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SISTEMAS DE IMPLANTAÇÃO DE SOJA EM ÁREAS DE ARROZ IRRIGADO E EFEITOS EM ATRIBUTOS FÍSICOS DO SOLO E EM CARACTERÍSTICAS AGRONÔMICAS E FISIOLÓGICAS DA PLANTA

Santa Maria, RS
2016

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Tese apresentada ao Curso de Pós-Graduação em Agronomia, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do título de **Doutor em Agronomia.**

Orientador: Profº Dr. Enio Marchesan

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RESUMO

SISTEMAS DE IMPLANTAÇÃO DE SOJA EM ÁREAS DE ARROZ IRRIGADO E EFEITOS EM ATRIBUTOS FÍSICOS DO SOLO E EM CARACTERÍSTICAS AGRONÔMICAS E FISIOLÓGICAS DA PLANTA

AUTOR: Gerson Meneghetti Sarzi Sartori
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As áreas de várzeas são predominantemente cultivadas com a cultura do arroz irrigado. No entanto, o monocultivo do arroz irrigado pode inviabilizar o uso dessas áreas para o cultivo do arroz. Uma alternativa para isso é o uso de rotação de culturas. A soja é uma cultura que pode ser utilizada em rotação com o arroz irrigado. Porém, em função de características dessas áreas como: drenagem deficiente, baixa condutividade hidráulica e presença de camada compactada próximo à superfície do solo, a produtividade da soja é usualmente limitada principalmente em anos de estresse hídrico. Diante disso, o objetivo de estudo da tese foi avaliar o efeito de sistemas de implantação e de semeadura da soja e da irrigação por faixas em propriedades físicas do solo, no crescimento e desenvolvimento radicular, no estresse oxidativo das plantas, na concentração de nutrientes no tecido das plantas e no rendimento de grãos de soja. Os experimentos foram realizados na área Experimental de Várzea da Universidade Federal de Santa Maria, RS, nas safras de 2013/14 e de 2014/15, e em Formigueiro, RS, na safra de 2013/14. Os níveis do fator A foram: sistemas de implantação e de semeadura: escarificação do solo com semeadura utilizando disco duplo na semeadora; sem escarificação do solo e semeadura em microcamalhão com haste sulcadora; semeadura com haste sulcadora; semeadura com disco ondulado e semeadura com disco duplo. Os níveis do fator D foram: com e sem irrigação por faixas. Com base nos resultados obtidos, observa-se que os sistemas com haste sulcadora, microcamalhão e com escarificação do solo reduzem a densidade do solo na camada de 0,00 – 0,20 m na linha de semeadura. Esses sistemas melhoram na linha de semeadura as propriedades físico-hídricas do solo como a densidade do solo, porosidade total, macroporosidade e capacidade de infiltração e armazenamento de água no solo. Os sistemas de implantação com semeadura utilizando disco duplo e disco ondulado apresentaram menor efeito de redução de densidade do solo na linha de semeadura e melhoria das propriedades físico-hídricas. A presença de uma camada compactada próximo a superfície do solo (camada de 0,07 – 0,15 m) causa estresse oxidativo nas plantas em épocas de déficit hídrico. O sistema com escarificação do solo e com semeadura utilizando haste sulcadora minimizam esses estresses e proporcionam maior crescimento e desenvolvimento de raízes de soja, nodulação, bem como maior rendimento de grãos. O uso da irrigação por faixas em condições de umidade do solo abaixo de 60% da capacidade de campo resulta em redução do estresse oxidativo, aumento do crescimento e desenvolvimento de raízes, proporcionando acréscimo na nodulação e no rendimento de grãos de soja em áreas com presença de camada compactada próximo a superfície do solo.

Palavras-chave: *Glycine max*. Escarificação do solo. Camada compactada. Mecanismos da semeadora. Rotação de culturas.

ABSTRACT

SOYBEAN TILLAGE SYSTEMS IN LOWLAND AREAS AND EFFECTS ON SOIL PHYSICAL CHARACTERISTICS AND PLANT AGRONOMIC AND PHYSIOLOGICAL RESPONSES

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The lowland areas are predominantly cultivated with irrigated rice. However, the monoculture of rice can to complicate the use of these areas for rice crop. An alternative to this is the use of crop rotation. The crop that may be used in rotation with rice is the soybean. But, some lowland areas present poor drainage, low hydraulic conductivity and compacted layer present in the soil sub-surface, soybean yield is usually limited especially in drought years. Thus, the objective this study was to evaluate the effect of tillage systems and soybean sowing and border irrigation on soil physical and hydraulic properties, oxidative stress in the leaf tissue of plants, root growth and development, nutrients content in leaf tissue of plants and soybeans yield. The experiments were performed in the Experimental Area of the Federal University of Santa Maria, during 2013/14 and 2014/15 growing season in Santa Maria-RS, Brazil and during 2013/14 growing season in Formigueiro, RS. Levels of factor A were: tillage and seeding systems: chisel plough with sowing using a offset double disc; no-till with sowing using a furrow opener upon a raised bed; sowing using a knife runner opener; sowing using a (fluted coulter disc) wavy disc with 12 waves and sowing using a offset double disc. The D factor levels were: irrigated and non-irrigated. The results showed that systems with sowing using knife, sowing on raised bed and chisel plough reduce soil bulk density in the layer from 0.00 to 0.20 m in the sowing row. These systems improve in the soil physical and hydraulic properties such as soil bulk density, total porosity, macroporosity and infiltration capacity and water storage in the soil. Tillage systems with sowing using offset double disc and (fluted coulter disc) wavy disc has less effect of soil bulk density reduction in the soybean sowing row and improvement of soil physical and hydraulic properties. The presence of a compacted layer in the soil sub-surface (layer from 0.07 to 0.15 m) causes oxidative stress in plants in drought seasons. The system using chisel plough and sowing using knife minimize those stresses and provide greater soybean roots growth and development, nodulation and higher grain yield. The border irrigation on soil moisture conditions below 60% of field capacity results in reduced oxidative stress, increased of roots growth and development, providing increase in nodulation and soybeans yield in areas with presence compacted layer in the soil sub-surface.

Keywords: *Glycine max*. Deep tillage. Compacted layer. Planter mechanism. Crop rotation.

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SUMÁRIO

1 INTRODUÇÃO

As áreas de várzea do Estado do Rio Grande do Sul são predominantemente utilizadas para a cultura do arroz irrigado. Anualmente, mais de 1 milhão de hectares são utilizados para o cultivo dessa cultura. No entanto, a maioria das áreas que anualmente são cultivadas com a cultura do arroz irrigado contém infestação elevada de plantas daninhas, algumas delas de difícil controle, como o arroz-vermelho, o capim arroz e as ciperáceas, por apresentarem algum grau de resistência aos herbicidas do grupo químico inibidores da enzima Aceto Lactato Sintase.

A cultura da soja, por não pertencer à mesma família de plantas do arroz, permite a utilização de herbicidas com mecanismo de ação diferente daqueles utilizados no arroz. Em função disso, a soja vem sendo introduzida em algumas dessas áreas como alternativa de rotação de culturas e de controle dessas plantas daninhas de difícil controle, além de contribuir na diversificação de renda na propriedade rural.

No entanto, a maioria das áreas de várzeas e/ou cultivadas com o arroz irrigado pertence à classe Planossolos. Uma característica desses solos é a drenagem deficiente devido a baixa permeabilidade. Além disso, em função das operações de preparo e de nivelamento superficial das áreas para a implantação do arroz, parte dessas áreas apresenta presença de camada compactada próximo à superfície do solo. A camada compactada ocorre devido elevação da densidade do solo, redução na quantidade de macroporos, na porosidade total, interferindo nas relações solo-ar-água. Com isso, principalmente em anos de déficit e excesso hídrico, as plantas de soja podem ser submetidas a condições de estresse com efeito severo no crescimento e no desenvolvimento do sistema radicular, na nodulação, na concentração de nutrientes no tecido, no crescimento das plantas, podendo afetar o rendimento de grãos.

Diante disso, é preciso realizar adequação das áreas com objetivo de minimizar os estresses que podem ocorrer, principalmente na região do sistema radicular, para que a utilização da soja como uma alternativa de rotação de culturas nas áreas de várzeas possa ser uma prática sustentável.

Com isso, há necessidade de conhecer o efeito de sistemas de implantação e de semeadura da soja como uso do sistema com escarificação do solo, sistema em microcamalhão, semeadura com haste sulcadora, com disco ondulado e duplo. Além de conhecer o efeito do uso da irrigação por faixas nessas áreas em épocas de déficit hídrico visando buscar maior potencial de rendimento de grãos.

A hipótese é que os sistemas de implantação com escarificação do solo e uso da haste sulcadora na semeadora são eficientes na “descompactação” do solo na linha de semeadura de soja, proporcionando maior crescimento das raízes, nodulação e rendimento de grãos de soja. E que a irrigação minimiza os estresses oxidativos e aumenta a nodulação e o rendimento de grãos de soja.

Assim, o objetivo geral da tese foi estudar o efeito da escarificação do solo, do uso do microcamalhão, da semeadura utilizando diferentes mecanismos sulcadores (haste sulcadora, disco ondulado e disco duplo) e da irrigação por faixas nas propriedades físico-hídricas do solo, no estresse oxidativo no tecido foliar das plantas, no crescimento e desenvolvimento radicular, na concentração de nutrientes no tecido foliar das plantas e no rendimento de grãos de soja.

2 REFERENCIAL TEÓRICO

As áreas de várzeas no Rio Grande do Sul (RS) ocupam área de 5.400.000 ha (PINTO et al., 1999). Dentre as classes de solo, os Planossolos predominam nessas áreas, representando, aproximadamente, 3.000.000 de ha (BAMBERG et al., 2009). Esses solos são imperfeitamente ou mal drenados, com horizonte superficial ou subsuperficial eluvial, de textura mais leve, contrastando abruptamente com o horizonte B, ou com transição abrupta conjugada com acentuada diferença de textura do horizonte A para o B, adensado, geralmente com elevada concentração de argila, e de permeabilidade lenta ou muito lenta.

Em áreas de várzeas, em condições de clima úmido, esses solos são considerados hidromórficos, com horizonte plânico, apresentando características de horizonte glei (EMBRAPA, 2013). Pelas suas características físicas e localização geográfica, os solos hidromórficos apresentam restrições de drenagem (MARCHEZAN et al., 2002), características que favorecem o cultivo do arroz irrigado, sendo cultivados anualmente mais de um milhão de hectares. As áreas que anualmente são cultivadas com a cultura do arroz irrigado são altamente infestadas com plantas daninhas, algumas delas de difícil controle, como o arroz-vermelho, o capim arroz e as ciperáceas, limitando a produtividade de grãos.

A rotação de culturas em solos de várzeas é uma prática indicada para aumentar a produtividade de grãos de arroz (THOMAS et al., 2000). A cultura da soja pode ser uma alternativa de cultivo viável (THOMAS et al., 2000; MISSIO et al., 2010). Como alternativa de rotação de culturas, pode quebrar o ciclo de doenças, insetos-praga e proporcionar indiretamente melhoria das condições físicas e químicas do solo (THOMAS et al., 2000), além de possibilitar a utilização de herbicidas com mecanismos de ação diferentes daqueles utilizados em arroz.

A soja consegue desenvolver mecanismos que permitem, em parte, superar as restrições impostas pela hipoxia que normalmente ocorre em solos de várzeas (THOMAS et al., 2000). Os mecanismos incluem a formação de raízes adventícias e hipertrofia do caule (FANTE et al., 2010), e rachaduras no caule, o que indica a formação de aerênquima (SCHOLLES & VARGAS, 2004). Na safra 2009/10, o cultivo da soja nessas áreas foi em aproximadamente 11.100 ha, ultrapassando a 280.000 ha na safra de 2014/15 (IRGA, 2016). No entanto, a produtividade média não ultrapassou aos 2400 kg ha^{-1} (IRGA, 2016).

Nas áreas de várzeas em que é realizada a sistematização para o cultivo do arroz irrigado, há alterações nas propriedades químicas do solo (MARCHEZAN et al., 2002), bem como aumento da densidade do solo, devido ao intenso tráfego de máquinas (NUNES et al., 2002; PARFITT et al., 2014). Além disso, há aumento dos valores de resistência mecânica do solo à penetração, principalmente na camada de 0,10 a 0,20 m, devido ao sistema de manejo para o arroz irrigado (PEDROTTI et al., 2001). Em função do aumento da densidade do solo, muitas áreas de várzeas possuem camada compactada próxima à superfície do solo, o qual influencia a porosidade total e a macroporosidade do solo (DRESCHER et al., 2011).

Diante disso, quando são cultivadas culturas de sequeiro nesses solos, a exemplo da soja, observa-se dificuldades no crescimento e no desenvolvimento das plantas (BAMBERG et al., 2009). A presença dessa camada compactada próxima à superfície do solo favorece a predisposição das plantas a estresses tanto pelo excesso como déficit hídrico, podendo ocorrer formação elevada de espécies reativas de oxigênio (EROs), tais como, radical anion superóxido, peróxido de hidrogênio e radical hidroxil (VASCONCELOS et al., 2009). As EROs são altamente reativas e tóxicas à célula, podendo causar danos às proteínas, aos lipídios, aos carboidratos e ao DNA (GILL& TUTEJA, 2010). O estresse induzido pelo acúmulo de EROs pode ser minimizado pelo sistema de defesa antioxidante presente na célula vegetal, podendo ser enzimático ou não-enzimático.

A cultura da soja, por ser uma leguminosa, apresenta grande demanda de nutrientes, especialmente o nitrogênio, sendo este extraído predominantemente através da fixação biológica por bactérias fixadoras *(Bradyrhizobium japonicum e Bradyrhizobium elkanii)* (BRANDELERO et al., 2009). A fixação biológica de nitrogênio pelas bactérias simbióticas em associação com leguminosas desempenha um papel essencial no fornecimento de nitrogênio para as plantas (SICZEK & LIPIEC, 2011). Os processos que envolvem a fixação biológica de nitrogênio na cultura da soja apresentam diversas interações entre a planta e a bactéria fixadora, sendo a eficiência controlada por fatores internos, tais como sinais químicos e hormonais, e externos, como o conteúdo de água no solo e aeração (SICZEK & LIPIEC, 2011).

No entanto, o excesso hídrico no solo, que é um fator resultante principalmente de solos compactados ou com deficiência de drenagem (LANZA et al., 2013), resulta em falta de oxigênio no sistema radicular das plantas de soja. Com isso, pode haver inibição da fixação biológica de nitrogênio (FANTE et al., 2010). Isso se deve principalmente à concentração limitada de oxigênio (AMARANTE & SODEK, 2006), que se torna insuficiente para manter a taxa normal de respiração das raízes (LANZA et al., 2013). Além do excesso hídrico, a camada compactada favorece a ocorrência de déficit hídrico em períodos de falta de chuvas, prejudicando a fixação de nitrogênio, que é um processo metabólico muito sensível à falta de água (GIL-QUINTANA et al., 2013; KING et al., 2014). Sendo assim, a presença da camada compactada no solo contribui para a formação de excesso e déficit hídrico, tornando-se importante controlar adequadamente o conteúdo de água no solo, pois ambos os fatores podem interferir na nodulação e na fixação de nitrogênio e no rendimento de grãos de soja, que está correlacionado em mais de 40% com a nodulação (BRANDELERO et al., 2009).

Dessa forma, estudo de alternativas de manejo do solo são importantes para que o desempenho agronômico da soja cultivada em áreas de várzea onde há a presença de uma camada compactada, não se seja prejudicado. A escarificação do solo, o sistema em microcamalhão ou o uso de diferentes mecanismos da semeadora, durante a operação de semeadura, a exemplo do disco duplo desencontrado, disco ondulado, haste sulcadora, entre outros mecanismos, utilizados na abertura do sulco para distribuição dos fertilizantes, podem influenciar nas características físicas do solo, reduzindo a camada adensada nessa região. Nesse sentido, o emprego de semeadoras equipadas com haste sulcadora associado ao disco de corte tem sido uma alternativa para a descompactação do solo (DRESCHER et al., 2011), pois influencia o microambiente próximo a semente (REIS et al., 2004), refletindo-se na emergência das plântulas e no teor de água no solo (KOAKOSKI et al., 2006). Esse efeito pode estar atrelado à maior profundidade do sulco causada pela haste sulcadora (VERUSCHKA et al., 2006). Em estudo realizado por Koakoski et al. (2007), avaliando dois mecanismos rompedores do solo, encontraram que mecanismo rompedor tipo facão proporcionou maior porosidade do solo e menor resistência à penetração. Drescher et al. (2011) encontraram que o mecanismo facão somado aos discos de rompimento do solo foram efetivos em aumentar a macroporosidade, diminuir a microporosidade e a densidade do solo, mitigando a compactação do solo especificamente onde cresceram as raízes. Segundo Pivetta et al. (2011) os implementos com hastes são os mais adequados para descompactação do solo.

Outra alternativa de manejo que pode minimizar parte dos efeitos causados pela camada compactada do solo, em períodos de déficit hídrico, é a irrigação (KIRNAK et al., 2013). O estresse hídrico pode causar redução do potencial hídrico foliar, fechamento estomático, diminuição da taxa fotossintética, redução da parte aérea, aceleração da senescência e abscisão das folhas (FERRARI et al., 2015), sendo a água um dos principais fatores que afeta o rendimento de grãos de soja (FERNANDES & TURCO, 2003).

3 DESENVOLVIMENTO

3.1 ARTIGO 1

Different Soybean Tillage Systems and Physical Changes in the Surface Layers of Two Albaqualf Soils

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ABSTRACT

A compacted subsurface soil layer can be a limiting factor for soybean growing, reducing soybean yield. The aim of this study was to evaluate the effect of different tillage systems on the physical characteristics of two Albaqualf soils of the Central Plains region in the state of Rio Grande do Sul in southern Brazil. Two experiments were conducted in Albaqualf soils: one in Santa Maria, RS, during the 2013/14 and 2014/15 crop seasons, and another in Formigueiro, RS, during the 2013/14 crop season. A randomized block experimental design with four replications was used. The treatments were: sowing using a offset double disc (T1); sowing using a (fluted coulter disc) wavy disc with 12 waves (T2); sowing with a knife runner opener (T3); sowing with a knife runner opener + press wheel mechanism for ground levelling (T4); sowing using a furrow opener upon a raised bed (T5); chisel plough + sowing using a offset double-disc (T6). In the 2014/15 growing season, the T4 factor was changed using a knife runner opener 0.05 m from the planting row. A smaller reduction in the compacted subsurface soil layer was observed for both T1 and T2, which exhibited high soil bulk density values for the 2013/14 and 2014/15 crop seasons. Furthermore, T3, T5 and T6 led to a reduction in bulk density and increasing total porosity, macroporosity in the soil, and grain yield, which consequently increased water infiltration, water storage capacity, and crop yield in areas with the presence of a compacted subsurface soil layer.

Keywords: compacted layer, deep tillage, raised bed, planter mechanism.

INTRODUCTION

An increase in cultivation of soybean in rotation with rice has been observed in recent crop seasons in lowland areas. This increase can be explained by the presence of weeds difficult to control in rice cropping areas, and by the need for rural income diversification. The use of crop rotation also indirectly improves physical and chemical soil conditions (Thomas et al., 2000). The predominant soil class in lowlands of Rio Grande do Sul is Albaqualf (Bamberg et al., 2009) formed inhydromorphic environment (Borges et al., 2004) with limited water drainage (Marchezan et al., 2002). When Albaqualf soils are cultivated with rainfed crops, as is the case of soybeans, plant growth and development may be hindered, mainly due to their naturally unfavorable physical conditions (Bamberg et al., 2009).

During the systematization process of land areas for irrigated rice, compacted soil layers can be found near the surface (Nunes et al., 2002; Reichert et al., 2008). Soil compaction is a major cause of physical degradation of agricultural soils (Mazurana et al., 2013), which indirectly it influences infiltration, hydraulic conductivity, temperature, and aeration of the soil (Borges et al., 2004). The effects of soil compaction on aeration can be evaluated by the amount of macropores (Valicheski et al., 2012). Soil compaction is manifested by increased bulk density and reduction in total porosity and macroporosity of the soil (Drescher et al., 2011), along with increased resistance to penetration (Spera et al., 2012). A study conducted by Mentges et al. (2013), evaluating hydro-physical and mechanical changes in the soil after eight years of rice crops grown in a conventional tillage system, found an increase in bulk density and a decrease in total porosity and macroporosity.

A compacted soil layer reduces the water infiltration rate (Bonini et al., 2011) and decreases the least limiting water range in the soil profile (Kaiser et al., 2009). Furthermore, water availability to plants can be reduced as the soil structure is one of factors which directly influence water availability to crops by determining the arrangement of soil particles and therefore the distribution of pore diameters (Klein and Libardi, 2000). Soil compaction increases water retention but reduces water availability to plants.

Soybean producing areas may be adversely affected after years of stress from either lack or excess of water because both retention and availability of water can affect plant growth and yield (Costa et al., 2013) by affecting water uptake by plants (Carlesso, 1995). The study of management practices that improve the hydro-physical properties of the soil becomes essential to optimize soybean cultivation in such areas. Hypothesis this work is that sowing with a knife runner opener, sowing using a furrow opener upon a raised bed and chisel plough + sowing using a offset double disc improving soil physical quality.

Thus, the aim of this study was to evaluate the effect of different soybean tillage systems on the physical characteristics of the subsurface layer of two Albaqualf (Planossolos) soils of the Central Plains region in the state of Rio Grande do Sul in Brazil.

