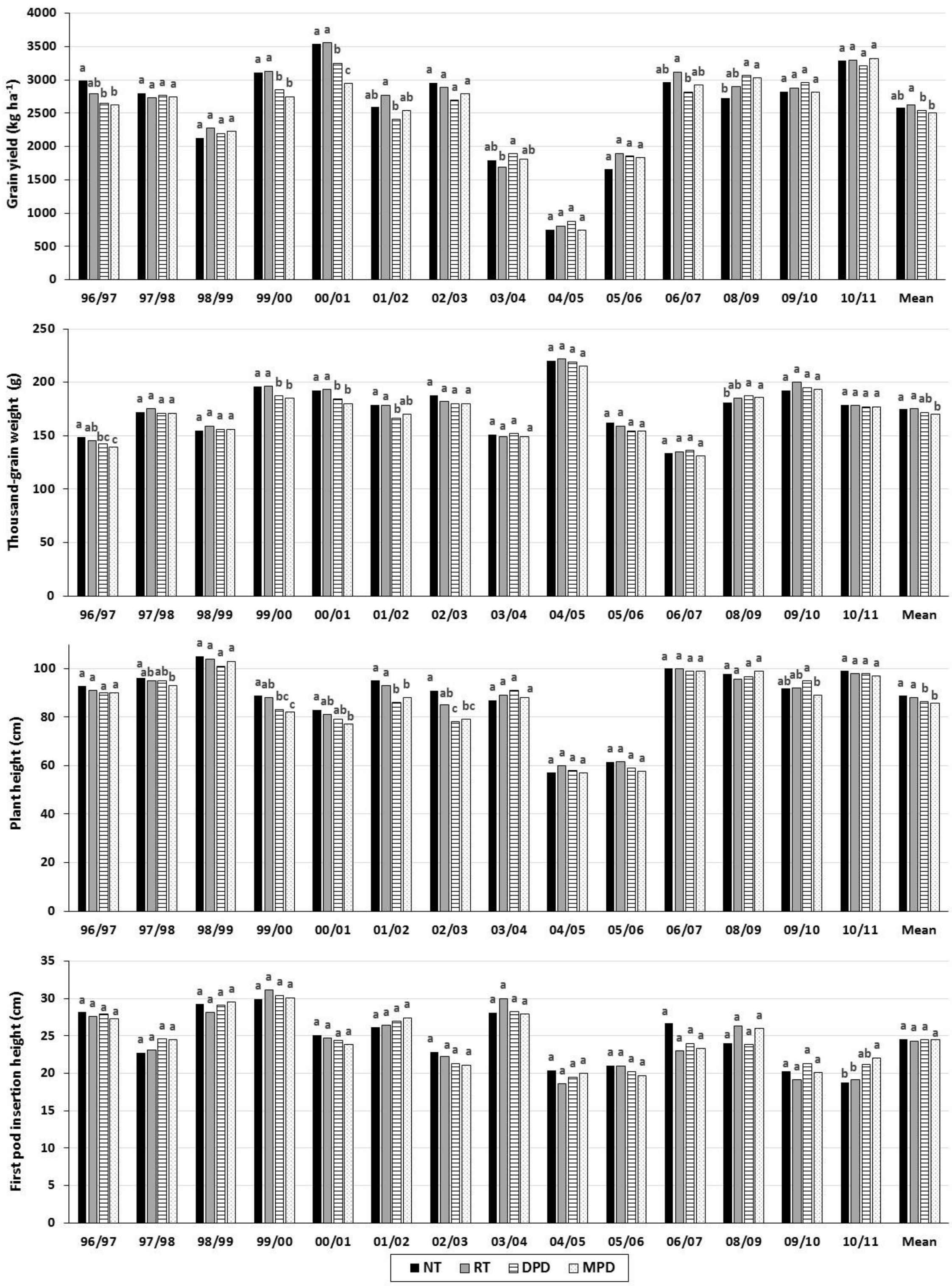

Fig 2. Grain yield, thousand-grain weight, plant height and first pod insertion height of soybean plants according to long-term soil management systems (crop seasons 1996/1997 to 2010/2011), in an Oxisol of Passo Fundo, Brazil. NT, no-tillage; RT, reduced-tillage; DPD, disk plowing + disking; MPD, moldboard plowing + disking. For each crop season, similar letters on top of the columns indicate statistically equal values among soil management systems (Tukey test, $P \geq 0.05$).