MATERIALS AND METHODS

Two experiments were performed: Experiment 1 during the 2013/14 and 2014/15 crop season and Experiment 2 during the 2013/14 crop season. Experiment 1 was carried out in the experimental lowland area of the Phytotechnology and Plant Science Department of the Federal University of Santa Maria (Universidade Federal de Santa Maria - UFSM), Santa Maria, Rio Grande do Sul (RS), Brazil, in soil classified as an Albaqualf (Soil Survey Staff, 2014), or *Planossolo Háplico Eutrófico* (Santos et al., 2013). The soil of the surface layer where the experiment was conducted belongs to the silty loam textural class (Table 1). We found 245, 208, and 547 g kg^{-1} of clay, sand, and silt, respectively, in the center of the two layers, and the following chemical properties, at 60 days before sowing, in the 0.0-0.2 m layer: pH(H_2O) (1:1) 5.4; P 18 mg dm^{-3}; K 60 mg dm^{-3}; Ca^{2+} 5.3 cmol$_c$ dm^{-3}; Mg^{2+} 2.4 cmol$_c$ dm^{-3}, and organic matter (OM) 2.0 % for the 2013/14 crop season; and pH(H_2O) (1:1) 5.4, P 15.3 mg dm^{-3}, K 44 mg dm^{-3}, Ca^{2+} 8.3 cmol$_c$ dm^{-3}, Mg^{2+} 3.1 cmol$_c$ dm^{-3}; and OM 2.0 % for the 2014/15 crop season.

The 2013/14 crop season experiment was carried in an area which previously contained a soybean crop and the 2014/15 crop season experiment was carried out in an area which previously contained irrigated rice. After the preceding soybean and rice crops were harvested, the areas received 2.0 Mg ha^{-1} of lime and then disked and leveled. In the off-season, ryegrass was sown in the area, which was desiccated with glyphosate at rate of 960 g ha^{-1} a.i.. By the time the experiments were set up, practically no ryegrass remained.

A randomized block experimental design was used with four replications. The treatments were different soybean tillage systems (Figure 2): sowing using a offset double disc (T1); sowing using a (fluted coulter disc) wavy disc with 12 waves (T2); sowing with a knife runner opener (T3); sowing with a knife runner opener + press wheel mechanism for ground levelling (T4); sowing using a furrow opener upon a raised bed (T5); chisel plough + sowing using a offset double disc (T6). In the 2014/15 growing season, the T4 factor was changed using a knife runner opener 0.05 m from the planting row.

Experiment 2 was carried out in a non-systemized area with gently rolling topography in the neighboring municipality of Formigueiro in soil classified as an Albaqualf (Soil Survey Staff, 2014), or *Planossolo Háplico Eutrófico típico* (Santos et al., 2013). In this experiment, the clay, sand, and silt found in the soil in the center of the 0.0-0.1 and 0.1-0.2 m layers were 360, 252, and 387 g kg^{-1}, respectively, and the textural class was silty clay loam in both layers (Table 1). At 50 days prior to sowing, the 0.0-0.2 m layer had the following physical-chemical properties: pH(H_2O) (1: 1) 5.2, P 2.2 mg dm^{-3}, K = 112 mg dm^{-3}, Ca^{2+} 10.5 $cmol_c$ dm^{-3}, Mg^{2+} 8.0 $cmol_c$ dm^{-3}, and OM. 1.6 %.

Beef cattle were raised in the experimental area in the municipality of Formigueiro, and prior to the experiment the native pasture was desiccated with glyphosate at rate of 960 g ha^{-1} a.i.. A randomized block experimental design was used, with four replications. The treatments were the same as in Experiment 1 during the 2013/14 crop season, but without the raised bed system.

Chisel plough for Experiment 1 was performed at 45 and 19 days before sowing for the 2013/14 and 2014/15 crop season, respectively, in friable soil. For experiment 2, deep tillage was carried out at the time of sowing. Tillage depth in both experiments was about 0.25 m, and knife were spaced at a distance of 0.35 m. The knife runner opener the furrow opener upon a raised bed,, the offset double disc, and the fluted coulter disc (wavy disc with 12 waves) system had working depths of approximately 0.18, 0.12, 0.10, and 0.08 m, respectively. Sowing was carried out on November 7, 2013 and November 14, 2014, for Experiment 1. Due to a 245 mm rainfall two days after sowing during the 2013/14 crop season, reseeding took place on November 26, 2013. For experiment 2, sowing took place on

November 5, 2013. The soybean cultivar used for both experiments was BMX Tornado at a seed density of 26 seeds m^{-2} in rows spaced at 0.50 m.

Sowing of T1, T2, T3, T4, and T6 was carried out with a MF 407 planter, weighing approximately 2,210 kg. Raised bed seeding (T5) was performed with a KF 8/5 - A seeder, weighing approximately 3870 kg. The average seeding speed for experiments 1 and 2 was 3.3 and 3.5 km h^{-1}, respectively. At sowing the average water volume content in the soil was 26 m^3 and 34 m^3 in the 0.0-0.2 m layer for Experiment 1 and 2, respectively. The experimental units were 40 × 3 m and 60 × 3 m for experiments 1 and 2, respectively, with an area of 15 m^2 each.

The variables analyzed from the soil samples were soil bulk density (BD), total porosity (TP), microporosity (Micro), macroporosity (Macro), micropore/macropore ratio, degree of compaction (DC), water content retained at field capacity, available water, and maximum soil water storage. Evaluations were performed at 10 days prior to sowing during the V6 and R3 soybean growth stages in both experiments in the 2013/14 crop season, and during growth stage R3 in the 2014/15 season.

For soil analysis, soil samples were collected from the 0.0-0.1 and 0.1-0.2 m depth layers in the planting row using volumetric rings of 4.0 cm height and 4.8 cm diameter. After collection, soil samples were sent to the laboratory and analyzed using the volumetric ring technique associated with a table tension with a 0.60-m water column, following the techniques described by Donagema et al. (2011). We considered the water retained at field capacity of -10 kPa and the permanent wilting point at -1500 kPa. To determine water availability, the permanent wilting point was subtracted from the field capacity.

The degree of compaction (DC) was calculated using the following equation: $DC = (BD/BD_{ref}) \times 100$, which relates bulk density in the field (BD) to a reference density value restrictive to plant growth. Soil DC was calculated by using two strategies to estimate density reference, namely: BD_c LLWR = 1.83803 - 0.00078 × clay as proposed by Reichert et al. (2009) in which LLWR (Least Limiting Water Range) is zero, and BD_c LLWR = 1.77000 - 0.00063 × clay according to Jones (1983) when considering restriction to root growth.

Water infiltration capacity was also evaluated in Experiment 1 in the V6 and R7 crop stages for the 2013/14 and 2014/15 crop seasons, respectively. The evaluations were performed in the planting row using the double ring infiltrometer method. Readings were taken over a 3-h period, as proposed by Sato et al. (2012).

The results were subjected to the test of the assumptions of the mathematical model (normality and homogeneity of variances). Analysis of variance was performed using the F test and the means of the treatments, when significant, were compared by the Tukey test at 5 % probability.

RESULTS

Experiment 1

Soil physical properties at ten days before sowing (Table 2) indicated the presence of a more severely compacted soil layer at 0.1-0.2 m in both crop seasons (2013/14 and 2014/15). This can be inferred by the high values of bulk density (BD) and reduced values of total porosity (TP) and macropores compared to the 0.0-0.1 m layer. In this same layer, macro values indicate a restriction in aeration with values below 0.10 m^3 m^{-3}. Moreover, by comparing the density values observed with the reference values of density restrictive to plant and root growth (Table 2), these values are very close in the 0.1-0.2 m layer, which indicates a marked degree of compaction in this soil layer in both crop seasons. In the 0.1-0.2 m layer there were distinct responses arising from the different tillage systems in both crop seasons on the hydro-physical characteristics of the soil evaluated at different times after soybean seeding.

In the 2013/14 season (Table 3), soil water retention and availability, well as bulk density and microporosity were not significantly affected by the tillage systems at the V6 stage in the 0.0-0.1 m and 0.1-0.2 m layers. However, T1 (offset double disc system) exhibited lower TP and Macro, and a greater micropore/macropore ratio in the 0.0-0.1 m layer compared to the other systems. No difference was found for the variables evaluated in the 0.1-0.2 m layer.

Similar to observations in the V6 stage, in the R3 stage there was lower macroporosity (Macro) and TP and a greater micropore/macropore ratio in T1.. For soil water retention, in systems using a offset double-disc and a (double fluted-counter) wavy disc with 12 waves (T2), there was higher water retention compared to the shank and raised bed systems in the 0.0-0.1 m layer, without any differences in the 0.1-0.2 m layer. The fluted coulter disc (T2) and knife runner opener (T3) systems led to greater availability of water in the 0.0-0.1 and 0.1-0.2 m layer, respectively. For BD, there was no significant difference for the 0.1-0.2 m layer, where the highest densities were found in soil systems that used either offset double-disc or fluted coulter disc. Furthermore, low macropore values were found in depths up to 0.2 m in both systems; the highest macropore value was observed in the raised bed and knife runner opener system in the 0.0-0.1 and 0.1-0.2 m layers, respectively.

In the 2014/15 season (Table 4), the results were similar to those observed in the 2013/14 season. In the evaluation carried out during the R3 stage, there were no significant differences among the systems for water retention and availability, or for the quantity of micropores in the 0.0-0.1 and 0.1-0.2 m layers. Higher BD, lower TP, lower quantity of macropores, and higher micropore/macropore ratio were observed in both layers for the double disc system. Use of the knife runner opener near the planting row led to lower BD and greater TP in the 0.1-0.2 m layer, which is also the layer with the greatest amount of macropores in the deep tillage system.

Furthermore, the systems tested in this study influenced maximum water storage in the soil in the 0.0-0.2 m layer, and water infiltration capacity in both crop seasons. The offset double disc and the fluted coulter disc systems led to lower water storage capacity in the V6 and R3 stage (Figure 1a). In the knife runner opener , raised bed, and chisel plough systems, there was water storage capacity of 8, 9, and 6 mm, respectively, which is higher than the average of the double disc at V6, which was 11, 12, and 11 mm, respectively, which, in turn, was higher than the capacity of the offset double disc at R3. Similar results were found in the 2014/15 season (Figure 1c) in the evaluation at R3 in the knife runner opener, raised bed, and chisel plough systems, where the soil exhibited a water infiltration capacity of 12, 6, and 7 mm, which is higher than in the offset double disc system. Water infiltration capacity (Figure 1d) was highest for the chisel plough system, followed by the knife runner opener and raised bed systems (2013/14 season). These systems increased infiltration capacity by 97, 31, and 15 %, respectively, compared to the average of systems using offset double disc and fluted coulter disc. In the 2014/15 season, the increase was 173, 57, and 18 % for these same systems.

Overall, comparing the average values of all tillage systems in both seasons and evaluation periods with offset double disc values in the 0.0-0.1 m layer, there was an overall 10 % reduction in soil bulk density compared to the offset double disc system, as well as a 13 % increase in porosity and 76 % increase in soil macroporosity compared to the offset double disc.

In the 0.1-0.2 m layer, BD decreased by 11 % comparing the average of all systems with the offset double disc. In addition, there was an increase of 11 % in TP and 35 % in Macro in the average of all systems compared to the offset double disc.

As a result, the offset double disc had the lowest grain yield, with an average yield of 4082 and 3759 kg ha^{-1} in the 2013/14 and 2014/15 crop season, respectively, compared to the knife runner opener raised bed, and chisel plough systems, where the grain yield values were

4405, 4345 and 4484 kg ha^{-1} for the 2013/14 season, respectively, and 4327, 4013, and 4749 kg ha^{-1} for the 2014/15 season, respectively (Sartori et al., 2015).

Experiment 2

Soil physical properties (Table 2) also indicated the presence of compacted soil up to the depth of 0.2 m, which was more evident in the 0.0-0.1 m layer. Noteworthy is the high value of BD, over 1.6 Mg m^{-3}, and the low macroporosity, less than 0.05 m^{3} m^{-3}, in both layers. Moreover, in both layers evaluated (0.0-0.1 and 0.1-0.2 m), the density values observed were higher than the restrictive reference density values for plant and root growth (Table 2), which can also be observed by the degree of compaction (DC) higher than 100 %.

This experiment did not show any differences in soil water retention and availability and microporosity in the soil during the V6 stage (Table 5). During the same period of evaluation, there was a lower BD and micropore/macropore ratio for knife runner opener and chisel plough systems. Moreover, these systems led to an increase in Macro and TP compared to the offset double disc and fluted coulter disc systems in the 0.0-0.1 m layer. In the 0.1-0.2 m layer, the knife runner opener system caused the greatest reduction in BD and the micropore/macropore ratio, as well as increased TP and Macro of the soil. In stage R3, in both the 0.0-0.1 and 0.1-0.2 m layers, the offset double disc and fluted coulter disc systems showed the highest BD values and micropore/macropore ratio. In addition, these systems exhibited increased micropores in the 0.0-0.1 m layer. For the knife runner opener and chisel plough systems, there was a reduction in BD, an increase in TP and Macro, and a reduction in the micropore/macropore ratio.

Furthermore, the shank and deep tillage systems showed greater water storage in the soil compared to the offset double disc system. These systems showed an increase of 11 and 5 mm in V6, and 18 and 17 mm in R3 in water storage, respectively, compared to the offset double disc system.

In the 0.0-0.1 m layer, considering the average values for fluted coulter disc, knife runner opener , knife runner opener + press wheel mechanism for ground levelling, and chisel plough systems in both evaluation periods, there was a 7 % reduction in BD in relation to the offset double disc system. Moreover, in the double disc system, the TP and macropores in the soil were 8 and 93 %, respectively, which is lower than the averages of the other systems. These systems in the 0.1-0.2 m layer reduced BD by 11 % when compared to the offset double disc system, and showed an increase from 15 to 132 % in TP and Macro.

Therefore, grain yield in the offset double disc system had the lowest average, with an average yield of 2642 kg ha^{-1}, compared to the knife runner opener system, which was 2970 kg ha^{-1}, and the chisel plough system, which was 2698 kg ha^{-1} (Sartori et al., 2015).

DISCUSSION

The soils on which the experiments were preformed have a layer of high bulk density near the soil surface. The 0.1-0.2 m layer in Experiment 1 and the 0.0-0.1 m layer in experiment 2 stand out mainly because of their higher BD values (Nunes et al., 2014), which resulted in poor aeration porosity (Gubiani et al., 2014; Nunes et al., 2014). This may be related to the fact that, in Experiment 1, the area was used for growing irrigated rice, where decompaction of the soil occurred as deep as 0.07 m, mainly due to the tillage practice of discing (Munareto et al., 2010). This partially explains the lower density of the surface layer (0.0-0.1 m) in the area of Experiment 1. The increased BD values in the 0.1-0.2 m layer may be associated with the fact that the areas in which Experiment 1 took place were systematized in both crop seasons. In a study carried out by Nunes et al. (2002) in Albaqualf soils in the municipality of São João do Polêsine about 40 km northeast from the town of Santa Maria, researchers found that systematization increased soil subsurface density, due to the traffic of heavy machinery. Similarly, Parfitt et al. (2014) found that the average BD of 1.60 Mg m^{-3} (prior to systematization) changed to 1.67 Mg m^{-3} as result of the systematization process and machine traffic. Thus, a denser soil layer in the areas of Experiment 1 may also be associated with the systematization process of the area. In addition, the study carried out by Pedrotti et al. (2001), evaluating the compaction of an Albaqualf soil under different management systems, found that all of the tillage systems evaluated had soil mechanical resistance to penetration values higher than 2.0 MPa, especially in the 0.1-0.2 m layer, and maximum resistance values were observed in the management system with continuous irrigated rice crops. According to the same author, conventional tillage contributes to physical degradation of the soil due to increased soil mechanical resistance to penetration. In Experiment 2 of this study, beef cattle were raised in the area prior to the experiment; due to cattle trampling, the higher density layer was concentrated closer to the soil surface. A study conducted by Capurro et al. (2014) found a higher density in the 0.09 to 0.12 m layer and associated this result with accumulation of pressures imposed by animal trampling. Another study by Vzzotto et al. (2000), also evaluating the changes in physical properties of an Albaqualf soil subjected to cattle trampling, found reduced porosity and increased BD in the top 0.05 m layer.

The effects of tillage systems in reducing soil compaction in planting rows were more expressive in the deeper layer (0.1-0.2 m). This may be associated with the presence of higher organic matter content in soil surface, greater microorganism activity and wetting and drying cycles that contribute to differentiation between the soil layers (Drescher et al., 2011), and higher root volume, which do not allow significant changes in BD (Capurro et al., 2014). In addition, from the uppermost soil layer to approximately 0.07 m in depth, the effect of tillage equipment on the soil is greater (Munareto et al., 2010), which contributes to a reduction in soil compaction. The double and notched disc tillage systems had the least impact on reduction in BD in the soybean crop in the planting row, and this can be explained by less action in depth and lateral soil movement in the planting row of these systems compared to the knife runner opener raised bed, and chisel plough systems.

However, the fluted coulter disc, by having a larger contact area, could also be an important tool for soil decompression in the planting row. A study conducted by Santos et al. (2010) found that notched discs affected the soil less than flat blades. According to these authors, these results may be due to the fact that there is no additional load on the equipment to increase its penetration in the soil. In this regard, Mion and Benez (2008), evaluating the efforts of five furrow opening mechanisms (even discs, corrugated discs, undulated discs, double discs, and shanks) with variation in vertical load, found that the shank promotes greater soil mobilization with less horizontal effort, reaching higher work depths because only the tip of the shank promotes resistance.

As for the discs, according to the Mion and Benez (2008), more power is needed for them to penetrate, cut through soil and straw, and overcome rolling resistance and friction on the sides of the discs.These authors found that the wave disc showed the greatest lateral force values in relation to other mechanisms for vertical loads of 1500, 2250, and 3000 N. Considering the average of all vertical loads in absolute numbers, the soil area mobilized by the corrugated disc was second only to the shank. Thus, in our study the reduced impact of the fluted coulter disc system can be partially explained by the lack of load on the seeder to provide greater penetration and decompression effect on the compacted soil layer.

Offset double disc and fluted coulter disc were less effective in reducing BD and increasing Macro, as observed in both experiments. In contrast, shank, raised bed, and chisel plough systems had positive effects in terms of reducing BD and increasing the percentage of macropores and TP. This response may be associated with the different working depths of the systems. The soil depth for the shank was approximately 0.18 m at the time of sowing, 0.12 m for the raised beds, and 0.25 m for the chisel plough system. The depth of the offset double disc and fluted coulter disc in soil was approximately 0.1 and 0.08 m, respectively.

The lower effect of the offset double disc may be associated with its performance at shallower soil depths (Drescher et al., 2011). The our results are in agreement with those obtained by Koakoski et al. (2007), wherein the breaker type knife system promoted, on average, a 24.3 % increase in soil porosity compared to the offset double disc system. Increasing the depth of action of the shanks (0.17 m) increases the volume of soil favorable to root growth, due to the reduction of the compacted layer in the planting row (Nunes et al., 2014). These authors found that use of the shank leads to increased Macro and TP and BD and resistance to penetration of the compacted layer in the planting row, corroborating the results found in this study. This reduction in BD and consequent increase in TP are related to increased Macro.

Except for Experiment 1 during the 2013/14 crop season, in the offset double disc system, macro was under 10 %, which may be critical since gas flow and water movement in the soil are closely related to macro to ensure root oxygenation (Silva et al., 2005). This may be related to the maintenance of high levels of BD; soils with lower density have higher porosity (Gubiani et al., 2014).

Soybean tillage systems howed less effect on water retention and availability compared to other variables, possibly because these properties are more influenced by soil properties. Soils with finer particles (clay or silt) and higher organic matter content have higher water retention, because organic matter is important for water availability and retention (Reichert et al., 2009b).. Furthermore, Klein and Libardi (2000) report that the soil structure and texture, type and amount of clay, and organic matter content are the factors that affect water availability to crops.

Soil microporosity was also little affected in either experiment by the tillage systems evaluated, corroborating results found by Drescher et al. (2011), in which microporosity did not respond to soil management practices, because it is a soil characteristic .

An important effect of the tillage systems on the soil was increased water infiltration capacity, especially for the chisel plough and knife runner opener systems. This can be explained by greater reduction in BD in the deepest soil layer studied (0.1-0.2 m) for these systems, and consequent increase in hydraulic conductivity (Camara and Klein, 2005). The changes caused by agricultural use on pore distribution, mechanical properties, and water and gas transport processes within the soil are related to BD (Gubiani et al., 2014). In addition, an increase in BD decreases soil water content (Gubiani et al., 2015).

Increased soil macroporosity with the use of chisel plough, knife runner opener, and raised bed systems may have contributed to increased capacity for water infiltration because water infiltration can decrease when there are compacted layers, due to reduced Macro (Bonini et al., 2011). These results are consistent with studies from Camara and Klein (2005), in which soil tillage to an average depth of 0.25 m increased the water infiltration rate.

Increased infiltration capacity for chisel plough, knife runner opener, and raised bed systems may explain why these systems had greater soil water storage potential. The greater quantity of macropores facilitates drainage and contributes to water storage in the soil layers underlying excess water which infiltrates the tillage layer (Kunz et al., 2013).

Finally, based on the results obtained in the two experiments, chisel plough, knife runner opener and raised bed systems reduce BD in the planting row. These systems improve the hydro-physical characteristics of the soil, such as BD, TP, Macro, infiltration capacity, and water storage in the soil, resulting in higher grain yield in Albaqualf soils with the presence of a compacted layer near the soil surface. The offset double disc and fluted coulter disc systems showed less effect on BD reduction in the planting row under the conditions simulated by these experiments.

CONCLUSIONS

Soybean tillage systems with the use of offset double disc and fluted coulter disc showed less effect of tillage and maintained higher bulk density layer in the planting row.

Chisel plough, raised bed, and knife runner opener systems reduce soil bulk density in the planting row, thus increasing total porosity, macroporosity, and grain yield.

Chisel plough and the use of knife runner opener increase water infiltration rate and storage in the soil.