The global analysis of the results reveals that conservation systems (NT and RT) provided, in the majority of cases, soybean yields that were similar to or higher than conventional tillage systems (DPD and MPD), particularly in well-drained soils and warmer climates, as in Brazil. Therefore, farmers who adopt NT have the opportunity to increase profitability due to similar or higher soybean yields and to lower production costs by reducing some mechanized operations (fuel, machinery maintenance, and manpower economy), as emphasized by Dickey et al. (1994). In addition, the NT system has other benefits compared to mechanized tillage systems, such as improving soil and water conservation by reducing erosion, improving soil water retention (Alvarez and Steinbach, 2009; Putte et al., 2010; Jin

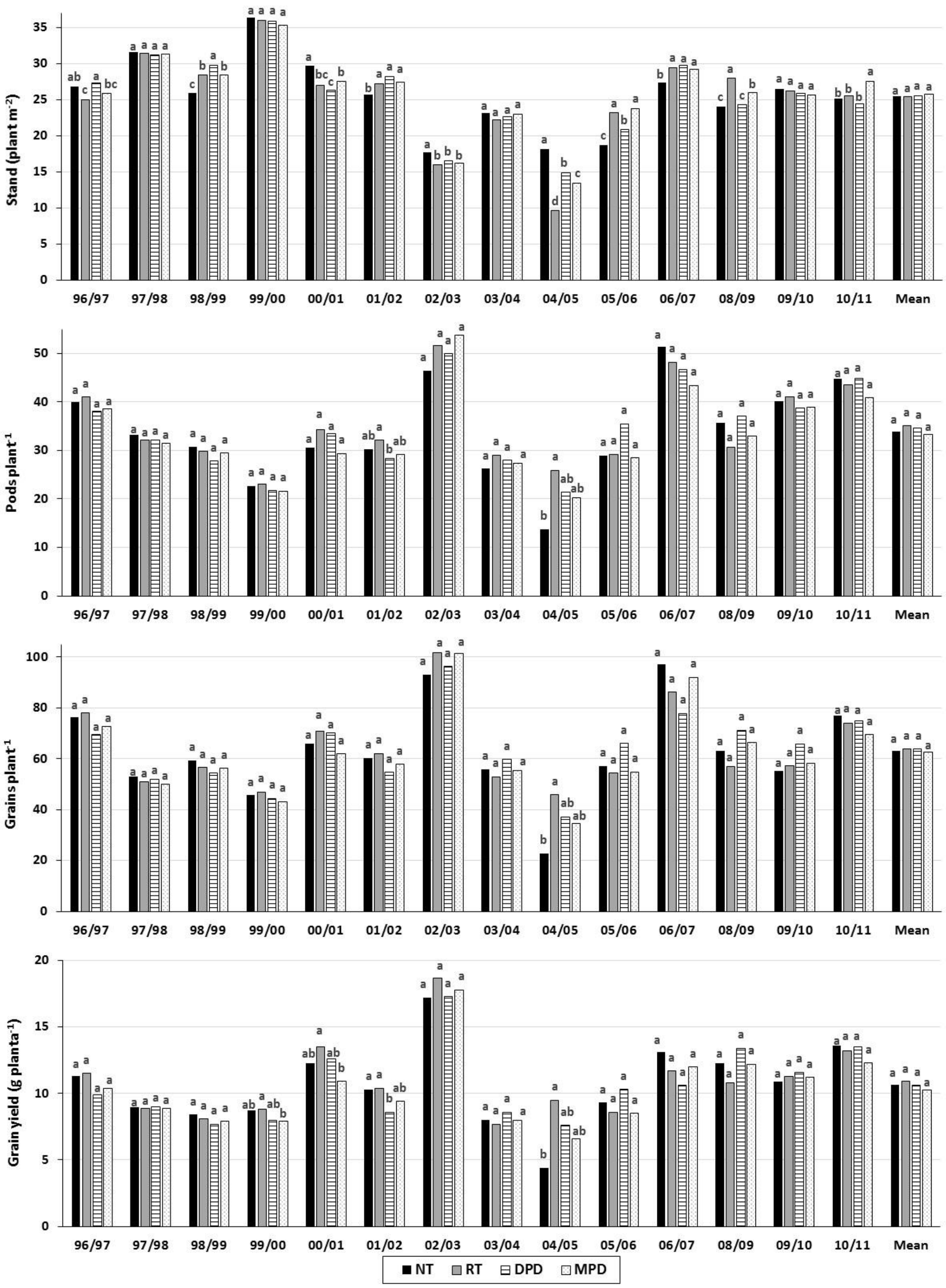

Fig 3. Soybean plant stand and yield components (the number of pods per plant, the number of grains per plant, and the grain yield per plant) according to long-term soil management systems (crop seasons 1996/1997 to 2010/2011), in an Oxisol of Passo Fundo, Brazil. NT, no-tillage; RT, reduced-tillage; DPD, disk plowing + disking; MPD, moldboard plowing + disking. For each crop season, similar letters on top of the columns indicate statistically equal values among soil management systems (Tukey test, $P \geq 0.05$).

et al., 2011), increasing soil organic carbon (Bhattacharyya et al., 2009; Babujia et al., 2010), and reducing the time that is required between the rainfall and the mechanized seeding procedure (Franchini et al., 2012).

Soybean agronomic characteristics as affected by soil management systems

The average thousand-grain weight and plant height of soybean plants in 14-crop season were, respectively, 2.3 and 3.5 % higher in conservation systems (NT and RT) compared to conventional tillage systems (DPD and MPD) and were significantly higher in only two crops (1999/2000 and 2000/2001), showing similar values in nine and eight crop seasons, respectively (Fig 2). In turn, the first pod insertion height of the soybean plants did not differ among the treatments in 13 of the 14 crop seasons that were analyzed (Fig 2). Therefore, these three agronomic characteristics were poorly sensitive to the soil management systems, and only the plant height showed a good correlation (R^2 = 0.64) with the soybean crop yield. Lança-Rodrigues et al. (2009) obtained distinct results in a short-term experiment (one crop season) in Botucatu (São Paulo State, Brazil), in which the soybean plant height was similar in all of the soil tillage systems (NT, RT and