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Table 1. Particle size distribution and soil textural class in two soil layers. Santa Maria and Formigueiro, RS, Brazil, 2015

Particle size⁽¹⁾	**0.0-0.1 m**	**0.1-0.2 m**
	g kg^{-1}	
	Experiment 1 - Santa Maria	
Clay	214	276
Sand	210	206
Silt	576	518
Textural class	silty loam	silty loam
	Experiment 2 - Formigueiro	
Clay	318	403
Sand	287	218
Silt	395	379
Textural class	silty clay loam	silty clay loam

(1) Determined by the pipette method (Donagema et al., 2011). Sand: 2 to 0.05 mm, silt: 0.002 to 0.05 mm, clay: <0.002 mm.

Table 2. Soil water retention at field capacity (θ_{FC}), available water (AW), bulk density (BD), total porosity (TP), microporosity (Mi), macroporosity (Ma), Mi/Ma ratio, reference bulk density value restrictive to plant and root growth (BD_{ref}), and degree of compactness (DC) in two soil layers ten days prior to sowing. Santa Maria 2013/14 and 2014/15 crop season and Formigueiro 2013/14 crop season

Layer	**θ_{FC} (-10 kPa)**	**AW**	**BD**	**TP**	**Mi**	**Ma**	**Mi/Ma**	**BD_{ref}⁽¹⁾**	**BD_{ref}⁽²⁾**	**DC⁽¹⁾**
m	——— mm ———		Mg m^{-3}	——— m^3 m^{-3} ———				Mg m^{-3}	Mg m^{-3}	%
		Santa Maria – Experiment 1 (2013/14 crop season)								
0.0-0.1	38	27	1.33	0.53	0.40	0.13	3:1	1.67	1.64	80
0.1-0.2	35	21	1.67	0.42	0.36	0.06	6:1	1.62	1.60	103
		Formigueiro – Experiment 2 (2013/14 crop season)								
0.0-0.1	33	24	1.62	0.37	0.36	0.02	18:1	1.59	1.57	102
0.1-0.2	30	21	1.58	0.36	0.35	0.04	9:1	1.52	1.52	104
		Santa Maria – Experiment 1 (2014/15 crop season)								
0.0-0.1	36	24	1.45	0.43	0.33	0.10	4:1	1.67	1.64	87
0.1-0.2	34	22	1.60	0.37	0.30	0.08	4:1	1.62	1.60	99

The methods used were according to Donagema et al. (2011). θ_{FC} and AW: determined by Richards extractor device (Soils Moisture Equipment); BD: volumetric method; TP: calculation method with particle density; Mi: tension table method: 0.6 m tension; Ma: difference between TP and Mi. ⁽¹⁾ BD_{ref} and DC: determined as proposed by Reichert et al. (2009); and ⁽²⁾ BD_{ref}: as proposed by Jones (1983).

Table 3. Soil water retention at field capacity (Θ_{FC}), available water (AW), bulk density (BD), total porosity (TP), microporosity (Mi), macroporosity (Ma), and Mi/Ma ratio in the treatments at different soil depths. Santa Maria, Brazil. Experiment 1 in the 2013/14 crop season

Tillage system	**θ_{FC} (-10 kPa)**	**AW**	**BD**	**TP**	**Mi**	**Ma**	**Mi/Ma**
	——— mm ———		Mg m^{-3}	——— m^3 m^{-3} ———			
				V6(1)			
				0.0-0.1 m			
Offset double disc (DD)	36^{ns}	23^{ns}	1.34^{ns}	0.48 c	0.36^{ns}	0.12 b	2.9:1 a
Fluted coulter disc	34	23	1.30	0.49 bc	0.36	0.14 ab	2.7:1 ab
Knife	33	23	1.28	0.51 abc	0.35	0.16 ab	2.2:1 ab
Knife+ M	32	23	1.24	0.52 ab	0.34	0.19 a	1.8:1 b
Raised Bed	33	23	1.25	0.54 a	0.34	0.21 a	1.6:1 b
Chisel plough + DD	32	24	1.30	0.50 bc	0.33	0.17 ab	1.9:1 ab
Mean	33	23	1.29	0.51	0.35	0.17	2.2:1
CV (%)	5.8	8.2	5.56	3.26	5.3	18	20.45
				0.1-0.2 m			
Offset double disc (DD)	33^{ns}	19^{ns}	1.60^{ns}	0.42^{ns}	0.33^{ns}	0.10^{ns}	$3.3:1^{ns}$
Fluted coulter disc	30	16	1.62	0.42	0.31	0.10	3.8:1
Knife	32	19	1.44	0.49	0.33	0.16	2.1:1
Knife+ M	31	19	1.48	0.45	0.33	0.14	2.5:1
Raised Bed	31	18	1.46	0.45	0.32	0.13	2.6:1
Chisel plough + DD	31	18	1.53	0.48	0.32	0.16	2.2:1
Mean	31	18	1.52	0.45	0.32	0.13	2.7:1
CV (%)	5.4	8.8	6.21	7.5	4.0	25.3	28.7
				R3(1)			
				0.0-0.1 m			
Offset double disc (DD)	37 ab	25 ab	1.41^{ns}	0.49 b	0.38 ab	0.11 c	3.5:1 a
Fluted coulter disc	39 a	28 a	1.37	0.51 ab	0.41 a	0.10 c	3.9:1 a
Knife	33 c	24 ab	1.27	0.54 a	0.40 a	0.14 bc	2.9:1 ab
Knife+ M	34 bc	23 b	1.28	0.53 ab	0.35 b	0.18 ab	1.9:1 b
Raised Bed	33 c	21 b	1.26	0.55 a	0.35 b	0.20 a	1.7:1 b
Chisel plough + DD	37 ab	26 ab	1.35	0.53 ab	0.39 a	0.14 bc	2.8:1 ab
Mean	35	24	1.32	0.52	0.38	0.15	2.8:1
CV (%)	4.0	8.9	5.13	4.0	4.0	14.1	20.6
				0.1-0.2 m			
Offset double disc (DD)	35^{ns}	22 ab	1.63 ab	0.48 a	0.36^{ns}	0.13 b	2.9:1 b
Fluted coulter disc	35	22 ab	1.64 a	0.42 b	0.36	0.06 c	5.7:1 a
Knife	35	23 a	1.37 c	0.52 a	0.37	0.20 a	1.9:1b
Knife+ M	34	21 b	1.35 c	0.51 a	0.35	0.16 ab	2.1:1 b
Raised Bed	35	22 ab	1.40 bc	0.52 a	0.35	0.16 ab	2.1:1 b
Chisel plough + DD	35	21 b	1.30 c	0.52 a	0.36	0.16 ab	2.2:1 b
Mean	35	22	1.45	0.49	0.36	0.15	2.8:1
CV (%)	3.5	3.5	6.9	4.6	3.4	12.1	19.75

^{ns}: no significant at $p \leq 0.05$. Means not followed by the same letter in the column differ by the Tukey test at 5 % probability. (1) Plant development stage. The methods used were according to Donagema et al. (2011); θ_{FC} and AW: determined by Richards extractor device (Soils Moisture Equipment); BD: volumetric method; TP: calculation method with particle density; Mi: table method: 0.6 m tension; Ma: difference between TP and Mi; M: press wheel mechanism for ground leveling.

Table 4. Soil water retention at field capacity (θ_{FC}), available water (AW), bulk density (BD), total porosity (TP), microporosity (Mi), macroporosity (Ma), and Mi/Ma ratio in the treatments at different soil depths. Santa Maria, Brazil. Experiment 1 in the 2014/15 crop season

Tillage system	**θ_{FC} (-10 kPa)**	**AW**	**BD**	**TP**	**Mi**	**Ma**	**Mi/Ma**
	mm		Mg m^{-3}	m^3 m^{-3}			
				R3(1)			
				0.0-0.1 m			
Offset double disc (DD)	36^{ns}	24^{ns}	1.58 a	0.38 b	0.33^{ns}	0.05 c	5.9:1 a
Fluted coulter disc	35	23	1.31 b	0.48 a	0.32	0.14 b	2.3:1 b
Knife	34	22	1.19 b	0.53 a	0.30	0.21 a	1.3:1 b
Knife[2]	36	23	1.34 b	0.47 a	0.32	0.15 ab	2.1:1 b
Raised Bed	35	23	1.34 b	0.47 a	0.32	0.15 ab	2.1:1 b
Chisel plough + DD	36	24	1.31 b	0.49 a	0.31	0.18 ab	1.7:1 b
Mean	35	23	1.34	0.47	0.32	0.15	2.6:1
CV (%)	4.6	8.3	7.38	8.26	7.6	19.5	30.47
				0.1-0.2 m			
Offset double disc (DD)	34^{ns}	23^{ns}	1.66 a	0.35 c	0.31^{ns}	0.07 c	4.5:1 a
Fluted coulter disc	34	22	1.54 ab	0.39 bc	0.29	0.09 bc	3.0:1 ab
Knife	36	23	1.37 c	0.46 a	0.32	0.13ab	2.3:1 b
Knife[2]	39	26	1.45 bc	0.43 ab	0.31	0.11 abc	2.7:1 b
Raised Bed	35	22	1.50 abc	0.41 abc	0.30	0.11 abc	2.8:1 b
Chisel plough + DD	34	22	1.40 bc	0.45 ab	0.30	0.15 a	2.2:1 b
Mean	35	23	1.49	0.41	0.31	0.11	2.9:1
CV (%)	11.0	16.7	4.76	6.77	6.15	18.72	21.8

^{ns}: no significant at $p \leq 0.05$. Means not followed by the same letter in the column differ by the Tukey test at 5 % probability. (1) Plant development stage. The methods used were according to Donagema et al. (2011); θ_{FC} and AW: determined by Richards extractor device (Soils Moisture Equipment); BD: volumetric method; TP: calculation method with particle density; Mi: table method: 0.6 m tension; Ma: difference between TP and Mi;[2] knife runner opener 0.05 m from the planting row.

Table 5. Soil water retention at field capacity (θ_{FC}), available water (AW), bulk density (BD), total porosity (TP), microporosity (Mi), macroporosity (Ma), and Mi/Ma ratio in the treatments at different soil depths. Formigueiro, Brazil. Experiment 2 in the 2014/15 crop season

Tillage system	**θ_{FC} (-10 kPa)**	**AW**	**BD**	**TP**	**Mi**	**Ma**	**Mi/Ma**
	mm		Mg m^{-3}	m^3 m^{-3}			
				V6$^{(1)}$			
				0.0-0.1 m			
Offset double disc (DD)	33^{ns}	24^{ns}	1.46 ab	0.43 ab	0.35^{ns}	0.08 ab	5.1:1 ab
Fluted coulter disc	35	26	1.55 a	0.39 b	0.36	0.04 b	8.6:1 a
Knife	31	23	1.29 b	0.49 a	0.34	0.16 a	2.4:1 b
Knife+ M	31	23	1.30 ab	0.49 ab	0.33	0.16 a	2.1:1 b
Chisel plough + DD	32	26	1.27 b	0.50 a	0.35	0.19 a	2.3:1 b
Mean	33	25	1.4	0.46	0.34	0.12 a	4.1:1
CV (%)	6.5	6.3	8.2	9.5	7.4	39.9	40.8
				0.1-0.2 m			
Offset double disc (DD)	35^{ns}	24^{ns}	1.46 a	0.43 b	0.35^{ns}	0.07 b	5.3:1 a
Fluted coulter disc	34	28	1.47 a	0.42 b	0.37	0.07 b	5.6:1 a
Knife	33	27	1.28 b	0.50 a	0.34	0.16 a	2.1:1 b
Knife+ M	32	23	1.31 ab	0.49 ab	0.34	0.15 a	2.3:1 b
Chisel plough + DD	33	25	1.38 ab	0.46 ab	0.35	0.12 ab	2.9:1 ab
Mean	33	25	1.38	0.46	0.35	0.11	3.6:1
CV (%)	8.8	9.2	5.4	6.3	8.9	21.1	32.2
				R3$^{(1)}$			
				0.0-0.1 m			
Offset double disc (DD)	37 a	26 ab	1.43 ab	0.44 bc	0.36 a	0.07 a	5.2:1 a
Fluted coulter disc	38 a	27 a	1.57 a	0.38 c	0.37 a	0.05 a	6.9:1 a
Knife	31 b	23 bc	1.30 bc	0.49 ab	0.32 ab	0.17 b	2.0:1 a
Knife+ M	30 b	22 c	1.28 c	0.50 a	0.30 b	0.19 b	1.7:1 b
Chisel plough + DD	32 b	24 abc	1.21 c	0.52 a	0.32 ab	0.20 b	1.7:1 b
Mean	33	24	1.36	0.47	0.34	0.14	3.5
CV (%)	6.0	6.0	4.8	5.62	6.4	23.4	37.9
				0.1-0.2 m			
Offset double disc (DD)	37^{ns}	27^{ns}	1.52 a	0.40 b	0.37^{ns}	0.04 b	9.5:1 a
Fluted coulter disc	38	27	1.54 a	0.40 b	0.37	0.04 b	10.6:1 a
Knife	35	27	1.22 b	0.52 a	0.36	0.16 a	2.3:1 b
Knife+ M	35	25	1.22 b	0.52 a	0.36	0.16 a	2.2:1 b
Chisel plough + DD	33	28	1.22 b	0.52 a	0.36	0.16 a	2.5:1 b
Mean	36	27	1.35	0.47	0.36	0.11	5.4:1
CV (%)	8.9	15.0	6.9	7.6	12.1	28.2	35.7

^{ns}: no significant at $p \leq 0.05$. Means not followed by the same letter in the column differ by the Tukey test at 5 % probability. (1) Plant development stage. The methods used were according to Donagema et al. (2011); θ_{FC} and AW: determined by Richards extractor device (Soils Moisture Equipment); BD: volumetric method; TP: calculation method with particle density; Mi: table method: 0.6 m tension; Ma: difference between TP and Mi; M: press wheel mechanism for ground leveling..

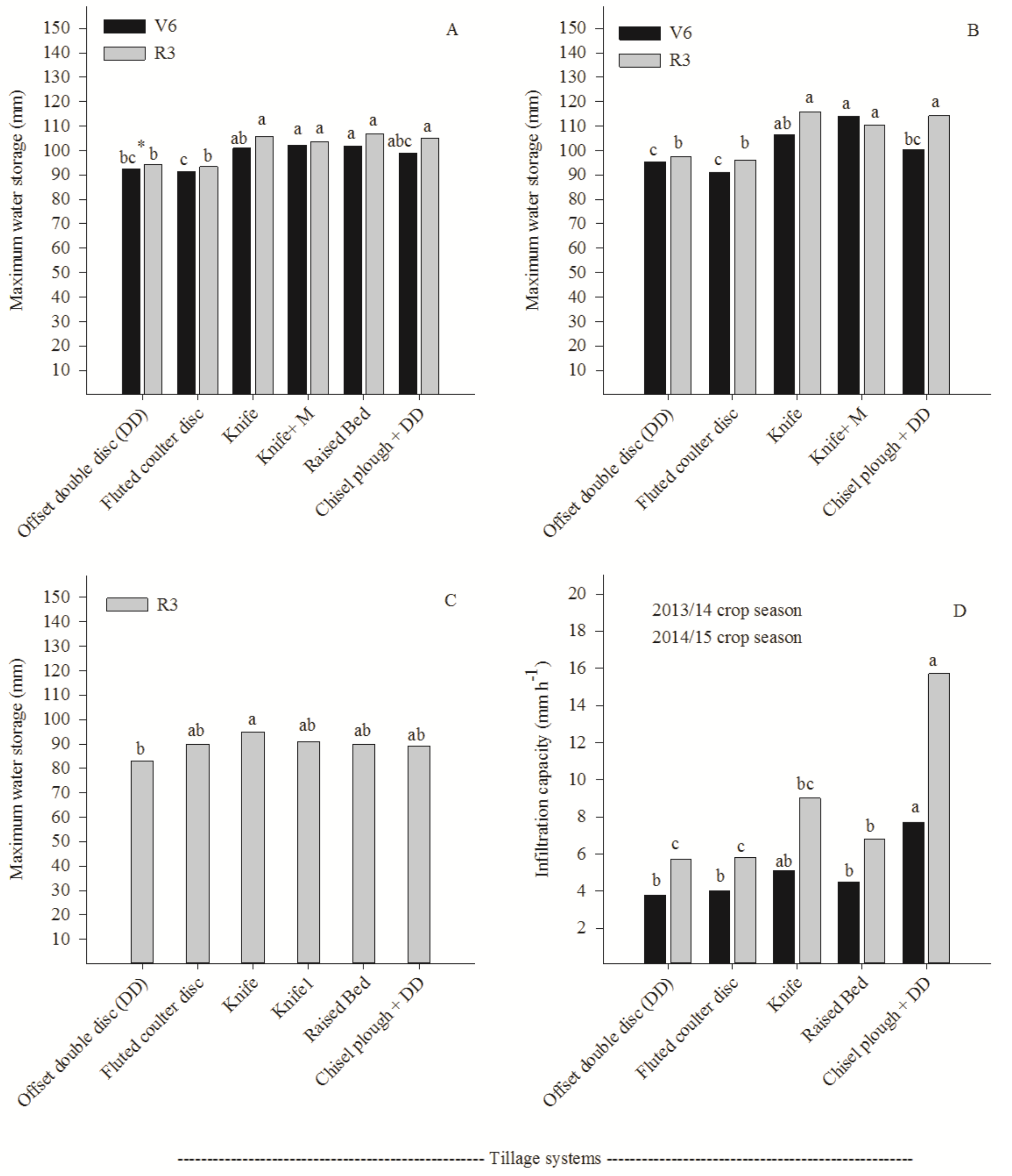

Figure 1. Maximum water storage in the soil at 0.0-0.2 m as a function of tillage systems in V6 and R3 plant growth stages in Santa Maria, 2013/14 (a) and 2014/15 (c) crop seasons; and Formigueiro 2013/14 crop season (b). Water infiltration capacity in soil in Santa Maria, Brazil (d). Experiment 1, 2013/14 and 2014/15 crop seasons. Bars followed by the same letters do not differ significantly by the Tukey test at 5 % probability.

Figure 2. Tillage systems used for soybean: sowing with offset double disc (a); sowing with a fluted coulter disc (b); sowing with a knife runner opener (c); sowing with a knife runner opener + press wheel mechanism for ground levelling (1) (d); sowing with knife 0.05 m from the planting row (e); raised bed system (f); and chisel plough + sowing using a offset double disc (g). Santa Maria. Brazil. Arrow indicates position in which the soil press wheel mechanism for ground levelling was placed.

3.2 ARTIGO 2

Growth and development of soybean roots according to planting management systems and irrigation in lowland areas

Crescimento e desenvolvimento de raízes de soja em função do manejo de implantação e da irrigação em área de várzea

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ABSTRACT

The presence of a compacted soil layer near the ground surface in paddy fields may limit the growth and development of soybean roots. The objective of this study was to evaluate different planting management systems and irrigation on growth and development of soybean root systems in lowland area. The experiment was carried out in 2013/14 and 2014/15 crop seasons in randomized complete block design with factorial treatment (3x2), with four replications. The treatments consisted of different planting management systems: sowing with double disc (A1); sowing with shank (A2) and deep tillage + sowing with double disc (A3), and irrigation: irrigated (D1) and non irrigated (D2). Planting management systems

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and irrigation influenced the growth of soybean roots. When double disc was used, roots have lower growth and increase in diameter. Use of shanks and deep tillage provide increased growth and development of soybean roots and greater depth distribution. An additional 55mm of irrigation during the V4 soybean development stage provides increased surface area and root volume in when the soil moisture reaches values below 60% of field capacity.

Key words: *Glycine max* L., compacted layer, shank, deep tillage, root system.

RESUMO

A presença de uma camada compactada próxima à superfície do solo em áreas de várzeas pode limitar o crescimento e desenvolvimento das raízes de soja. O objetivo do trabalho foi avaliar diferentes manejos de implantação e irrigação no crescimento e desenvolvimento do sistema radicular de soja em área de várzea. O experimento foi realizado nas safras 2013/14 e 2014/15 no delineamento experimental de blocos ao acaso em esquema fatorial (3x2), em faixa, com quatro repetições. Os tratamentos constaram de diferentes manejos de implantação da cultura: semeadura com disco duplo desencontrado (A1); semeadura com haste sulcadora (A2) e escarificação do solo + semeadura com disco duplo desencontrado (A3), e de irrigação: com irrigação (D1) e sem irrigação (D2). Os manejos de implantação e a irrigação influenciaram no crescimento das raízes de soja. No disco duplo, as raízes apresentam menor crescimento e aumento do diâmetro. Os manejos com haste sulcadora e escarificação do solo proporcionam maior crescimento e desenvolvimento de raízes de soja e maior distribuição em profundidade. Uma irrigação suplementar de 55mm no estádio V4 de desenvolvimento das plantas de soja proporciona aumento da área superficial e do volume de raízes em soja, quando a umidade do solo atinge valores abaixo de 60% da capacidade de campo.

Palavras-chave: ***Glycine max*** L., camada compactada, haste sulcadora, escarificação do solo, sistema radicular.

INTRODUCTION

Cultivation of soybean has been occupying a substantial space in irrigated rice areas of the state of Rio Grande do Sul - Brazil. However, most of these areas are flat and prone to the formation of a hydromorphic environment (BORGES et al., 2004), which makes drainage of the area difficult. Moreover, there is a compacted subsurface soil layer due to tillage, which causes the soil disruption, influencing the amount of macropores (VALICHESKI et al., 2012) and also total porosity (DRESCHER et al., 2011).

In addition to these factors, an increase in soil bulk density and penetration resistance (SPERA et al., 2012) also occurs; thereby, reducing root depth in the soil (OLIVEIRA et al., 2012). Thus, the compacted soil layer can affect the soil-air-water relationship, limiting growth and development of the root system (CARDOSO et al., 2006).

According QUEIROZ-VOLTAN et al. (2000), the soybean root system under normal cultivation conditions, is distributed almost entirely within the first 15cm of soil. However, when there is any physical limitation of the soil, there may be a reduction in root growth. According to OLIVEIRA et al. (2012), soil compaction increases the diameter of soybean roots, and this inhibits its development.