DPD). However, the thousand-grain weight and the first pod insertion height of the soybean plants were higher in the NT and DPD systems compared to RT. Lopes et al. (2007) reported a greater plant height and first pod insertion height of soybean plants that were cultivated in NT compared to conventional tillage (plowing plus disking). However, these researchers found no significant difference between treatments in the thousand-grain weight or grain yield. The three soybean yield components (the number of pods per plant, the number of grains per plant, and the grain yield per plant) showed similar values in all of the treatments in 12, 13 and 10 crops, respectively (Fig 3). In the 2004/2005 crop season (which was the most affected by the drought season), these three yield components were lower in NT compared to RT, though this pattern did not differentiate the grain yield between treatments, due to higher plant survival (higher plant stand) in the NT system (Fig 3). Reduced-tillage had a higher grain yield per plant in the 1999/2000 and 2000/2001 crop seasons compared with that observed in the MPD, and the conservation systems (NT and RT) were better in this attribute in relation to DPD in the 2001/2002 crop. Other experiments obtained fewer pods per plant in NT compared to RT and DPD (Lança-Rodrigues et al., 2009) and conventional tillage with plowing and harrowing (Lopes et al., 2007). However, these differences did not affect the soybean yield, which was similar among the treatments.

Materials and methods

Site description

The long-term field experiment was set up at Embrapa Trigo (National Wheat Research Center from the Brazilian Agricultural Research Corporation), in the Passo Fundo county (28º15’ S, 52º24’ W; altitude of 678 m a.s.l.), Rio Grande do Sul State, southern Brazil, during the growing seasons from 1996/1997 to 2010/2011 (Note: the 2007/2008 crop was damaged by hail precipitation; therefore, its results will not be considered in this work). The soil of this field was a loamy Oxisol (Latossolo Vermelho distrófico in the Brazilian Soil Classification System), with clay, silt and sand in the surface layer (0-0.20 m) of 720, 130 and 150 g kg^{-1}, respectively. The climate in the area, according to the Köppen climate classification (Koeppen, 1931), is humid subtropical (Cfa), with a mean annual temperature of 17.7 °C; a mean maximum temperature of 28.3 °C in January; and a mean minimum temperature of 8.9 °C in June and July). The mean annual precipitation is 1803 mm, with a mean of 198 mm in September (the wettest month) and 100 mm in April (the driest month).