In this context, it is essential to assess planting management systems that reduce the compacted soil and consequently promote higher root growth and development of soybean plants. Among the available managements, deep tillage and sowing with shank have provided positive effects on soil decompression within the crop row (DRESCHER et al., 2011). Irrigation is also an important tool because the water content in the soil directly interferes in soybean roots (HOSSNE et al., 2015).

As a result, this study aimed to evaluate the effect of different planting management systems and irrigation on growth and development of soybean root systems in a lowland area.

MATERIALS AND METHODS

The experiment was carried out during the 2013/14 and 2014/15 crop seasons in the experimental lowland area of the Federal University of Santa Maria (UFSM), in southern Brazil, in soil classified as Albaqualf (SOIL SURVEY STAFF, 2014). For each crop season, the experiment was set up at a different location within the experimental area.

The soil at the experimental area had the following physical and chemical characteristics to the 30 days before sowing: clay = 25%; pH_{water} (1:1) = 5.4; P = 18mg dm^{-3}; K = 60mg dm^{-3}; Ca = 5.3$cmol_c$ dm^{-3}; Mg = 2.4$cmol_c$ dm^{-3} and organic matter (OM) = 2.0% for the 2013/14 crop season and; clay = 26%; pH_{water} (1:1) = 5.4; P = 15.3mg dm^{-3}; K = 44mg dm-3; Ca = 8.3$cmol_c$ dm^{-3}; Mg = 3.1$cmol_c$ dm^{-3} and OM. = 2.0% for the 2014/15 crop season.

The experiment followed a randomized strip-block design in a factorial scheme (3x2), with strip plots for both factor A and for factor D, with four replications. The factor A was composed of different planting management systems: sowing with a double disc (A1); sowing with a shank (A2) and deep tillage + sowing with double discs (A3). The D factor was: irrigated (D1) and non irrigated (D2).

Deep tillage was carried out at a depth of 25cm at 45 prior to sowing for the 2013/14 crop season and 19 days prior to sowing for the 2014/15 season. The working depth was approximately 18cm for the shank and 10cm for the double discs. Sowing took place on November 7th and 14th of 2013 and 2014, respectively, using a fertilizer seeder. Due to 245mm rainfall two days after sowing (2013/14), re-sowing took place on November 26th, 2013. The soybean cultivar used was the BMX Tornado RR with 26 seeds m^{-2}, and 0.5m distance between rows.

Fertilization at sowing as well as additional crop treatments was performed according to the technical indications for crop (EMBRAPA, 2012). Border irrigation was performed when the average soil moisture was at 58% of field capacity in the 0-20cm layer. During the experiment 55mm irrigation was performed in the V4 stage of the plants, according to scale (FEHR & CAVINESS, 1977), for the 2013/14 crop.

The soil penetration resistance was evaluated. The evaluation was conducted at the sowing line in the 0-20cm layer using a digital Falker® PLG 1020 penetrometer at the V6 growth stage of plants.

To evaluate the root systems, at the V6 and R3 growth stages, five plants were collected per repetition in sequence at the sowing line using a 40x40x25 (length, width and depth) soil monolith. After the collection, the root system was separated from shoot and soil by washing with water. After washing, the two plants from the extremities of the monolith were discarded, and only the three plants at the center were scanned using a Epson Expression® 11000XL scanner and analyzed using the software WinRhizo®. The values obtained were: root length (cm), projected area (cm^2), surface area (cm^2), average diameter (mm), total volume (cm^3), number of tips and number of root forks.

After these assessments, using the same root, dry mass was analyzed by drying in an oven with forced air circulation at a temperature of 65°C until constant weight, after which mass was verified using a precision scale. In the R5 stage, evaluation of dry mass was performed in two soil layers: 0-10 and 10-20cm. Samples were collected by soil monoliths of 20 x 20 x 10cm (length, width and depth) in each layer containing the roots of two plants. After collection, the root system and soil were separated by washing with water and then oven dried to obtain the dry mass, with the results expressed in mg cm^{-3} of soil.

The data were submitted to the assumptions of the mathematical model (normality and homogeneity of variances). Analysis of variance was performed using the F test and means, when significant were compared by Tukey test at 5% probability of error.

RESULTS AND DISCUSSION

In both crop seasons, the soil in which the experiment was performed had penetration resistance above 2MPa at layer 7 to 15cm (Figure 1A, B). According to BOTTA et al. (2010) and BORTOLUZZI et al. (2014), values of soil penetration resistance as high as 2MPa are considered to be critical to the growth and development of plant roots. Both deep tillage and shank reduced values of soil penetration resistance at the sowing line to below 1MPa and 1.5MPa for the 2013/14 and 2014/15 crop seasons, respectively. Use of double discs resulted in a smaller decrease in soil penetration resistance; thereby, maintaining the presence of the compacted soil layer in the sowing line, since the resistance to penetration is used as an indication of the degree of soil compaction (BEULTER & CENTURION, 2004).

Regarding the dry mass of roots in the V6 and R3 growth stages, there was no interaction between the planting management system and irrigation (Table 1). Deep tillage and sowing with shank provided the highest amount of dry matter in soybean roots in V6 and R3 growth stages in the 2013/14 crop season and in R3 in the 2014/15 season; there were no effects linked to irrigation. In the evaluation at the R5 stage, there was interaction between the planting management systems and irrigation in the 2013/14 crop season. According to the results 94; 90 and 89% (2013/14 season) and 92; 88 and 89% (2014/15 season) of the total assessed roots were concentrated in the 0-10cm layer when using double discs, shank and deep tillage, respectively. However, in the 10-20cm layer, in both crop seasons, there was a higher concentration of roots when sowing with shank and deep tillage when compared to the double discs, indicating further deepening the roots in these types of soil management.

Another important result is that, especially in the layer subjected to greater stress from the root system (0-10cm layer) irrigation promoted greater dry mass of roots in the double disc system in the 2013/14 crop season.

These results support the studies of BOTTA et al. (2010), which reported greater root growth of soybean in the topsoil with increasing soil penetration resistance. The greatest growth and roots depth in planting management systems using shank and deep tillage may be associated with greater reduction in soil penetration resistance at the sowing line, as seen in figures 1A and 1B. NUNES et al. (2015) evaluated the effect of sowing maize using three shank depths, and reported that working the soil with a shank at 17cm resulted in an increase in soil macroporosity and total porosity and reduced penetration resistance, resulting in greater dry mass and root length, growth at greater soil depths.

Total root length, diameter and number of root forks did not differ among planting management systems; only the effect of irrigation was observed which resulted in greater root length, observed in V6 in the 2013/14 crop season (Table 2). However, the shank provided greater projected area and surface area of roots. In the 2014/15 crop season, the use of shanks and deep tillage presented greater root length, projected area, surface area, number of forks, volume and number of root tips in relation to the double disc; no difference was found as to the average diameter of roots.

In the evaluation carried out in R3 (Table 3), 2013/14 crop season, the use of shank and deep tillage provided the best results in root length, projected area, surface area and number of root tips. However, at this stage there was an increase in average root diameter for the double disc system. According to SILVA & ROSOLEM (2002), increase in root diameter and decrease in root length are among the morphological changes that can occur in roots as a result of growth restriction. According to FOLONI et al. (2006), the increase in diameter occurs as a means to increase the force exerted in the stretching process of the root meristem cells to penetrate compacted soil. In the 2014/15 crop season a positive effect was also observed for both of the mentioned parameters in systems with shank and deep tillage, no significant differences were reported for the other evaluated parameters.

Generally, according to the results reported for root growth and development in three growth stages (V6, R3 and R5), in the 2013/14 and 2014/15 crop seasons, sowing with shank and deep tillage provided greater root growth and development for soybeans grown in lowland area. This can be explained by the greater effect of these types of management in increasing the total porosity and soil macroporosity, in addition to the reduction of soil penetration resistance at the sowing line, as aforementioned. According to CARDOSO et al. (2006), the root system benefits from increased oxygenation capacity and water infiltration into the soil, features that possibly have been improved in these two planting management systems. Additionally, irrigation should be noted because the soybean root system is influenced by the water content (HOSSNE et al., 2015). In this study, except for a period of 15 days there was no rainfall in the 2013/14 crop season, 55mm irrigation in V4 plant growth stage resulted in higher root surface area and volume; in other periods and in the 2014/15 crop season there was balanced distribution of rainfall (Figure 1 C, D), with no need for irrigation, rainfall alone was sufficient to prevent water deficits and possibly impact the root growth. In Iran, MASOUMI et al. (2014), evaluating levels of water deficit in five soybean cultivars, found decreased root length and volume. According to MASOUMI et al. (2014), this is due to the imbalance in the allocation of photosynthetic substances throughout the roots.

In this sense, it is evident that the presence of a compacted layer located close to the soil surface is a limiting factor for the growth and development of the soybean root system in lowland areas. Thus, loosening part of this compacted layer, especially the top layer, up to a depth of 15cm, which concentrates greater volume of roots, is a key practice in order to promote better root growth.

CONCLUSION

Planting management systems using shank and deep tillage in lowland areas provide greater root growth of soybean plants grown in these areas. An additional irrigation of 55mm at V4 growth stage of soybean plants provides increased surface area and root volume when soil moisture reaches values below 60% of area field capacity lowland areas.

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Table 1 - Root dry mass (mg plant^{-1}) and root dry mass (mg cm^{-3} soil) of soybean plants (BMX Tornado RR cultivar) in two soil depths (D) according to the planting management systems and irrigation. Santa Maria, RS - Brazil. 2015.

Planting management systems	Root dry mass (mg plant $^{-1}$)			
	V6[1]	R3	V6	R3
	------- 2013/14 crop season -------		------ 2014/15 crop season ------	
Double Disc (DD)	1825 b[*]	4450 b	1300 a	1966 b
Shank	2733 a	5150 ab	1350 a	3825 a
Deep tillage + DD	2462 a	5883 a	1675 a	4000 a
Irrigation				
Irrigated (I)	2372 a	5167 a	-	-
Non-irrigated (NI)	2308 a	5155 a	-	-
Average	2340	5161	1441	3263
CV (%)	20.6	11.7	31.5	16.2
	Root dry mass (mg cm^{-3} soil)			
Planting management systems	R5			
	-------------------------- 2013/14 crop season ---------------------------			
	D (0-10 cm)		D (10 – 20 cm)	
	Irrigated	Non irrigated	Irrigated	Non irrigated
Double Disc (DD)	A 2.6 a	B 2.3 c	A 0.1c	A 0.2 c
Shank	A 2.9 a	A 3.2 a	B 0.3 b	A 0.4 a
Deep tillage + DD	A 2.9 a	A 2.8 b	A 0.4 a	B 0.3 b
Average	2.8	2.8	0.3	0.3
CV (%)	6,3		9,2	
	--------------------------- 2014/15 crop season --------------------------			
Double Disc (DD)		2.2 a		0.2 b
Shank		3.0 a		0.4 a
Deep tillage + DD		3.3 a		0.4 a
Average		2.8		0.4
CV (%)		18.7		19.3

[*] Means preceded by the same capital letter in line and followed by same letter in the column do not differ by Tukey test at 5% probability. [1]plant development stage.

Table 2 - Length (L), projected area (PA), surface area (SA), average diameter (AD), the number of forks (F), root volume (V) and number of roots tips (NT) of the BMX Tornado RR soybean cultivar according to the planting management systems. Santa Maria, RS - Brazil. 2015.

Planting management systems	L (cm)	PA (cm^2)	SA (cm^2)	AD (mm)	F	V (cm^3)	NT
				V6[1]			
	---------------------------- 2013/14 crop season ----------------------------						
Double Disc (DD)	1139 a[*]	88 ab	235 ab	0.6 a	5607 a		
Shank	1297 a	102 a	310 a	0.7 a	5258 a		
Deep tillage + DD	935 a	69 b	215 b	0.7 a	3871 a		
Irrigation							
Irrigated (I)	1204 a	86 a	271 a	0.7 a	5097 a		
Non irrigated (NI)	1043 b	86 a	236 b	0.7 a	4727 a		
Average	1124	86	253	0.7	4912		
CV (%)	9.4	12.3	15.8	6.0	27.4		
	----------------------- 2014/15 crop season --------------------------------						
Double Disc (DD)	959 c	61 b	191 b	0.6 a	3557 b	3 b	1118 b
Shank	1357 b	85 a	270 a	0.6 a	4510 a	4 a	1385 a
Deep tillage + DD	1588 a	94 a	289 a	0.6 a	4826 a	4 a	1535 a
Average	1301	80	250	0.6	4298	3	1346
CV (%)	8.0	7.0	7.6	5.5	9.7	6.8	6.8
	V (cm^3)		NT				
Planting	---------------------------- 2013/14 crop season ----------------------------						
management systems	I	NI	I	NI			
Double Disc (DD)	B 4.1 b	A 5.5 a	A 1451.0 a	B 1017.7 a			
Shank	A 7.1 a	B 5.3 a	A 1038.0 ab	A 1246.0 a			
Deep tillage + DD	A 3.9 b	A 3.6 b	A 852.6 b	A 872.5 a			
Average	5,0	4,8	1113.8	1045.4			
CV (%)	14.3		14.3				

[*] Means preceded by the same capital letter in line and followed by same letter in the column do not differ by Tukey test at 5% probability. [1]plant development stage.

Table 3 - Length (L), projected area (PA), surface area (SA), average diameter (AD), the number of forks (F), volume (V) and number of root tips (NT) of the BMX Tornado RR soybean cultivar according to the planting management systems and irrigation. Santa Maria, RS - Brazil. 2015.

Planting management systems	L (cm)	PA (cm^2)	SA (cm^2)	AD (mm)	F	V (cm^3)	NT
				R3[1]			
	---------------------------- 2013/14 crop season ----------------------------						
Double Disc (DD)	1418 b[*]	168 b	519 b	1.1 a	8531 a	14 a	1660 b
Shank	1991 a	215 a	678 a	1.0 b	10580 a	17 a	1986 a
Deep tillage + DD	1878 a	189 ab	546 ab	0.9 b	10234 a	16 a	2173 a
Irrigation							
Irrigated (I)	1710 a	187 a	605 a	1.09 a	10321 a	17 a	1810 a
Non irrigated (NI)	1815 a	195 a	557 b	1.04 a	9243 a	15 b	2069 a
Average	1762	191	3087	1.06	9782	16	1939
CV (%)	21.3	24.8	14.4	11.7	31.8	28.4	24.9
	---------------------------- 2014/15 crop season ----------------------------						
Double Disc (DD)	2526 a	169 a	506 b	0.6 a	9154 a	8 b	3233 a
Shank	3548 a	242 a	760 ab	0.7 a	13477 a	13 a	3900 a
Deep tillage + DD	3638 a	238 a	772 a	0.6 a	13520 a	12 a	4231 a
Average	3237	216	679	0.6	12050	11	3788
CV (%)	25.3	20.7	20.6	5.1	28.5	14.9	22.7

[*] Means followed by the same letter in the column do not differ by Tukey test at 5% probability. [1]plant development stage.

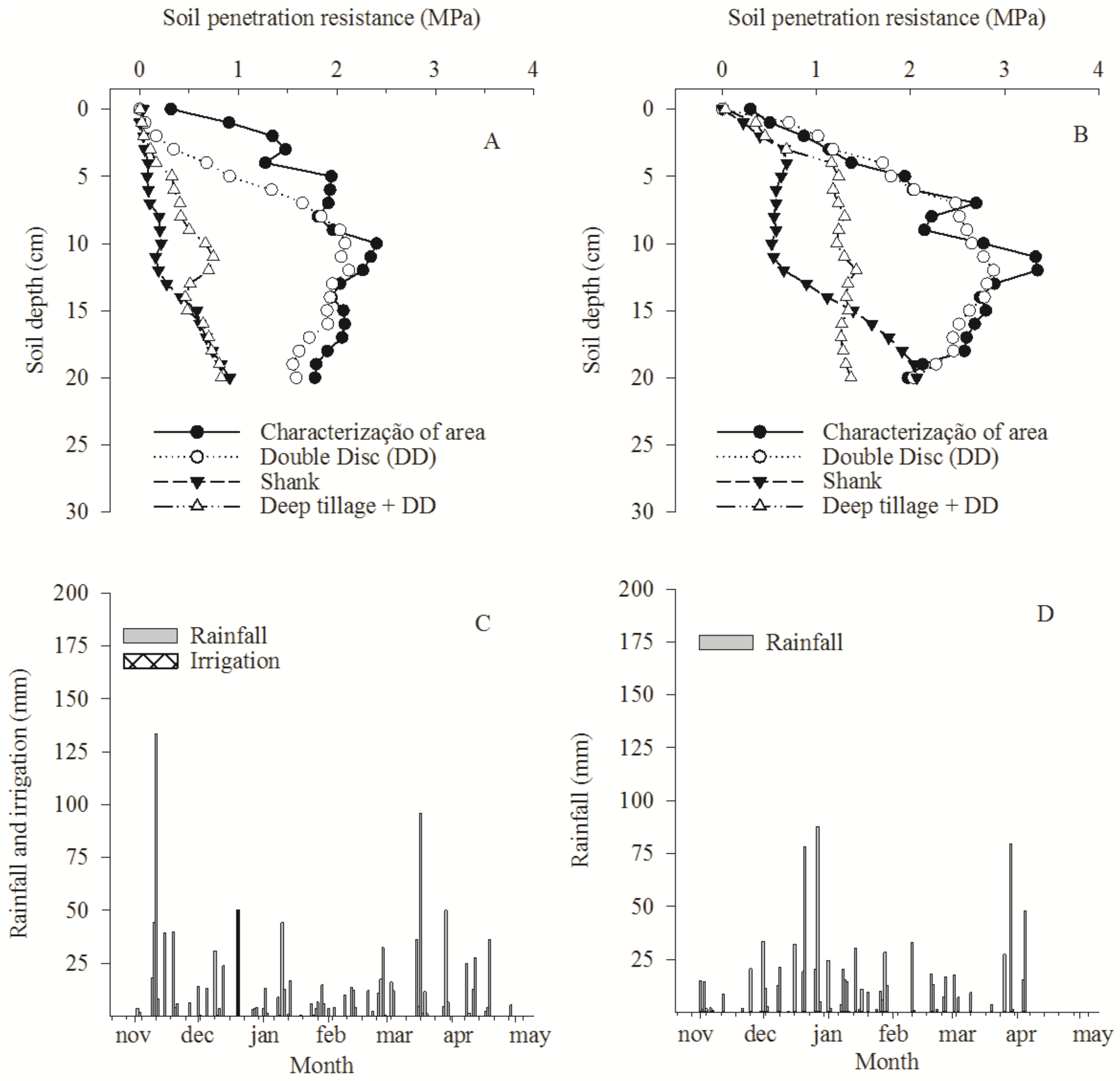

Figure 1 - Soil penetration resistance at the V6 growth stage for the 2013/14 (A) and 2014/15 (B) crop seasons, according to the planting management systems and rainfall and irrigation for 2013/14 (C) and rainfall 2014/15 (D) crop seasons, respectively. Santa Maria, RS - Brazil 2015. Average moisture in the soil layer 0-20 cm at the time of each evaluation was 32 and 31% (A, B), respectively.

3.3 ARTIGO 3

Physiological responses of soybean plants grown in paddy soil to tillage systems and border irrigation

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Abstract

Lowland areas used to grow irrigated rice have been found to have a compacted layer near the soil surface that may impair root growth and cause oxidative stress in soybean plants. This study aimed to evaluate the effects of tillage systems and border irrigation in the mitigation of oxidative stresses in soybean plants grown in these areas. Two field experiments were conducted in the 2013/14 and 2014/15 growing seasons. The experimental design was a strip randomized block design with four replications. The A factor was composed of tillage systems: seeding with driller equipped with offset double disc (DD) (A1); driller with knife opener (A2) and chisel plough + driller using DD (A3). The D factor was irrigated (D1) and non-irrigated (D2) treatments. In general, leaf tissues taken from the chisel plough and knife systems showed a lower concentration of hydrogen peroxide (H_2O_2), lipid peroxidation

(TBARS) and a decrease of superoxide dismutase (SOD) activity compared to the DD in the 2013/14 growing season. In 2014/15, season treatments differed only in the concentration of H_2O_2. The activity of guaiacol peroxides (POD) in leaves was lower for the offset double disc and chisel plough in the 2013/14 and 2014/15 growing seasons, respectively. Irrigation decreased the concentration of H_2O_2, TBARS and SOD activity in 2013/14. However no differences were observed in 2014/15. These results indicate that the chisel plough and knife mitigate oxidative stresses of soybean plants in areas with a compacted layer near the soil surface. Border irrigation during the vegetative growth stage reduces oxidative stress in soybean plants.

Key-words: compacted layer, chisel plough, seed openers, water stress, oxidative stress.

Introduction

Soybean crops have been grown in rotation with rice in the State of Rio Grande do Sul over the past decade. However, average yield over the last three years did not exceed 2500 kg ha^{-1}. This may be related to characteristics of the area's soil, which usually presents a compacted layer in its sub-surface.

The compacted layer may limit root growth, thus decreasing plant development under water stress periods (Botta et al., 2010). In wet years, the compacted layer favors the occurrence of flooding, reducing oxygen content in the soil and leading to a hypoxic environment in the root system. As a result, abiotic stresses may occur, causing oxidative stress in soybean plants.