Experimental design, treatments and plant materials

The experiment was carried out in randomized complete block design with three replications. The treatments, which were set up annually in the same area, consisted of four soil management systems (SMS): (1) permanent no-tillage (NT) in all seasons; (2) reduced-tillage (RT) with chisel plough (equipped with shanks that were spaced by 0.30 m, down to a 0.25 m depth) in winter and NT in summer; (3) disk plowing + disking (DPD) in winter and NT in summer; and (4) moldboard plowing + disking (MPD) in winter and NT in summer. Each experimental plot, with measures 4 m in width × 90 m in length (360 m^2), was divided into three parts (4 m × 30 m) for the application of three crop systems: (1) permanent monoculture of soybean [*Glycine max* (L.) Merril] in summer and wheat [*Triticum aestivum* (L.)] in winter (soybean/wheat); (2) crop rotation system, alternating soybean with corn [*Zea mays* (L.)] (1996-2002) or sorghum [*Sorghum bicolor* (L.) Moench] (2003-2010) in summer (odd seasons: wheat/soybean; even seasons: corn or vetch [*Vicia sativa* (L.)]/sorghum; (3) crop rotation system with two subsequent summers with soybean, followed by a summer with corn (1996-2002) or sorghum (2003-2010) (season 1: wheat/soybean; season 2: oat [*Avena sativa* (L.)]/soybean; season 3: vetch/corn or sorghum). The soybean results from these three crop systems were joined in the corresponding soil management system to be discussed in this paper, in order to focus on soil tillage effects on soybean productivity, topic considered most relevant by the authors, since it was necessary to choose only one study factor (soil management system or crop rotation system) due to statistic issues, as it will be explained in the topic “statistical analyses”. Soybean was sown in November of every crop season, and the cultivars that were used were: BR-16 (1996/1997 and 1997/1998), BRS 137 (1998/1999 and 1999/2000), BRS 154 (2000/2001-2003/2004), BRS 153 (2004/2005), BRS 244 RR (2005/2006), BRS Charrua RR (2006/2007), BRS 255 RR (2007/2008-2009/2010), and BRS Tertulia RR (2010/2011). The row spacing was 0.45 m, and the plant density was according to the recommendation for each cultivar. The fertilizers were applied according to the indications for the winter and summer crops and based on the results of the soil analysis. The sowing and management of the crops, and the weed, pest and disease controls were performed in accordance with regional technical indications for their crops.

Plant sampling

The yield was determined by harvesting soybean plants at maturity at 10 m in length of three center rows that were spaced 0.45 m (13.5 m^2) from each plot and recording the grain weight after adjusting the moisture content to 13 %. This sample was used to calculate the thousand-grain weight.

For agronomic characteristic evaluations, the plants were harvested at maturity at 2 m in length of a row from each plot. Among the recorded data were plant height, first pod insertion height, plant stand, and soybean yield components (the number of pods per plant, the number of grains per plant, and the grain yield per plant), which were evaluated at crop maturity.

Statistical analyses

The data were analyzed by the GENES® system (Federal University of Viçosa; Viçosa county, Minas Gerais State, Brazil), which is designed for PC statistical packages (Cruz, 2013). The ANOVA was performed separately for each harvest season. A combined statistical analysis considering jointly all of the growing seasons was also performed. When the ANOVA resulted in a significant *P* value ($P \leq 0.05$), the Tukey test was used for multiple comparisons of the treatments means ($P \geq 0.05$). It was necessary to choose one of the study factors (soil management system or crop rotation system), since the statistical analysis did not allow unfold the analysis for both effects, due to high unbalance of the experimental design that could be accounted – in part – to the number of data collected in crop rotation system in last level was three times the first one. In this way, the data was not suitable for neither analysis with time series error structure nor ANOVA with no error structure correction due to possible autocorrelation effect when both study factors was present.

Conclusions

The evaluation of the grain yield results over time demonstrates that the variation in the weather conditions, particularly those that affect soil water availability and promote water stress, is the primary determinant of the soybean crop yield. During the 14 successive crops, conservation systems provided grain yield and plant agronomic characteristics that were similar or significantly better than conventional tillage, in the majority of the cropping seasons. These findings demonstrate that NT and RT are suitable methods in environmental and economic terms, particularly NT, because it has lower production costs by reducing some mechanized operations. The soybean agronomic characteristics [plant height, first pod insertion height, plant stand, and yield components (the number of pods per plant, the number of grains per plant, and the grain yield per plant)] were not sensitive to soil management systems in most cases; thus, these evaluations are not considered to have potential to assess the effects of tillage systems on the soybean crop yield.

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