One of the consequences of water stress is an increased production of reactive oxygen species (ROS), such as superoxide, hydrogen peroxide and hydroxyl radical (Vasconcelos et al., 2009; Masoumi et al., 2011b; Kausar et al., 2012; Fanaei et al., 2015). ROS are highly reactive and toxic to cells, causing damage to proteins, lipids and DNA (Gill and Tuteja, 2010; Hossain et al., 2012; Kausar et al., 2012; Fanaei et al., 2015). The induced stress of ROS accumulation can be minimized by the antioxidant system present in the plant cell, which may be enzymatic or non-enzymatic (Sharma and Dubey, 2005; Fanaei et al., 2015). The enzymatic system consists of enzymes, such as dismutase superoxide, peroxidase ascorbate and catalase (Gill and Tuteja, 2010; Bonnecarrère et al., 2011). The non-enzymatic system consists of ascorbate peroxidase, glutathione, α-tocopherol, carotenoids and flavonoids (Gill and Tuteja, 2010). Furthermore, water stress can produce changes in the chlorophyll A and chlorophyll B ratio and carotenoids (Fanaei et al., 2015).

Based on these findings, there is a need to study the effect of different tillage systems in order to minimize stresses that may occur in areas with a compacted layer present in the soil sub-surface, specifically under conditions of deficit or excess of water. Another alternative that could minimize the effects of the compacted soil layer in drought periods is irrigation.

Therefore, the objective of this work was to evaluate the physiological responses of soybean plants, grown in paddy soil with compacted layer in the soil sub-surface, to different tillage systems and border irrigation.

Material and methods

Experimental design, planting and treatments

The experiment was conducted in the 2013/14 and 2014/15 growing seasons at an experimental lowland area in Santa Maria located at 29°43'S, 53°43"W, Rio Grande do Sul State, in an Albaqualf soil (Soil Survey Staff, 2014).

The experiment was conducted under different paddies for each year of study. The physical and chemical properties of he soil at 60 days before seeding are as follow: clay = 25%; pH $_{water}$ (1:1) = 5.4; P = 18 mg dm^{-3}; K = 60 mg dm^{-3}; Ca = 5.3 cmol$_c$ dm^{-3}; Mg = 2.4

cmol$_c$ dm^{-3} and OM = 2.0 % (season 2013/14) and clay = 26%; pH $_{water}$ (1:1) = 5.4; P = 15.3 mg dm^{-3}; K = 44 mg dm^{-3}; Ca = 8.3 cmol$_c$ dm^{-3}; Mg = 3.1 cmol$_c$ dm^{-3} and OM = 2.0 % (season 2014/15).

Average values for soil bulk density, total porosity, microporosity and macroporosity in the layer from 0.0 to 0.2 m were: 1.50 Mg m^{-3}, 0.48 m^{3}m^{-3}, 0.36 m^{3}m^{-3} and 0.10 m^{3}m^{-3}, respectively (season 2013/14) and 1.53 Mg m^{-3}, 0.40 m^{3}m^{-3}, 0.32 m^{3}m^{-3} and 0.09 m^{3}m^{-3}, respectively (season 2014/15).

The experimental design used for both years of study was a strip randomized block in a factorial scheme (3x2) with four replicates. The tested treatments were: Factor A (Crop Tillage systems): seeding with driller equipped with offset double disc (DD) (A1); driller with knife opener (A2) and chisel plough + driller using DD (A3). Factor D: irrigated (D1) and non-irrigated (D2) treatments.

The chisel plough was performed at 45 and 19 days before seeding for the 2013/14 and 2014/15 growing season, respectively. This operation was performed at 0.25 m depth with the knife spaced at 0.35 m.

The seeding took place on November 7 and 14 for the 2013/14 and 2014/15, respectively. After 245 mm of rainfall over four days, beginning on the second day after seeding for the 2013/14 season, the experiment was re-seeded on November 26, 2013. The seeding depth with knife and offset double disc was approximately 0.18 and 0.10 m, respectively.

The seeds were treated with fipronil (250 g L^{-1}) and carbendazim + thiram (150 g L^{-1} + 350 g L^{-1}), at 150 mL and 200 mL per 100 kg^{-1} of seed, respectively. They were also inoculated with *Bradyrhizobium japonicum* (100g per 50kg^{-1} of seeds). The fertilization in the 2013/14 crop for experiment 1 and 2 was 30 kg ha^{-1} of nitrogen (N), 60 kg ha^{-1} of P_2O_5 and 60 kg ha^{-1} of K_2O. However, for experiment 1, because of re-seeding, an additional 10 kg ha^{-1}

of nitrogen (N), 20 kg ha^{-1} of P_2O_5 and 20 kg ha^{-1} of K_2O were used. In the 2014/15 season fertilization consisted of 13 kg ha^{-1} of nitrogen (N), 55 kg ha^{-1} of P_2O_5 and 87 kg ha^{-1} of K_2O. The other crop treatments were performed according to the research recommendations for the soybean crop in Rio Grande do Sul.

For 2013/14, a 55 mm irrigation was applied when the average soil moisture reached 58 % of field capacity (FC) at a 0-20 cm depth. Soybean plants were at the V4 growth. However, two irrigations were performed in the 2014/15 growing season, the first of 41 mm at R3 growth stage and the second of 46 mm at R5 growth stage, according to Fehr and Caviness (1977). The soil moisture content at the 0-20 cm layer in R3 and R5 stages was at 61 % and 54 % of FC, respectively.

Irrigations were always initiated after 4 pm taking an average of 8h from the beginning to the end of the irrigation event (3-7 cm water depth throughout the experimental area). A drainage of the area was performed immediately after each irrigation event.

Samples were taken after complete drainage of the experimental area at 0, 1 and 6 days after irrigation (DAI) at V4 growth stage in the 2013/14 growing season. In the 2014/15 growing season, samples were taken following similar procedures at 0, 1 and 5 DAI at R5 growth stage.

Physiological parameters

Sampling and extraction of enzymes

At each sampling, the third fully developed leaf from the main stem of five plants was collected for each replicate. Samples were immediately stored in liquid nitrogen. Subsequently, the enzyme extraction was obtained from 1.0 g of the leaf tissue, macerated with liquid nitrogen and homogenized with 3.0 mL of 0.05 M sodium phosphate buffer (pH 7.8), containing 1.0 Mm EDTA and 1 % Triton X-100. The homogenate was centrifuged at

13,000 g for 20 minutes at 4 °C. The supernatant was used for the enzyme activity and the protein content determination (Zhu et al., 2004).

Determination of hydrogen peroxide (H_2O_2)

The hydrogen peroxide concentration was determined according to Loreto and Velikova (2001), where 0.05g of frozen leaf material (aerial part) was homogenated in 2 mL of 0.1% trichloroacetic acid. The homogenate was centrifuged at 12,000 g for 15 min. Then, 0.5 mL of the supernatant was added to 0.5 mL of 10 mM phosphate potassium buffer (pH 7.0) and 1 mL of 1M KI. The H_2O_2 concentration of the supernatant was assessed by comparing its absorbance at 390 nm using a standard calibration curve.

Estimation of lipid peroxidation (TBARS)

The degree of lipid peroxidation was estimated following the method of El-Moshaty et al. (1993), where 1.0 g of frozen root and shoot samples were homogenized in 4 mL of 0.2 M citrate-phosphate buffer (pH 6.5) containing 0.5 % Triton X-100, using mortar and pestle. The homogenate was filtered with two paper layers and centrifuged for 15 min at 20,000 g. One milliliter of the supernatant fraction was added to an equal volume of 20 % (w/v) TCA containing 0.5 % (w/v) of thiobarbituric acid (TBA). The mixture was heated at 95ºC for 40 min. and then quickly cooled in an ice bath for 15 min., and centrifuged at 10,000 g for 15 min. The absorbance of the supernatant at 532 nm was read and corrected for unspecific turbidity by subtracting the value of the absorbance at 600 nm. The lipid peroxides were expressed as nmol MDA mg^{-1} protein, by using an extinction coefficient of 155 L $mmol^{-1}$ cm^{-1}.

Superoxide dismutase (SOD)

The activity of superoxide dismutase (SOD) was determined by the method of Misra and Fridovich (1972). Approximately 200 mg of frozen shoot leaf were homogenized in 5 mL of L^{-1} 100 nmols of potassium phosphate buffer (pH 7.8) containing 0.1 nmol L^{-1} EDTA, 0.1

% (v/v) of Triton X-100 and 2 % of PVP (w/v). The extract was centrifuged at 22,000 x g for 10 min at 4° C and the supernatant was used. The reaction mixture consisted of 1 mL final volume, containing glycine buffer (pH 10.5), 1 nmol L^{-1} of epinephrine and enzymatic material. The epinephrine was the last component added. The adrenochrome formation in the first 4 min. was determined by a spectrophotometer at 480 nm. One unit of the SOD activity was expressed as the enzyme amount required to cause 50 % inhibition of epinephrine oxidation under the experimental conditions used.

Guaiacol peroxides (POD)

Guaiacol peroxidase was measured according to Zeraik et al. (2008). The reaction mixture contained 1.0 mL potassium phosphate buffer (100 mM, pH 6.5), 1.0 mL of guaiacol (15 mM) and 1.0 mL of H_2O_2 (3 mM). After homogenization, 50 uL of leaf extract was added to this solution. Guaicol oxidation to tetraguaiacol was measured through of increase in the absorbance at 470 nm.

Determination of chlorophyll and carotenoids

The carotenoids, chlorophyll A and chlorophyll B concentrations were extracted following the method of Hiscox and Israeslstam (1979) and estimated with the help of Lichtenthaler’s formula (Lichtenthaler, 1987). Frozen leaves (0.05 g) were incubated at 65ºC in dimethylsulfoxide (DMSO) until tissues were completely bleached. Absorbance of the solution was then measured at 663 and 645 nm for chlorophyll and 470 nm for carotenoids in a spectrophotometer. Chlorophyll and carotenoid concentrations were expressed as mg g^{-1} fresh weight (FW).

Protein estimation

For the preparation of all enzymes, the protein was determined following the method of Bradford (1976) using bovine serum albumin.

Soil moisture, oxygen content and rainfall

The soil moisture and oxygen content were monitored in the 2013/14 crop season. The soil moisture was monitored throughout the period of plant development using CSI model sensors (CS616-L25), connected to a CR1000 DATALOGGER data collector device. The soil oxygen content was obtained by the ICT-SOM oxygen meter using oxygen sensors (ICT-O2 model). The soil moisture and the soil oxygen sensors were placed in the middle of planting rows at a depth of 0-20 cm and 0-10 cm, respectively. The rainfall data were obtained from the automatic weather station of the 8th DISME/INMET, located at the Crop Science Department of UFSM, approximately 500 m from the experiment.

Statistical analysis

Data were tested for assumptions of the mathematical model (normality and homogeneity of variances). The data variance analysis of the experiments was performed using the F test. The average factors were compared using the Tukey test ($p \leq 0.05$) when significant.

Results and Discussion

Plants showed different physiological responses to tillage systems and irrigation during the drought period in each crop season. In the 2013/14 season, the leaf hydrogen peroxide (H_2O_2) concentration at 0 and 1 day after irrigation (DAI) showed higher values in the chisel plough system compared to the other systems (Table 1). However, there was no effect of irrigation. At 6 DAI (Table 2), there was an interaction between tillage systems and irrigation. Higher H_2O_2 concentrations in the double disk system were observed compared to the other treatments. In the non-irrigated system the leaf H_2O_2 concentration was higher, except for the chisel plough system where there was no difference between irrigated and non-irrigated systems.

In the 2014/15 season, differences between tillage systems were also observed for leaf H_2O_2 concentration, however not for irrigated and non-irrigated treatments (Table 5). Soybean plants in the tillage system with offset double disc and knife showed higher leaf H_2O_2 concentrations at 0, 1 and 5 DAI, when compared to the chisel plough system.

Considering the higher water stress periods at 6 and 5 DAI in the 2013/14 and 2014/15 crops, respectively, H_2O_2 concentration was 33 and 25% lower in the chisel plough system compared to the system with the offset double disc in the 2013/14 and 2014/15 seasons, respectively.

According to Chen et al. (2007), low concentrations of H_2O_2 have the function of mediating signal transduction in response to abiotic stress in plants cells. According to Masoumi et al. (2011a), the increase in reactive oxygen species (ROS), such as H_2O_2 is common when there is water stress. This increase can indicate water stress inducing the plant’s defenses (Mohamed and Akladious, 2014). In this sense, plants in the chisel plough system probably were affected by less water stress, since the system aids root growth and a deeper search for water in the soil profile.

Leaf lipid peroxidation (MDA) in the 2013/14 season presented an interaction between crop tillage systems and irrigation (Table 2). MDA was higher in the offset double disc system in all evaluation periods and had the lowest values in the chisel plough and knife systems. Moreover, the addition of irrigation was an important for minimizing the stress caused by the water deficit. The addition of irrigation reduced leaf lipid peroxidation at 1 and 6 DAI regardless of the crop tillage system used. However, in the 2014/15 crop (Table 5), there were no differences between treatments.

The different responses of plants between the crop seasons may be related to the time period when the water deficit occurred, being at V4 and R5 stages, respectively, in the first and second growing seasons. Therefore, the plant response, i.e. the oxidative damage, may be different according to the plant developmental stage.

Based on the results obtained for the first growing season, it is evident that the presence of a compacted layer near the soil surface caused stress in soybean plants, one of the first signs being oxidative damage (Mohamed and Akladious, 2014). Therefore, the use of a chisel plough or knife system for the soybean seeding in areas with soil physical constraints, as in this study, may be an alternative to minimize stresses in the plants.This may be associated to the improvement of soil physical properties offered by these two systems in the soil, resulting in higher soil oxygen content, as can be observed throughout the growing period in the knife system (Figure 1 A).

In the watershed height evaluation (Figure 2 A) at 01 DAI, it was already lower than 0.30 m from the ground surface for all systems, i.e., there was no more free water promoting an anoxic environment in the region near the root system. The time control of the border irrigation is extremely important, in order that the plants' root system is exposed as little time as possible to anoxic conditions, since the oxygen deficiency caused by too much water in the soil is one of the factors that may damage the growth of crop plants such as soybean (Boru et al., 2003). This is due to the elevated ROS formation in the root system submitted to flooding, anoxia and, subsequently, the re-oxygenation resulting in oxidative stress (Amor et al., 2000).

Therefore, if the border irrigation is performed properly and quickly, the shorter the time between the irrigation and water drainage of the area, as in the present study (12 hours), significantly contributes to reducing stresses caused by the compacted layer of the soil in drought periods. These results were observed through the hydrogen peroxide and lipid peroxidation concentrations (Table 1 and 2), as shown above.

Lipid peroxidation is considered one of the most damaging processes in living beings, because it damages the integrity of cell membranes (Gill and Tujeta, 2010). In addition, lipid peroxidation can damage the chloroplast structure and inhibit chlorophyll synthesis and, thus, photosynthesis (Ella et al., 2003). According to Li et al. (2012), increased lipid peroxidation in soybean may be the result of an increased amount of reactive oxygen species, such as H_2O_2, causing a loss of the cell's membrane function and oxidative damage.

Due to the increased H_2O_2 concentration there was an increased activity of leaf superoxide dismutase (SOD) (Table 2) in the 2013/14 season. There was interaction between tillage systems and irrigation in relation to SOD. SOD activity was higher for the offset double disc system at 1 and 6 DAI. In the same period, except for the knife at 1 DAI, the lowest SOD activity was observed in irrigated systems, thereby demonstrating the importance of the tillage system and, also by reducing oxidative stress in soybean plants grown in areas with the presence of a compacted soil layer, mainly in drought periods. According to Vasconcelos et al. (2009), water stress is one of the main environmental factors causing negative physiological changes in plants. The results obtained by Masoumi et al. (2010) also showed higher SOD activity content in drought conditions when compared with optimal irrigation conditions. Mohamed and Akladious (2014) also found increased SOD, H_2O_2 and lipid peroxidation in soybean leaves during water stress.

According to our results, the effects of tillage systems and border irrigation were more pronouced at 6 DAI (2013/14 season). The concentration of H_2O_2 and MDA and the SOD activity in the knife system were, on average, 14, 5 and 5 % lower, respectively, than in the double disk system. In the chisel plough, the reduction was 33, 9 and 14 %, respectively, compared to the same system prior to the 2013/14 crop. Concerning irrigation, in the same period, H_2O_2, lipid peroxide concentration and SOD activity was, on average, 15, 24 and 20% lower due to irrigation.

In the 2014/15 season, the tillage system effect on the H_2O_2 concentration was diagnosed in all evaluation periods (at 0, 1, and 5 DAI). The greatest difference was observed between the chisel plough system and the offset double disc system. At 0, 1 and 5 DAI in the chisel plough system, the H_2O_2 concentration in plants was 23, 20 and 25% lower in comparison to that of the offset double disc system (2014/15 season).

According to Tuteja and Gill (2010), SOD is one of the most effective antioxidant enzymes and is present in all aerobic organisms and all sub-cellular compartments, representing the plant's first line of defense. SOD acts in the detoxification process, converting the superoxide anion radical into hydrogen peroxide (Damanik et al., 2012). According to Saher et al. (2005), the increase in SOD can be due to the activation of a pre-existing one or a new SOD enzyme.

The guaiacol peroxide activity (POD) (Table 3) showed a different behavior (2013/14 season). The lowest POD activity was observed in the double-disc non-irrigated system. This may be associated to a high plant stress in those treatments, as observed in the results obtained from hydrogen peroxide, lipid peroxides and SOD activity. As a result, the plants' defense system is less pronounced due to the excessive physiological damage compared to conditions of more moderate stress (Masoumi et al., 2010).

In the 2014/15 season (Table 5) at 0 DAI, the chisel plough system presented lower POD activity. At 1 and 5 DAI there was an interaction between the tillage systems and border irrigation. The system with chisel plough showed lower POD activity when compared to the other systems in the presence of irrigation, but there were no differences between the systems without irrigation. In addition, for the double-disc system, the POD activity was greater when there was irrigation. The lower POD activity in the chisel plough indicates lower oxidative stress, which was also indicated by the lower H_2O_2 concentration in the chisel plough system.

The degree of oxidative stress in the cell is determined by the amount of hydrogen peroxide, superoxide and hydroxyl radicals. Therefore, the review of the activities of superoxide dismutase and peroxidase is important in the elimination of toxic levels of ROS in the cells (Apel and Hirt, 2004). The leaf chlorophyll A (Table 3) and B (Table 4) concentrations in the 2013/14 season were generally higher for the double disk system. This might be associated with a dilution effect of the tissue pigments due to the increased plant growth in comparison to that of the knife and chisel plough systems. The plant height and dry mass of shoots at V6 stage were 23, 27 and 28 cm and 4.9, 5.8 and 7.1 g plant^{-1} for double-disc, knife and chisel plough systems, respectively (results not shown).

The ratio of chlorophyll A and B in the offset double disc system was lower at 1 DAI (Table 4), with no differences at 6 DAI (Table 1). At 6 DAI, irrigation increased this ratio. The carotenoid concentration, in general, was lower in the knife and chisel plough systems at 0 and 1 DAI (Table 4). At 6 DAI (Table 2), there were no differences between the tillage systems, and a higher concentration with irrigation when compared to non-irrigation.

In the 2014/15 season (Table 6) at 5 DAI, plants grown in knife and chisel plough systems contained a higher chlorophyll A concentration, but no differences were observed in relation to irrigation. However, for chlorophyll B and the ratio between chlorophyll A and B, there were differences between the tillage systems at 0 DAI only, where in the knife and chisel plough systems, there was chlorophyll A, as well as a lower ratio between them. As for the irrigation treatment, at 5 DAI plants had lower chlorophyll B content in the irrigated system. In that season, there was no difference in the carotenoid concentration between the tillage systems and irrigation.

However, this increase in photosynthetic pigment content in the double-disc system in the previous crop may be associated to the increased plant stress in this system. Carotenoids play a sunscreen role, both by the dissipation of excess energy or heat or by cleaning ROS (Gill and Tujeta, 2010). In their study, Kljak and Grbesa (2015) found a positive correlation between carotenoid levels and TBARS concentration, thereby demonstrating an important role in the plants’ non-enzymatic defense system.

The plant responses to the tillage systems and irrigation treatments were more evident in 2013/14, when compared to the 2014/15 growing seasson. This may be associated to the different rainfall conditions between the two seasons (Figure 1, A and B). In the 2014/15 season there was a higher average rainfall during the plant cycle, which may have minimized the effects of the tillage systems and of the irrigation during the drought period. Moreover, in this season, water deficit occurred during the reproductive phase (R3), unlike the previous season when the water deficit occurred in the vegetative phase (V4).

In this study, the tillage systems were found to be important crop pratices in reducing oxidative stress in soybean plants due to the presence of a compacted soil layer, especially during drought periods. It is also evident that border irrigation, associated to the tillage system, contributes to minimizing drought stress of soybean plants grown in rotation with rice.

Conclusions

The presence of a compacted layer in the soil sub-surface caused oxidative stress in soybean plants during moderate drought periods.

Chisel plough and knife tillage systems decreased the oxidative stresses of soybean plants grown in areas with a compacted soil layer.

Border irrigation in crop areas with a compacted soil layer may reduce oxidative stresses in soybean plants.

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Table 1 - Hydrogen peroxide (H_2O_2) at 0 and 1 days after irrigation (DAI), chlorophyll A (Chlor A), ratio between chlorophyll A and B (A/B), and carotenoids (CAROT) at 6 DAI, according to the tillage systems and irrigation. 2013/14 crop, BMX Tornado cultivar. Santa Maria, Rio Grande do Sul State, 2015.

Tillage systems	H_2O_2 (µmol g^{-1})	CHLOR A (mg g^{-1} FW)	A/B	CAROT (mg g^{-1} FW)
	- 0 DAI[1] -	-------------------- 6 DAI --------------------		
Offset double disc (DD)	0.90 b[*]	1.08 b	0.90 b[*]	1.08 b
Knife	0.96 b	1.07 b	0.96 b	1.07 b
Chisel plough +DD	1.06 a	1.24 a	1.06 a	1.24 a
Irrigation				
Irrigated	0.96 ns	1.07 b	0.96 ns	1.07 b
Non-irrigated	0.99	1.19 a	0.99	1.19 a
Mean	0.97	1.13	0.97	1.13
CV %	5.47	6.00	5.47	6.00
	- 1 DAI -		--- 1 DAI ---	
Offset double disc (DD)	0.95 b		0.95 b	
Knife	1.07 ab		1.07 ab	
Chisel plough +DD	1.12 a		1.12 a	
Irrigation				
Irrigated	1.05 ns		1.05 ns	
Non-irrigated	1.05		1.05	
Mean	1.05		1.05	
CV %	6.29		6.29	

[*] means not followed by the same lowercase letter in the column differ by the Tukey test ($p \leq 0.05$); ^{ns} not significant; [1] 0 DAI, 1 DAI and 6 DAI is equivalent to 20, 21 and 27 days after the plants emergence (DAE), respectively;

Table 2 - Lipid peroxidation (TBARS) and superoxide dismutase (SOD) activity at 0, 1 and 6 days after irrigation (DAI) and hydrogen peroxide (H_2O_2) concentration at 6 DAI, according to the tillage systems and irrigation. 2013/14 crop, BMX Tornado cultivar. Santa Maria, Rio Grande do Sul state, 2015.

Tillage systems	TBARS (nmol of MDA g^{-1} FW)		SOD (Un. Enzyme mL^{-1})	
	Irrigation			
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
	0 DAI[1]			
Offset double disc (DD)	0.49 Aa[*]	0.49 Aa	4.11 Ab	4.04 Ab
Knife	0.42 Ab	0.39 Bb	4.56 Aa	4.32 Aab
Chisel plough +DD	0.34 Bc	0.39 Ab	3.95 Bb	4.67 Aa
Mean	0.42	0.42	4.21	4.34
CV %	2.88		5.30	
	1 DAI			
Offset double disc (DD)	0.35 Bb	0.48 Aa	4.11 Bb	5.14 Aa
Knife	0.36 Ba	0.45 Ab	4.67 Aa	4.56 Bc
Chisel plough +DD	0.22 Bc	0.36 Ac	4.04 Bb	4.89 Ab
Mean	0.31	0.43	4.27	4.86
CV %	0.69		0.80	
	6 DAI			
Offset double disc (DD)	0.59 Bb	0.90 Aa	5.30 Bb	7.05 Aa
Knife	0.66 Ba	0.76 Ab	5.67 Ba	6.12 Ab
Chisel plough +DD	0.59 Bb	0.76 Ab	4.98 Bc	5.70 Ac
Mean	0.61	0.81	5.32	6.29
CV %	0.27		0.91	
	H_2O_2 (µmol g^{-1})			
	6 DAI			
Offset double disc (DD)	1.19 Ba	1.26 Aa		
Knife	0.84 Bb	1.26 Aa		
Chisel plough +DD	0.82 Ab	0.82 Ab		
Mean	0.95	1.11		
CV %	6.29			

[*]means not followed by the same lowercase letter in the column and uppercase letter in the row differ by the Tukey test ($p \leq 0.05$); [ns] not significant in the column; [1] 0 DAI, 1 DAI and 6 DAI is equivalent to 20, 21 and 27 days after the plants emergence (DAE), respectively.

Table 3 - Guaiacol peroxides (POD) and chlorophyll A (Chlor A) at 0, 1 and 6 days after irrigation (DAI), according to the tillage systems and irrigation. 2013/14 crop, BMX Tornado cultivar. Santa Maria, Rio Grande do Sul state, 2015.

Tillage systems	POD (nmol min^{-1} mL^{-1})		CHLOR A (mg g^{-1} FW)	
	Irrigation			
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
	0 DAI[1]			
Offset double disc (DD)	200.52 Ab*	214.06 Ans	1.75 Aa	1.70 Aa
Knife	214.06 Ab	196.01	1.40 Ab	1.01 Bb
Chisel plough +DD	268.19 Aa	186.90 B	1.32 Ab	0.80 Bc
Mean	227.59	198.99	1.49	1.17
CV %	8.55		4.29	
	1 DAI			
Offset double disc (DD)	200.97 Ac	196.46 Aab	1.46 Aa	1.25 Bb
Knife	336.31 Aa	214.51 Ba	0.83 Bb	1.44 Aa
Chisel plough +DD	237.06 Ab	178.42 Bb	0.88 Ab	0.82 Ac
Mean	258.11	196.46	1.06	1.17
CV %	3.34		5.16	
	6 DAI			
Offset double disc (DD)	295.48 Ab	218.79 Bc	-	-
Knife	358.64 Aa	345.11 Ab	-	-
Chisel plough +DD	342.85 Ba	545.86 Aa	-	-
Mean	332.32	369.92	-	-
CV %	3.65		-	

*Means not followed by the same lowercase letter in the column and uppercase letter in the row differ by the Tukey test (*p* ≤ 0.05); ^{ns} not significant in the column; [1] 0 DAI, 1 DAI and 6 DAI is equivalent to 20, 21 and 27 days after the plants emergence (DAE), respectively.

Table 4 - Chlorophyll B (Chlor B) at 0, 1 and 6 days after irrigation (DAI), chlorophyll A and B ratio (A/B), and carotenoids (CAROT) at 0 and 1 days after irrigation (DAI), according to the tillage systems and irrigation. 2013/14 crop, BMX Tornado cultivar. Santa Maria, Rio Grande do Sul state, 2015.

Tillage systems	CHLOR B (mg g^{-1} FW)		A/B	
	Irrigation			
	Irrigated	Non-irrigated	Irrigated	Non-irrigated
	0 DAI[1]			
Offset double disc (DD)	0.72 Aa[*]	0.75 Aa	2.40 Ab	2.26 Ab
Knife	0.45 Ab	0.30 Bb	3.11 Aa	3.33 Aa
Chisel plough +DD	0.44 Ab	0.34 Bc	2.98 Ba	3.35 Aa
Mean	0.54	0.46	2.83	2.98
CV %	2.70		4.14	
	1 DAI			
Offset double disc (DD)	0.54 Aa	0.40 Bb	2.71 Ac	3.10 Ab
Knife	0.29 Bb	0.57 Aa	3.38 Ab	2.53 Ac
Chisel plough +DD	0.22 Ab	0.21 Ac	3.97 Aa	3.85 Aa
Mean	0.35	0.39	3.35	3.16
CV %	3.52		7.16	
	6 DAI			
Offset double disc (DD)	0.16 B^{ns}	0.25 Aa	-	-
Knife	0.16 B	0.21 Ab	-	-
Chisel plough +DD	0.16 B	0.27 Aa	-	-
Mean	0.16	0.24	-	-
CV %	6.44		-	
	CAROT (mg g^{-1} MF)			
	0 DAI		1 DAI	
Offset double disc (DD)	0.54 Aa[*]	0.57 Aa	0.57 Aa	0.49 b
Knife	0.46 Ab	0.37 Bb	0.35 Bb	0.57 Aa
Chisel plough +DD	0.48 Ab	0.34 Bb	0.38 Ab	0.34 Ac
Mean	0.49	0.43	0.43	0.47
CV %	4.31		7.47	

[*] Means not followed by the same lowercase letter in the column and uppercase letter in the row differ by the Tukey test ($p \leq 0.05$); ^{ns} not significant in the column; [1] 0 DAI, 1 DAI and 6 DAI is equivalent to 20, 21 and 27 days after the plants emergence (DAE), respectively.

Table 5 - Hydrogen peroxide (H_2O_2), lipid peroxidation (TBARS), superoxide dismutase (SOD) and guaiacol peroxides (POD) at 0, 1 and 5 days after irrigation (DAI), according to the tillage systems and irrigation. 2014/15 crop, BMX Tornado cultivar. Santa Maria, Rio Grande do Sul state, 2015.

Tillage systems	H_2O_2 (μmol g^{-1})	TBARS (mmol de MDA g^{-1} FW)	POD (nmol min^{-1} mL^{-1})	
	------------------------------- 0 DAI -------------------------------			
Offset double disc (DD)	0.92 a	0.63 ns	240.05 ab	
Knife	0.90 ab	0.59	279.37 a	
Chisel plough +DD	0.71 b	0.54	213.17 b	
Irrigation				
Irrigated	0.81 ns	0.56 ns	245.88 ns	
Non-irrigated	0.87	0.62	242.51	
Mean	0.84	0.59	244.20	
CV %	17.48	18.36	14.37	
	------------------------------- 1 DAI -------------------------------			
			Irrigated	Non-irrigated
Offset double disc (DD)	1.05 a	0.44 ns	493.90 Aa	317,01 Bns
Knife	1.05 a	0.47	311.37 Ab	355,22 A
Chisel plough +DD	0.84 b	0.53	377.23 Ab	339,16 A
Irrigation				
Irrigated	0.98 ns	0.49 ns		
Non-irrigated	0.98	0.47		
Mean	0.98	0.48	365.65	
CV %	9.59	15.45	11.08	
	------------------------------- 5 DAI -------------------------------			
Offset double disc (DD)	1.17 a	0.53 ns	516.33 Aa	389.00 Bns
Knife	1.23 a	0.54	485.9 Aab	392.18 A
Chisel plough +DD	0.88 b	0.49	364.35 Ab	459.69 A
Irrigation				
Irrigated	1.11 ns	0.55 ns		
Non-irrigated	1.07	0.50		
Mean	1.09	0.52	434.57	
CV %	14.83	12.50	16.77	

[*] Means not followed by the same lowercase letter in the column differ by the Tukey test ($p \leq 0.05$); ^{ns} not significant; [1] 0 DAI, 1 DAI and 6 DAI is equivalent to 75, 76 e 80 days after the plants emergence (DAE), respectively.

Table 6 - Chlorophyll A (Chlor A), chlorophyll B (Chlor B), chlorophyll A and B (A/B), and carotenoids (CAROT) at 0, 1 and 5 days after irrigation (DAI), according to the tillage systems and irrigation. 2014/15 crop, BMX Tornado cultivar. Santa Maria, Rio Grande do Sul State, 2015.

Tillage Systems	CHLOR A (mg g^{-1} FW)	CHLOR B (mg g^{-1} FW)	A/B	CAROT (mg g^{-1} FW)
	-------------------------------- 0 DAI[1] --------------------------------			
Offset double disc (DD)	1.20 ns	0.70 b	1.73 a	0.36 b
Knife	1.40	0.98 a	1.42 b	0.46 a
Chisel plough +DD	1.31	0.93 a	1.42 b	0.42 ab
Irrigation				
Irrigated	1.31 ns	0.89 ns	1.49 ns	0.41 ns
Non-irrigated	1.30	0.84	1.56	0.41
Mean	1.30	0.87	1.52	0.41
CV %	16.18	16.30	13.93	15.89
	-------------------------------- 1 DAI --------------------------------			
Offset double disc (DD)	1.44 ns	1.08 ns	1.40 ns	0.54 ns
Knife	1.52	1.09	1.43	0.51
Chisel plough +DD	1.66	1.36	1.31	0.57
Irrigation				
Irrigated	1.53 ns	1.09 ns	1.44 ns	0.53 ns
Non-irrigated	1.55	1.26	1.32	0.55
Mean	1.54	1.18	1.38	0.54
CV %	19.99	31.08	11.94	29.86
	-------------------------------- 5 DAI --------------------------------			
Offset double disc (DD)	1.31 b	0.87 ns	1.51 ns	0.44 ns
Knife	1.67 a	1.19	1.41	0.57
Chisel plough +DD	1.56 ab	1.16	1.39	0.53
Irrigation				
Irrigated	1.41 ns	0.95 b	1.50 ns	0.46 ns
Non-irrigated	1.62	1.20 a	1.38	0.56
Mean	1.51	1.08	1.44	0.51
CV %	16.50	26.06	9.91	28.9

[*] Means not followed by the same lowercase letter in the column differ by the Tukey test ($p \leq 0.05$); ^{ns} not significant; [1] 0 DAI, 1 DAI and 6 DAI is equivalent to 75, 76 e 80 days after the plants emergence (DAE), respectively.

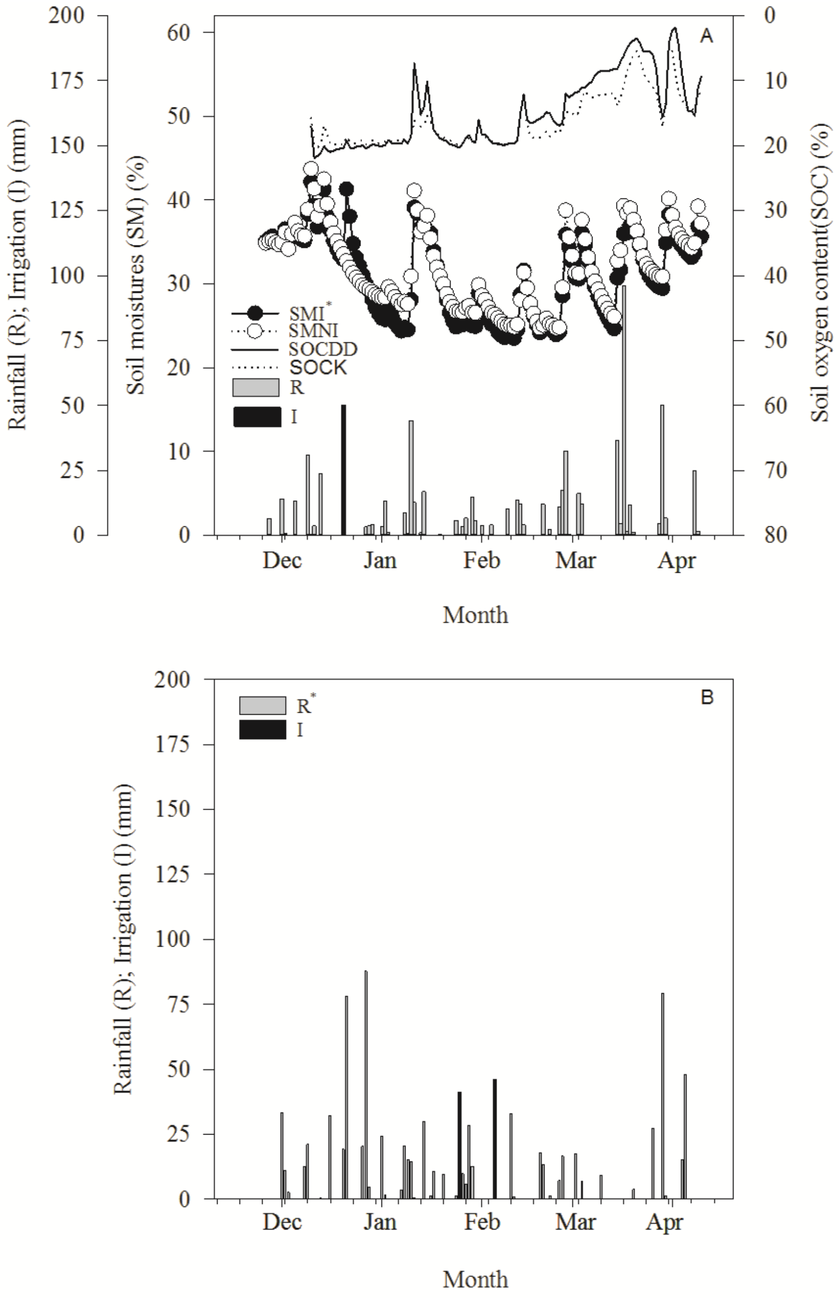

Figure 1 - Soil moisture of an irrigated and non irrigated, rainfall, irrigation and oxygen content in the soil in the 2013/14 crop (A) and rainfall and irrigation in the 2014/15 crop (B). Santa Maria, RS. 2015. SMI = Soil moisture irrigated; SMNI = Soil moisture non-irrigated; SOCDD = soil oxygen content in the offset double disc system; SOCK = soil oxygen content in the knife system; R = Rainfall; I = Irrigation.

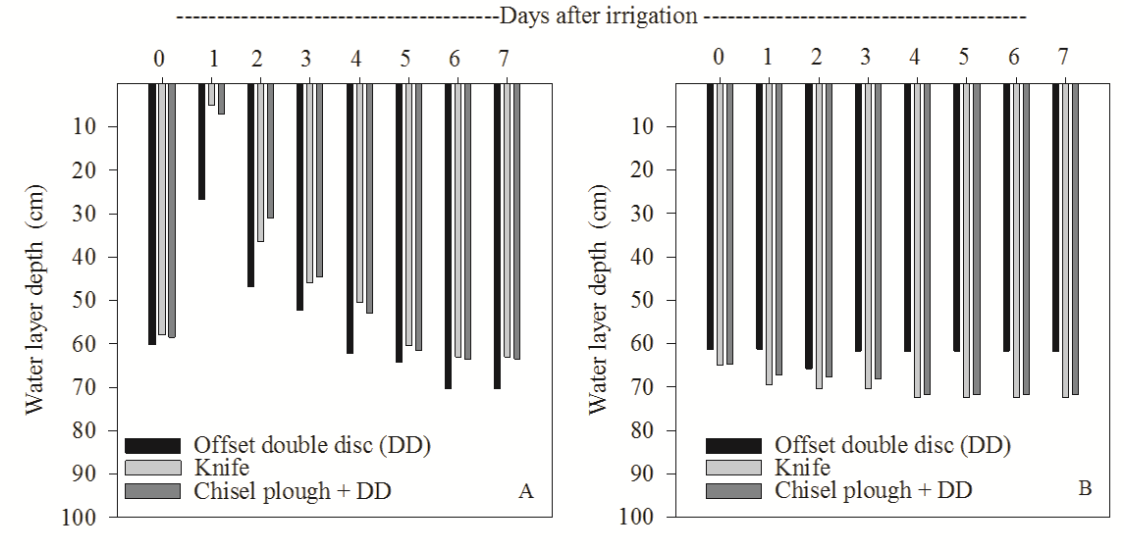

Figure 2 - Water layer depth for different tillage systems irrigated (A) and non-irrigated (B) in the 2013/14 crop. Santa Maria, RS. 2015.

Figure 3 - Figures A and B illustrate the tillage systems used: seeding with offset double disc (DD) in the planter (A), seeding using the knife in the planter (B), and chisel plough (C) with seeding using offset double disc in the planter. The D figure illustrates the border irrigation in the 2013/14 crop at V4 stage. Figure E illustrates the arrangement in the experimental area of treatments, irrigated and non-irrigated, and at 0 days after irrigation (DAI). Figure F shows the irrigation in the 2014/15 crop, at R5 stage.

3.4 ARTIGO 4

Rendimento de grãos de soja em função de sistemas de plantio e irrigação por superfície em Planossolos

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Resumo – O objetivo desse trabalho foi avaliar sistemas de implantação e irrigação suplementar em faixas irrigadas no rendimento de grãos de soja em áreas com presença de camada compactada próxima à superfície do solo. Dois experimentos foram conduzidos em Santa Maria-RS correspondendo às safras de 2013/2014 e 2014/2015 (Experimento 1), e outro em Formigueiro-RS na safra 2013/2014 (Experimento 2), ambos conduzidos em blocos ao acaso, em faixas, com quatro repetições). Os tratamentos consistiram de: Fator A (Sistemas de implantação: A1, semeadura com disco duplo desencontrado; A2, semeadura com disco ondulado de 12 ondas; A3, semeadura com haste sulcadora; A4, semeadura com haste sulcadora + mecanismo de acomodação do solo; A5, semeadura em microcamalhão e A6, escarificação do solo + semeadura com disco duplo desencontrado) e Fator D (com e sem irrigação). Na safra 2014/15 alterou-se o fator A4 por haste desencontrada 5 cm da linha de semeadura. O experimento 2 foi constituído apenas do fator A do experimento 1, porém sem o tratamento microcamalhão. Os sistemas com escarificação do solo e haste sulcadora são os que proporcionam maior rendimento de grãos. A irrigação realizada em umidade do solo abaixo de 60% da capacidade de campo resulta em acréscimo no rendimento de grãos.

Termos para indexação: *Glycine max*, camada compactada do solo, mecanismos da semeadora, áreas de várzea, nodulação.

Soybean yield under different planting systems and border irrigation on Alfisols

Abstract - The objective was to evaluate the effect of tillage systems and border irrigation on soybean yield in areas with presence of a compacted layer in the sub-surface. Two experiments were conducted at Santa Maria-RS in the 2013/14 and 2014/15 growing seasons (experiment 1) and other at Formigueiro-RS in 2013/14 crop season (experiment 2). Experiment 1 was a randomized block, factorial, with four replications. The tested treatments were: Factor A (Crop tillage systems: A1, sowing using double disc; A2, sowing using notched disc; A3, sowing using shank; A4, sowing using shank + soil accommodation mechanism; A5, raised bed system and A6, deep tillage + sowing using double disc). Factor D (irrigated and non-irrigated). In the 2014/15 growing season the factor A4 was changed using a shank 5 cm from the seeding line. The experiment 2 was performed as the factor A from experiment 1, but without the raised bed system. System with deep tillage and sowing using a shank provide higher soybean grain yield. The irrigation applied when soil moisture reached 60% of field capacity increased soybean grain yield.

Index terms: *Glycine max*, soil compaction, planter mechanism, lowland areas, nodulation.

Introdução

A cultura da soja é uma importante alternativa de cultivo para rotação de culturas em áreas de várzeas cultivadas com arroz irrigado, pois contribui para a interrupção de ciclos de doenças e insetos-praga e melhora nas condições físicas e químicas do solo (Thomas et al., 2000). Por ser de outra família de plantas utiliza-se herbicidas com mecanismos de ação diferentes daqueles utilizados no arroz, contribuindo para controle de plantas daninhas de difícil controle no arroz, especialmente o arroz vermelho (Missio et al., 2010).

A maioria das áreas utilizadas para o cultivo do arroz irrigado pertence à classe Planossolos (Bamberg et al., 2009). Esses solos são imperfeitamente ou mal drenados, com horizonte superficial ou subsuperficial eluvial, de textura mais leve, contrastando abruptamente com o horizonte B, ou com transição abrupta conjugada com acentuada diferença de textura do horizonte A para o B, adensado, geralmente com elevada concentração de argila, e de permeabilidade lenta ou muito lenta. Em áreas de várzeas, em condições de clima úmido, são considerados hidromórficos, com horizonte plânico, apresentando características de horizonte glei (Embrapa, 2013). Somado a isso, em função das práticas de preparo do solo para o cultivo do arroz irrigado, parte dessas áreas apresenta presença de camada compactada, em média na camada de 7 - 17 cm de profundidade, influenciando na quantidade de macroporos (Valicheski et al., 2012), na porosidade total (Drescher et al., 2011) e nas relações solo-ar-água. Em função das características intrínsecas dessa classe de solo, associada à presença de uma camada compactada ocorrem estresses nas plantas de soja em anos de excesso e de déficit hídrico, com efeitos negativos no crescimento das plantas e na fixação biológica de nitrogênio (Abreu et al., 2004), podendo interferir no rendimento de grãos da cultura.

Nesse contexto, torna-se fundamental identificar alternativas para a minimização desses estresses, pois o êxito de culturas como a soja depende da adequação do ambiente de várzea às suas exigências agronômicas (Vernetti Junior et al., 2009). Em anos de excesso de chuvas, é necessário reduzir o tempo de estresse da planta por falta de oxigênio, especialmente na região de maior volume de raízes e nódulos, o que pode ser feito através de implementos agrícolas para que as plantas possam apresentar melhor desempenho agronômico. A escarificação do solo, ou o uso de diferentes mecanismos da semeadora durante a operação de semeadura, a exemplo da haste sulcadora, tem apresentado efeitos positivos na descompactação do solo na linha de cultivo (Drescher et al., 2011). O sistema de implantação em microcamalhão, onde a água da irrigação é derivada no sulco entre dois microcamalhões, é muito utilizado nos Estados Unidos, Ásia, Austrália e México, pois permite o cultivo de soja, milho, sorgo, algodão e trigo em áreas excessivamente úmidas e/ou frias, com economia de água e excelentes rendimentos. Entretanto, no Brasil, essa prática é pouco utilizada pelos agricultores, pois não há informação suficiente sobre esse sistema, assim como sobre o uso de mecanismos da semeadora como disco duplo, disco ondulado e haste sulcadora para implantação de culturas como a soja em área de várzea.

Informações sobre o uso da irrigação em faixas ou canteiros no cultivo da soja em várzea são escassas, devido à ausência de pesquisas específicas sobre a rotação de culturas e sistemas de implantação em várzeas, com exceção do arroz. Consequentemente, estudos sobre o efeito da irrigação em soja nessas áreas são fundamentais, pois o estresse hídrico pode causar redução do potencial hídrico foliar, fechamento estomático, diminuição da taxa fotossintética, redução da parte aérea, aceleração da senescência e abscisão das folhas (Ferrari et al., 2015), uma vez que a água é um dos principais fatores que afeta o rendimento de grãos de soja (Fernandes & Turco, 2003). De acordo com Zhang et al. (2015), a irrigação contribui para diminuir os impactos climáticos negativos, especificamente seca e calor extremos na cultura da soja, podendo também minimizar parte dos efeitos causados pela camada compactada do solo (Kirnak et al., 2013).

Em função disso, o trabalho teve por objetivo avaliar sistemas de implantação e irrigação suplementar em faixas irrigadas no rendimento de grãos de soja em áreas com presença de camada compactada próxima à superfície do solo.

Material e Métodos

Foram realizados dois experimentos, sendo o experimento 1 na safra de 2013/14 e 2014/15 em Santa Maria, Rio Grande do Sul (RS) e o experimento 2 na safra de 2013/14 em Formigueiro, RS. O experimento 1 foi realizado em área de várzea sistematizada pertencente a Universidade Federal de Santa Maria, em locais diferentes da área experimental nos dois anos. O solo em que foi realizado o experimento é classificado como Planossolo Háplico Eutrófico arênico, pertencente à unidade de mapeamento Vacacaí (Embrapa, 2013) e continha os seguintes atributos físico-químicos aos 60 dias antes da semeadura na camada de 0,0 – 20 cm: argila = 25%; pH $_{\text{água}}$ (1:1) = 5,4; P = 18 mg dm^{-3}; K = 60 mg dm^{-3}; Ca = 5,3 cmol$_c$ dm^{-3}; Mg = 2,4 cmol$_c$ dm^{-3} e M.O. = 2,0 % (safra 2013/14), e argila = 26%; pH $_{\text{água}}$ (1:1) = 5,4; P = 15,3 mg dm^{-3}; K = 44 mg dm^{-3}; Ca = 8,3 cmol$_c$ dm^{-3}; Mg = 3,1 cmol$_c$ dm^{-3} e M.O. = 2,0 % (safra 2014/15). Nesta mesma época o solo continha valores médios na camada de 0,0 – 20 cm de densidade, porosidade total, microporosidade e macroporosidade de: 1,50 Mg m^{-3}, 0,48 m^{3}m^{-3}, 0,36 m^{3}m^{-3} e 0,10 m^{3}m^{-3}, respectivamente (safra de 2013/14) e 1,53 Mg m^{-3}, 0,40 m^{3}m^{-3}, 0,32 m^{3}m^{-3} e 0,09 m^{3}m^{-3}, respectivamente (safra de 2014/15). Aos dez dias antes da semeadura utilizando-se penetrômetro digital da marca Falcker modelo PLG 1020, o solo continha os seguintes valores de resistência à penetração: 0,2; 1,6; 2,1; 2,1; 1,9 e 1,7 MPa (safra 2013/14) e 0,2; 3,0; 2,3; 2,1; 1,0; 0,6 MPa (safra 2014/15) nas camadas do solo de 0 – 5, 5 – 10, 10 – 15, 15 – 20, 20 – 25 e 25 – 30 cm de profundidade, respectivamente. A umidade volumétrica do solo por ocasião da avaliação era de 26 e 20% para as safras 2013/14 e 2014/15, respectivamente.

O delineamento experimental foi o de blocos ao acaso, em esquema fatorial (6x2), em faixas, com quatro repetições. Os tratamentos consistiram: Fator A (Sistemas de implantação: A1, semeadura com disco duplo desencontrado; A2, semeadura com disco ondulado de 12 ondas; A3, semeadura com haste sulcadora; A4, semeadura com haste sulcadora + mecanismo de acomodação do solo; A5, semeadura em microcamalhão e A6, escarificação do solo + semeadura com disco duplo desencontrado) e Fator D (com e sem irrigação). Na safra 2014/15 alterou-se o fator A4 por haste desencontrada 5 cm da linha de semeadura. O experimento 2 foi realizado em área com relevo suave ondulado, sendo o solo classificado como Planossolo Háplico Eutrófico típico pertencente à unidade de mapeamento São Gabriel (Embrapa, 2013), com os seguintes atributos físico-químicos aos 50 dias antes da semeadura na camada de 0,0 – 20 cm: argila = 34%; pH $_{\text{água}}$ (1:1) = 5,2; P = 2,2 mg dm^{-3}; K = 112 mg dm^{-3}; Ca = 10,5 cmol$_c$ dm^{-3}; Mg = 8,0 cmol$_c$ dm^{-3} e M.O. = 1,6 %. Aos dez dias antes da semeadura, na camada de 0,0 – 20 cm o solo continha os seguintes valores de densidade, porosidade total, microporosidade e macroporosidade de: 1,60 Mg m^{-3}, 0,36 m^{3}m^{-3}, 0,35 m^{3}m^{-3} e 0,03 m^{3}m^{-3}, respectivamente, e resistência à penetração de 0,3; 3,0; 1,8; 1,4; 1,2 e 1,3 MPa nas camadas do solo de 0 – 5, 5 – 10, 10 – 15, 15 – 20, 20 – 25 e 25 – 30 cm de profundidade. Por ocasião da avaliação de resistência a penetração o solo continha umidade volumétrica média de 25,5%.

O delineamento utilizado para o experimento 2 foi em blocos ao acaso, com quatro repetições. Os tratamentos foram os mesmos do experimento 1 na safra 2013/14, porém, sem o tratamento microcamalhão e irrigação.

A escarificação do solo no experimento 1 na safra de 2013/14 foi realizada aos 45 dias antes da semeadura e na safra de 2014/15 aos 19 dias antes da semeadura. No experimento 2 a escarificação do solo foi realizada por ocasião da semeadura. A profundidade da escarificação do solo foi aos 25 cm, sendo o espaçamento entre as hastes do escarificador de 35 cm. A profundidade de trabalho da haste sulcadora, da haste sulcadora no sistema em microcamalhão, do disco duplo e do disco ondulado no solo foi aproximadamente de 18; 12; 10 e 8 cm, respectivamente.

A semeadura do experimento 1 foi realizada nos dias 7 e 14 de novembro de 2013 e 2014, respectivamente, utilizando uma semeadora adubadora pantográfica. Em decorrência de uma precipitação pluvial de 245 mm aos dois dias após a semeadura na safra 2013/14, foi realizada a ressemeadura do experimento no dia 26 de novembro de 2013. A semeadura do experimento 2 foi realizada no dia 5 de novembro de 2013. A cultivar de soja utilizada para ambos os experimentos foi a BMX Tornado RR (6863 RSF) na quantidade de 26 sementes m^{-2}, sendo 0,5 m a distância entre linhas.

As sementes foram tratadas com fipronil (250 g L^{-1}) e carbendazim + thiram (150 g L^{-1} + 350 g L^{-1}), na dose de 150 mL e 200 mL 100 kg^{-1} de semente, respectivamente. Também foram inoculadas com estirpes de *Bradyrhizobium japonicum* (100 g 50 kg^{-1} de semente). A adubação de base na safra de 2013/14 para o experimento 1 e 2 foi de 30 kg ha^{-1} de nitrogênio (N), 60 kg ha^{-1} de P_2O_5 e 60 kg ha^{-1} de K_2O. No entanto, para o experimento 1, em função da ressemeadura utilizou-se mais 10 kg ha^{-1} de nitrogênio (N), 20 kg ha^{-1} de P_2O_5 e 20 kg ha^{-1} de K_2O. Na safra de 2014/15 a adubação de base foi de 13 kg ha^{-1} de nitrogênio (N), 55 kg ha^{-1} de P_2O_5 e 87 kg ha^{-1} de K_2O. Os demais tratos culturais foram realizados conforme as recomendações técnicas para cultura (Embrapa, 2012).

A irrigação utilizada foi por superfície, em faixas irrigadas, utilizando-se uma vazão média de 5 Ls^{-1}. No experimento 1 foi realizada uma irrigação na safra de 2013/14, sendo a lâmina de irrigação de 55 mm quando a umidade média do solo se encontrava em 58% da capacidade de campo (CC) na profundidade de 0-20 cm, no estádio V4 das plantas e duas irrigações na safra de 2014/15, sendo uma de 41 mm no estádio R3 e a outra de 46 mm em R5, segundo escala de Fehr & Caviness (1977). A umidade do solo na camada de 0-20 cm em

R3 e R5 encontrava-se em 60,6% e 54,2% da CC, respectivamente. As unidades experimentais mediram 40 x 3 m e 60 x 3 m para os experimentos 1 e 2, respectivamente, sendo a área útil de 15 m^2 cada.

Avaliou-se o conteúdo de oxigênio do solo durante todo o ciclo da cultura na profundidade de 0-10 cm por meio do medidor de oxigênio modelo ICT-SOM, utilizando sensores de oxigênio modelo ICT-$O_{2,}$ sendo os sensores colocados na linha de semeadura. Avaliou-se, ainda, a densidade do solo (Ds), porosidade total (PT), microporosidade (Mi) e macroporosidade (Ma) do solo no estádio V6 das plantas. Para essa avaliação coletaram-se amostras de solo nas camadas de 0 – 10 e de 10 – 20 cm, na linha de semeadura da cultura, utilizando anéis volumétricos de 4,0 e 4,8 cm de altura e diâmetro, respectivamente. Após as coletas, as amostras de solo foram encaminhadas para laboratório sendo analisadas segundo as técnicas descritas por Donagema et al. (2011). A Ds foi determinada pelo método volumétrico, a PT foi assumida como a umidade de saturação, a Mi pelo método da mesa de tensão a 0,6 m e a Ma pela diferença entre PT e Mi.

Após a obtenção dos resultados realizou-se a média das duas camadas de solo, obtendo-se os resultados referente a camada de 0 – 20 cm.

Nas plantas, as variáveis avaliadas foram: estatura de plantas, área foliar, matéria seca da parte aérea, número e matéria seca de nódulos e rendimento de grãos. As cinco primeiras avaliações foram realizadas nos estádios V6 e R3, para ambos os experimentos, com exceção do índice de área foliar que foi apenas em V6 e da nodulação das plantas que, no experimento 2, foi realizada em R3.

Para avaliar a estatura das plantas, a área foliar, e a matéria seca da parte aérea, coletou-se a parte aérea de cinco plantas em sequencia na linha de cultivo rente ao solo, posteriormente acondicionadas em embalagens plásticas e encaminhadas para laboratório. Nas cinco plantas determinou-se a estatura com régua graduada e a área foliar em três plantas usando medidor portátil, modelo LI-3000C (LI-COR, Inc.), calculando-se após o IAF segundo Radin et al. (2003). Após essas avaliações, a parte aérea das cinco plantas foi seca em estufa de circulação forçada de ar a temperatura de 65°C até matéria constante.

Para a determinação da nodulação, coletou-se um monólito de solo de 40 x 40 x 20 cm (comprimento, largura e profundidade), com as raízes das cinco plantas para avaliar o número de nódulos por planta, a viabilidade de nódulos e matéria seca dos nódulos segundo metodologia de Vieira Neto et al.(2008). O rendimento de grãos foi avaliado no final do ciclo (R8) a partir da parcela útil de 10 m^2.

Os valores de precipitação pluvial para o experimento 1 foram obtidos da estação meteorológica automática do 8° DISME/INMET localizado no Departamento de Fitotecnia da UFSM, a aproximadamente 500 m do experimento. Para o experimento 2 foram obtidos por pluviômetro marca ACU RITE, instalado a 200 m do experimento. Os resultados avaliados foram submetidos ao teste das pressuposições do modelo matemático (normalidade e homogeneidade das variâncias). A análise da variância dos dados dos experimentos foi realizada através do teste F. As médias dos fatores, quando significativas, foram comparadas pelo teste de Tukey a 5% de probabilidade de erro.

Resultados e Discussão

A área em que foi realizado o experimento 1 continha resistência à penetração de 2,1 MPa na camada de 10 – 20 cm na safra de 2013/14 e de 3,0 MPa na camada de 5 – 20 cm na safra de 2014/15. Os sistemas de implantação influenciaram na qualidade física do solo no experimento 1 (Tabela 1). Os sistemas que utilizaram haste sulcadora na semeadora, o sistema em microcamalhão e a escarificação do solo reduziram a densidade média do solo na camada de 0 – 20 cm e aumentaram a porosidade total e macroporosidade do solo nessa mesma camada de solo na linha de semeadura, em comparação ao disco duplo e ondulado na safra de

2013/14 e 2014/15. Os discos duplos e ondulado não foram eficientes em reduzir a camada compactada na linha de semeadura, estando de acordo com os resultado obtidos por Drescher et al. (2011), em que o disco apresenta menor resposta de rompimento da camada compactada, estando isso associado ao menor efeito em profundidade no solo. De acordo com Nunes et al. (2014), o emprego da haste sulcadora proporciona aumento da macroporosidade, da porosidade total e redução da densidade do solo e resistência à penetração da camada compactada na linha de cultivo

Observou-se que os sistemas de implantação influenciaram a qualidade física do solo, com resposta no crescimento das plantas (estatura e matéria seca da parte aérea). De maneira geral, o sistema com escarificação do solo, seguido dos sistemas com haste sulcadora e microcamalhão resultaram em maior estatura de plantas e massa seca da parte aérea nos estádios V6 e R3 nas safras de 2013/14 e de 2014/15. Para o índice de área foliar (IAF), a maior resposta foi no sistema com escarificação do solo o qual proporcionou maior IAF. Além disso, houve maior número e matéria seca de nódulos no estádio V6 para o sistema com escarificação do solo na safra 2013/14 (Tabela 2). Resultado semelhante ocorreu para a safra 2014/15, em que houve maior número e matéria seca de nódulos em V6 e R3 para esse sistema, seguido dos sistemas com haste sulcadora e em microcamalhão. A menor nodulação foi verificada no sistema de semeadura utilizando disco duplo (safra 2013/14) e disco duplo e disco ondulado (safra 2014/15). Além disso, no sistema com disco duplo houve maior inviabilização de nódulos no estádio V6, em ambas as safras (Tabela 2 e 3).

Esse resultado está associado ao menor efeito de redução da camada compactada do solo por esses sistemas na linha de semeadura em comparação aos demais, visto que a nodulação e a fixação biológica de nitrogênio são afetadas pela presença de camada compactada do solo (Siczek & Lipiec, 2011). Esses autores encontraram redução do número de nódulos por planta e redução da atividade da nitrogenase na presença de camada compactada.

Um dos efeitos indiretos da presença de camada compactada do solo na fixação biológica de nitrogênio ocorre pela redução do conteúdo de oxigênio no solo, inviabilizando a respiração das raízes (Lanza et al., 2013). Além disso, a atividade da nitrogenase é altamente dependente da disponibilidade de oxigênio (Justino & Sodek, 2013). Sendo assim, no presente experimento (Figura 1 A), observa-se que o conteúdo de oxigênio no solo na safra de 2013/14 foi menor para a maioria dos meses de desenvolvimento das plantas no sistema com disco duplo, em comparação ao sistema com haste sulcadora. Nesse contexto, uma das possíveis explicações para maior nodulação no sistema com escarificação do solo, seguido dos sistemas com haste sulcadora e microcamalhão é que esses sistemas tenham proporcionado maior conteúdo de oxigênio no solo na linha de semeadura, em função do aumento da macroporosidade do solo o qual auxilia na drenagem e na aeração do solo.

Além de se ter verificado efeitos benéficos dos sistemas com haste (escarificação do solo, semeadura com haste sulcadora e semeadura em microcamalhão com haste sulcadora) na redução da camada compactada na linha de semeadura o que melhorou a qualidade física do solo, o crescimento e nodulação das plantas, se observou que a irrigação também é uma importante prática de manejo em soja cultivada em área com camada compactada.A realização de uma irrigação de 55 mm proporcionou maior estatura e matéria seca da parte aérea. Ruviaro et al. (2011), também encontraram resposta significativa da irrigação em comparação à testemunha sem irrigação, encontrando uma correlação de 93% entre o volume de água aplicado e a estatura das plantas. De acordo com Ferrari et al. (2015), o estresse causado por deficiência de água leva a ocorrência de plantas de soja pouco desenvolvidas, com pequena estatura e área foliar reduzida, pois uma das alterações provocada pelo estresse hídrico é a redução do potencial hídrico foliar, ocasionando fechamento estomático, e consequentemente, a diminuição das trocas gasosas, inibição de vários processos bioquímicos e fisiológicos, como a fotossíntese, respiração, absorção de íons, metabolismo dos nutrientes, entre outros. Somado a isso, a irrigação incrementou a matéria seca de nódulos (Tabela 2), visto que a nodulação é influenciada pelo conteúdo de água no solo (Siczek & Lipiec, 2011), sendo a fixação biológica de nitrogênio um processo metabólico muito sensível ao déficit de água em plantas de soja (Quintana et al., 2013; King et al., 2014).

A redução da camada compactada no solo na linha de semeadura pelos sistemas com haste impactou positivamente no rendimento de grãos de soja em ambas as safras. Na safra de 2013/14 (Tabela 3), o sistema com escarificação do solo proporcionou maior rendimento em comparação ao sistema utilizando o disco duplo, o qual, em números absolutos foi o sistema que apresentou o menor rendimento entre todos os sistemas testados. A escarificação do solo incrementou a produtividade em 10%. Na safra de 2014/15, os resultados foram semelhantes aos da safra 2013/14, em que o maior rendimento foi observado para o sistema com escarificação do solo, seguido dos sistemas de semeadura com haste sulcadora, haste sulcadora desencontrada a 5 cm da linha de semeadura e microcamalhão, sendo os menores rendimentos de grãos nos sistemas com disco ondulado e duplo. O sistema com escarificação do solo, seguido da semeadura com haste e haste desencontrada a 5 cm proporcionaram rendimento de 26, 15 e 12% superior ao disco duplo.

A irrigação de 55 mm, realizada em V4, resultou em aumento de 10% no rendimento de grãos na safra de 2013/14 e 8% na safra de 2014/15, quando foram aplicadas duas irrigações, de 41 mm e de 46 mm, nos estádio R3 e R5, respectivamente. A água é fundamental para que a planta expresse seu potencial de resposta a toda e qualquer tecnologia empregada pois, segundo Ruviaro et al. (2011), o uso da irrigação está diretamente relacionada à expressão do potencial da cultura. Essa limitação ocorre, pois a água está envolvida na maioria dos processos bioquímicos e fisiológicos da planta (King et al., 2014;

Du et al., 2015; Ferrari et al., 2015). Além disso, o aumento do rendimento de grãos em função da irrigação pode estar relacionado à maior nodulação das plantas, como foi verificado no presente estudo, pois a nodulação é um fator determinante no rendimento de grãos, estando correlacionada com 40% do rendimento (Brandelero et al., 2009).

No experimento 2, a área em que foi realizado esse estudo também apresentou uma camada compactada próxima a superfície do solo, sendo esta caracterizada entre 5 – 15 cm, possuindo valores de resistência do solo à penetração de até 3,0 MPa. Assim como observado nas duas safras de estudo no experimento 1, nesse experimento também se observou um efeito positivo dos sistemas com escarificação do solo e haste sulcadora na redução da camada compactada na linha de semeadura. De acordo com os resultados, esses sistemas reduziram a densidade do solo e aumentaram a porosidade total e a macroporosidade média na camada de 0 – 20 cm (Tabela 1). Em função disso, esses sistemas impactaram positivamente no crescimento, nodulação e no rendimento de grãos.

No sistema com escarificação do solo houve maior estatura de plantas em R3 e matéria seca da parte aérea e índice de área foliar em V6 (Tabela 1). Além disso, nesse sistema e no sistema com haste sulcadora as plantas apresentaram maior número e matéria seca de nódulos. Diferentemente do experimento 1, nesse experimento não se observou efeito na inviabilidade de nódulos. Isso pode estar atrelado às condições locais de solo de cada experimento, principalmente quanto ao relevo da área, que no experimento 1 é plano, e nesse é suavemente ondulado.

Para o rendimento de grãos, o uso da haste sulcadora na semeadora incrementou em 12% o rendimento em relação ao disco duplo (Tabela 3). Assim como observado no experimento 1, o menor rendimento de grãos foi no sistema com disco duplo, em função de seu menor efeito de rompimento da camada compactada do solo, o que afetou o crescimento e a nodulação das plantas, sendo que o último interfere na disponibilidade de nitrogênio às plantas (Siczek & Lipiec, 2011).

Nesse experimento, o sistema com escarificação do solo apresentou menor rendimento de grãos em comparação a haste sulcadora. A hipótese para tal fato é que a escarificação do solo para esse experimento foi realizada no mesmo dia da semeadura, seguida de duas gradagens para a uniformização da área para a semeadura que, somado a uma precipitação de aproximadamente 200 mm durante um período de três dias após a semeadura, pode ter causado maior desestruturação do solo em comparação a semeadura com haste sulcadora.

No experimento 2 (Formigueiro) o rendimento de grãos foi menor que no experimento 1 (Santa Maria), podendo isso estar atrelado à menor nodulação das plantas e também a menor precipitação pluvial para alguns meses comparado com Santa Maria (Figura 1 D), visto que a nodulação (Brandelero et al., 2009) e a disponibilidade de água estão diretamente relacionadas com o rendimento de grãos de soja (Ruviaro et al., 2011).

De acordo com os resultados obtidos nos dois experimentos e safras agrícolas, observa-se que há resposta diferenciada dos sistemas de implantação na redução da camada compactada e no rendimento de grãos de soja. Os sistemas com escarificação do solo, haste sulcadora e microcamalhão com haste sulcadora reduzem a densidade do solo, promovendo aumento da porosidade total e macroporosidade, incrementando o rendimento de grãos de soja em área com camada compactada. A utilização apenas dos mecanismos com disco duplo e disco ondulado de forma isolada, não é eficiente na redução da camada compactada quando comparado aos sistemas com haste, apresentando o menor rendimento de grãos.

Assim, em áreas que apresentam a presença de camada compactada próxima à superfície do solo, principalmente nas áreas em rotação com a cultura do arroz irrigado, recomenda-se o uso de sistemas com haste, seja escarificação do solo, ou apenas uso da haste sulcadora na semeadora isolada ou no sistema em microcamalhão, para que se tenha maior rendimento de grãos de soja. A irrigação suplementar em épocas de déficit hídrico, quando a umidade do solo se encontra abaixo de 60% da capacidade de campo também é uma prática recomendada, buscando minimizar os efeitos da camada compactada, e do déficit hídrico, promovendo aumento do rendimento de grãos da cultura da soja.

Conclusões

1. Os sistemas com escarificação do solo e haste sulcadora na semeadura proporcionam maior rendimento de grãos de soja em áreas que apresentam uma camada compactada próxima a superfície do solo.
2. Irrigação suplementar por faixas realizada em condições de umidade do solo abaixo de 60% da capacidade de campo resulta em acréscimo no rendimento de grãos de soja.

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Tabela 1. Densidade do solo (Ds), porosidade total (PT), microporos (Mi), macroporos (Ma), estatura de planta (E) e matéria seca da parte aérea (MSPA) nos estádios V6 e R3 e índice de área foliar (IAF) no estádio V6, em função dos sistemas de implantação e da irrigação. Cultivar BMX Tornado, Santa Maria safras 2013/14 e 2014/15 e Formigueiro safra 2013/14, RS. 2015.

Sistemas de implantação	Ds g cm3	PT	Mi cm^{3}cm^{-3}	Ma	E (cm)		MSPA (g planta^{-1})		IAF
	V6[1]				V6[1]	R3[1]	V6	R3	V6
-------------------------------- Safra 2013/14 --------------------------------									
Experimento 1 – Santa Maria									
Disco duplo (DD)	1,5	0,45	0,35	0,11	22,9 c[*]	52,3 ab	4,9 bc	19,7 ab	2,2 b
Disco ondulado	1,5	0,46	0,34	0,12	23,7 bc	52,8 ab	4,5 c	19,4 ab	2,2 b
Haste	1,4	0,50	0,34	0,16	26,7 ab	51,4 ab	5,8 b	20,5 ab	3,0 ab
Haste + MAS	1,4	0,49	0,34	0,17	26,0 abc	51 b	5,4 bc	17,8 b	2,6 b
Microcamalhão	1,4	0,50	0,33	0,17	26,4 ab	50,4 b	5,7 bc	19,7 ab	2,4 b
Escarificado + DD	1,4	0,49	0,33	0,17	28,1 a	56,8 a	7,1 a	23,1 a	3,9 a
Irrigação									
Com irrigação	-	-	-	-	28,2 a	54,8 a	6,4 a	19,9 ns	3,1 ns
Sem irrigação	-	-	-	-	23,0 b	50,0 b	4,7 b	20,1	2,4
Média	-	-	-	-	25,6	52,4	5,55	20	2,7
CV (%)	-	-	-	-	7,1	4,4	13,0	14,0	13,7
Experimento 2 - Formigueiro									
Disco duplo (DD)	1,5	0,43	0,35	0,08	16 ns	40 b[*]	3,2 ab	14 ab	2,4 ab
Disco ondulado	1,5	0,41	0,37	0,06	16,2	37,7 b	2,6 b	11,8 b	1,7 b
Haste	1,3	0,50	0,34	0,16	15,7	44,7 ab	3,5 ab	19,0 a	2,4 ab
Haste + MAS	1,3	0,49	0,34	0,16	16,6	43,7 ab	4,1 ab	16,1 ab	2,8 ab
Escarificado + DD	1,3	0,48	0,35	0,16	19,1	49,2 a	5,7 a	15,4 ab	3,8 a
Média	-	-	-	-	16,7	43,1	3,3	15,3	2,6
CV (%)	-	-	-	-	10,4	7,3	29,6	16,3	17,4
-------------------------------- Safra 2014/15 --------------------------------									
Experimento 1 – Santa Maria									
Disco duplo (DD)	1,6	0,37	0,32	0,06	12,2 cd[*]	38,7 c	2,7 ab	12,4 bc	0,4 b
Disco ondulado	1,4	0,44	0,31	0,12	11,9 d	37,9 c	2,5 b	9,9 c	0,4 b
Haste	1,3	0,50	0,31	0,17	14,1 bc	42,2 bc	3,0 ab	11,7 bc	0,5 b
Haste des,[2]	1,4	0,45	0,32	0,13	14,8 ab	46,5 b	3,1 ab	15,1 b	0,5 b
Microcamalhão	1,4	0,44	0,31	0,13	14,1 bc	47,2 b	3,2 ab	15,6 b	0,6 b
Escarificado + DD	1,4	0,47	0,31	0,17	16,6 a	61,3 a	3,9 a	21,6 a	1,0 a
Média	-	-	-	-	13,9	45,7	3,0	14,4	0,6
CV (%)	-	-	-	-	6,4	4,7	18,7	14,7	19,7

[ns] Não significativo na coluna; [*] Médias não seguidas da mesma minúscula na coluna diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro. MAS = mecanismo de acomodação do solo; [1]estádio de desenvolvimento das plantas; [2]haste desencontrada 5 cm da linha de semeadura.

Tabela 2. Número de nódulos por planta (NNP), matéria seca de nódulos por planta (MSNP) e percentual de nódulos inviáveis (NI) nos estádios V6 e R3. Cultivar BMX Tornado, Santa Maria safras 2013/14 e 2014/15 e Formigueiro safra 2013/14, RS. 2015.

Sistemas de implantação	NNP		MSNP^{3} (mg planta^{-1})		NI^{3} (%)	
	V6^{1}	R3^{1}	V6	R3	V6	R3
	------------------------------ Safra 2013/14 ------------------------------					
			Experimento 1 – Santa Maria			
Disco duplo (DD)	35,5 d*	88,4 ns	100,6 c			
Disco ondulado	51,9 bc	96,5	150,0 b			
Haste	53,6 bc	86,1	192,4 b			
Haste + MAS	61,8 ab	86,8	179,3 b			
Microcamalhão	42,3 cd	102,9	169,2 b			
Escarificado + DD	71,0 a	99,7	253,0 a			
Irrigação						
Com irrigação	54,7 ns	102,9 ns	193,3 a			
Sem irrigação	50,7	83,6	154,9 b			
Média	52,7	93,2	174,1			
CV (%)	17,8	21,1	24,8			
			Experimento 2 - Formigueiro			
Disco duplo (DD)	-	13,1 b*	-	13,5 b	-	4,2 ns
Disco ondulado	-	22,5 ab	-	38,1 b	-	9,6
Haste	-	29,8 a	-	68,3 ab	-	5,1
Haste + MAS	-	29,2 a	-	132,6 a	-	6,5
Escarificado + DD	-	28,1 a	-	56,3 ab	-	5,9
Média	-	24,5	-	61,8	-	6,3
CV (%)	-	18,2	-	61,0	-	44,1
	------------------------------ Safra 2014/15 ------------------------------					
			Experimento 1 – Santa Maria			
Disco duplo (DD)	15,0 c*	54,5 c	116,6 b	461,1 c	2,8 a	5,2 ns
Disco ondulado	19,6 bc	52,4 c	122,2 b	522,7 c	0,8 b	3,6
Haste	25,3 b	79,9 bc	222,2 a	642,2 bc	0,4 b	4,0
Haste desencontrada^{2}	25,6 b	74,8 bc	188,9 ab	667,7 bc	0,3 b	4,3
Microcamalhão	22,0 b	88,2 b	175,0 ab	760,0 ab	1,0 ab	2,3
Escarificado + DD	37,7 a	126,4 a	211,1 a	946,7 a	0,2 b	4,1
Média	24,2	79,4	172,7	666,7	0,9	3,9
CV (%)	11,0	15,2	19,2	14,3	88,9	45,2

^{ns} Não significativo na coluna; * Médias não seguidas da mesma minúscula na coluna diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro. MAS = mecanismo de acomodação do solo; ^{1}estádio de desenvolvimento das plantas; ^{2}haste desencontrada 5 cm da linha de semeadura; ^{3} houve interação entre os fatores para MSNP em R3 e NI em V6 e R3 na safra 2013/14 para o experimento 1; - não realizada a avaliação no estádio V6.

Tabela 3. Matéria seca de nódulos por planta (MSN) no estádio R3, percentual de nódulos inviáveis (NI) nos estádios V6 e R3 e rendimento de grãos em função dos sistemas de implantação e da irrigação. Santa Maria safras 2013/14 e 2014/15 e Formigueiro safra 2013/14, RS. 2015.

Sistemas de implantação	MSN (mg planta^{-1})		NI (%)			
	CI	SI	CI	SI	CI	SI
	R3[1]		V6[1]		R3	
	------------------------------ Safra 2013/14 ------------------------------					
	--------------------- Experimento 1 – Santa Maria ---------------------					
Disco duplo (DD)	352,2 NSc[*]	289,0 ab	3,4 Bns	11,9 Aa	6,1 NSns	7,6 ns
Disco ondulado	763,6 Aa	237,2 Bb	1,2 B	3,1 Ab	4,6 NS	3,8
Haste	591,1 Aab	438,3 Ba	1,7 NS	2,8 b	5,4 NS	6,7
Haste + MAS	591,1 Aab	296,6 Bab	1,2 NS	0,9 b	2,6 B	7,7 A
Microcamalhão	526,7 NSbc	421,1 ab	2,0 NS	2,1 b	6,0 NS	4,9
Escarificado + DD	570 Aab	306,6 Bab	2,8 NS	2,7 b	4,5 NS	4,2
Média	565,8	331,5	2,1	3,9	4,9	5,8
CV (%)	19,7		35,3		34,4	

Sistemas de implantação	---------------------- Rendimento de grãos (kg ha^{-1}) ---------------------		
	---------------- Safra 2013/14 ----------------		--- Safra 2014/15 ----
	Experimento 1- Santa Maria	Experimento 2- Formigueiro	Experimento 1- Santa Maria
Disco duplo (DD)	4082 b	2642 c	3759 d
Disco ondulado	4273 ab	2867 abc	3829 cd
Haste	4405 ab	2970 a	4327 b
Haste + MAS	4107 b	2917 ab	-
Haste desencontrada[2]	-	-	4222 b
Microcamalhão	4345 ab	-	4013 c
Escarificado + DD	4484 a	2698 bc	4749 a
Irrigação			
Com irrigação	4444 a	-	4311a
Sem irrigação	4121 b	-	3988 b
Média	4283	2819	4150
CV (%)	7,4	4,4	3,14

NS Não significativo na linha; ns Não significativo na coluna; [*] Médias não seguidas da mesma letra maiúscula na linha e minúscula na coluna diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro. MAS = mecanismo de acomodação do solo; CI = com irrigação; SI = sem irrigação. [1] estádio de desenvolvimento das plantas; [2]Haste desencontrada da linha de semeadura 5 cm.

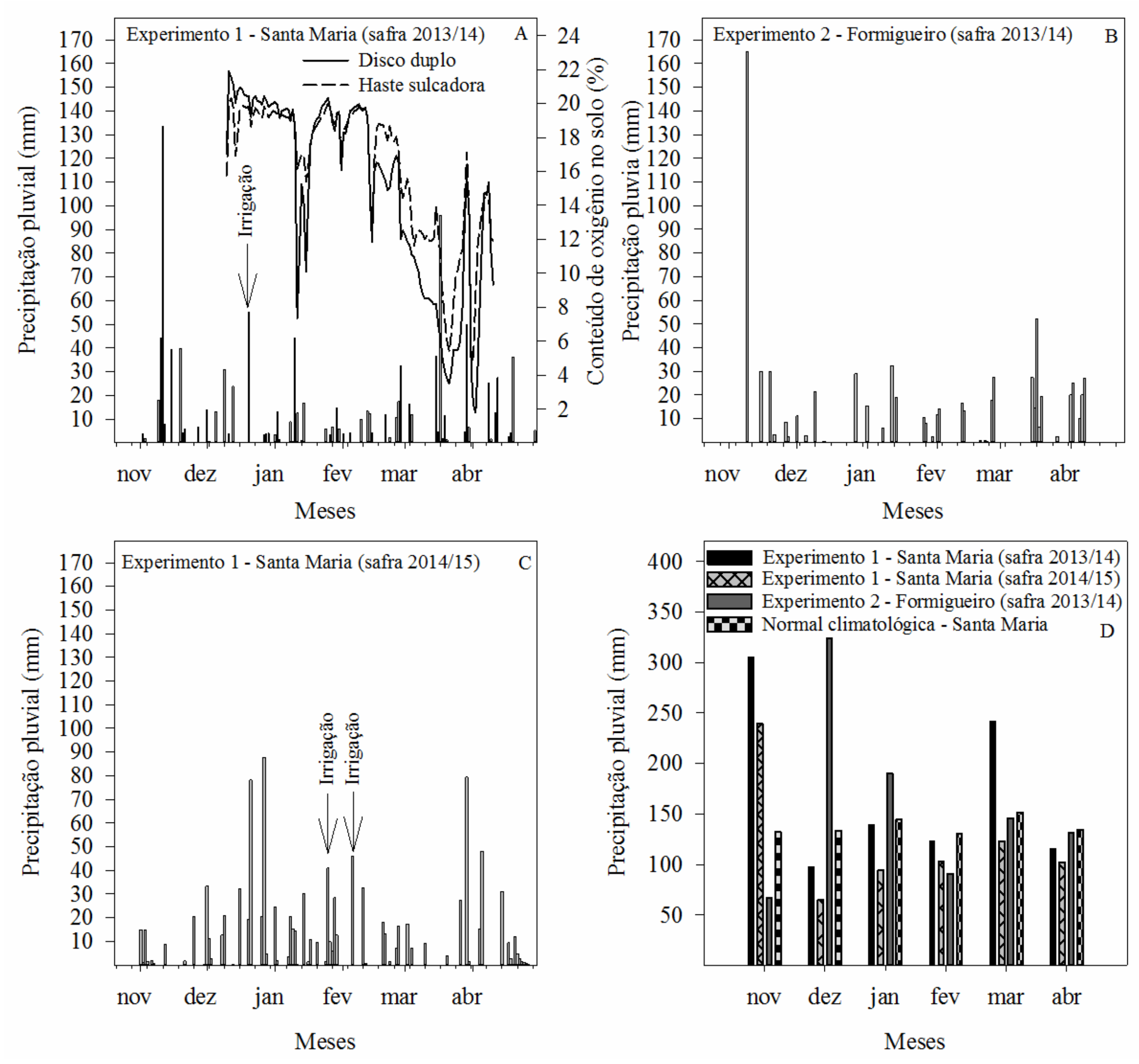

Figura 1. Precipitação pluvial diária para o experimento 1 em Santa Maria na safra 2013/14 e 2014/15 (A, C), experimento 2 em Formigueiro na safra 2013/14 (B) e precipitação pluvial mensal e normal climatológica para Santa Maria (D), e conteúdo de oxigênio no solo (A). Santa Maria safras 2013/14 e 2014/15 e Formigueiro safra 2013/14, RS. 2015.

3.5 ARTIGO 5

Sistemas de preparo do solo e de semeadura no rendimento de grãos de soja em área de várzea

Soil tillage systems and seeding on grain yield of soybean in lowland area

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RESUMO

A presença de camada compactada próxima à superfície do solo e a variabilidade das propriedades químicas do solo podem afetar o rendimento de grão de soja. Com o trabalho, objetivou-se avaliar a influencia de sistemas de preparo do solo e de semeadura e de locais de cultivo (áreas de corte e aterro) no rendimento dessa cultura. O experimento foi realizado na área experimental de várzea da Universidade Federal de Santa Maria, nas safras 2013/14 e 2014/15. O delineamento foi blocos ao acaso, com quatro repetições. Os tratamentos foram arranjados em parcelas subdivididas. As parcelas principais foram: área de corte (A1) e área de aterro (A2). As subparcelas foram os tipos de preparo do solo e de semeadura: com escarificação do solo e semeadura utilizando disco duplo na semeadora (D1); sem escarificação do solo e semeadura utilizando haste sulcadora na semeadora (D2); sem

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escarificação do solo e semeadura utilizando disco duplo na semeadora (D3). A cultivar utilizada foi a BMX Tornado. O tratamento com escarificação e haste sulcadora reduziu a resistência do solo à penetração e proporcionou maior teor de Mg e S no tecido foliar na safra 2013/14; e de N, P, K, Ca, Mg e S, em 2014/15. Esse tipo de preparo de solo possibilita maior rendimento de grão de soja sem diferenças entre as áreas de corte e de aterro.

Palavras-chave: compactação do solo, área de aterro, haste sulcadora, escarificação do solo.

ABSTRACT

The presence of soil compaction next to the soil surface and the variability of soil chemical properties can affect the soybean yield. The objective was to evaluate the influence of soil tillage systems and seeding on two sites area (cut and fill) on soybean grain yield. The experiment was conducted in lowland area of the Federal University of Santa Maria in 2013/14 and 2014/15 harvest. The design was a randomized block with four replications, with split plots. The main plots: the cuts area (A1) and fills area (A2). The subplots were tillage systems and seeding: deep tillage (D1); planter using shank (D2); planter using double disc (D3). The cultivar used was BMX Tornado and sowing on November 26 and 14 from 2013 and 2014, respectively. The treatment with deep tillage and planter using shank reduced the penetration resistance and provided greater content of Mg and S on 2013/14 and N, P, K, Ca, Mg e S on 2014/15. Those systems enables higher soybean yield, without difference between cut and fill area.

Key words: soil compaction, fill area, shank, deep tillage.

INTRODUÇÃO

O cultivo de soja em rotação com o arroz irrigado nas áreas de várzea teve um avanço significativo nas últimas safras, ultrapassando a 300 mil hectares na safra de 2014/15 (IRGA, 2014). No entanto, devido a alguns atributos físicos naturais dos solos nessas áreas e relevo predominantemente plano, o cultivo da soja pode ser prejudicado.

Destaca-se o hidromorfismo (BORGES et al., 2004) que, somado ao relevo plano, dificulta a drenagem de água (MARCHEZAN et al., 2002). Com isso, principalmente em anos de El Ninõ, em função da dificuldade de drenagem, o crescimento e desenvolvimento de culturas de sequeiro como a soja pode ser prejudicado nessas áreas. Além disso, em função das operações de preparo da área para o cultivo do arroz, tem-se verificado a presença de uma camada compactada próxima à superfície do solo, causando aumento da densidade do solo e redução da macroporosidade e porosidade total (MENTGES et al., 2013). Com isso, ocorre aumento da resistência do solo à penetração (SPERA et al., 2012), modificando a habilidade das raízes em extrair água e nutrientes (CALONEGO et al., 2011), podendo, com isso, interferir no rendimento de grãos das plantas. Além disso, muitas áreas de várzeas são sistematizadas, e esse processo causa desuniformidade nos atributos físico-químicos do solo entre as áreas de corte e aterro (MARCHEZAN et al., 2001). De acordo com REICHERT et al. (2008), a heterogeneidade dos atributos do solo afeta diferenciadamente o desenvolvimento e a produtividade das culturas agrícolas.

Dessa forma, com a presença de uma camada compactada próximo à superfície do solo, somado à desuniformidade que pode ocorrer dos atributos físico-químicos do solo em função da sistematização das áreas de várzeas, o cultivo da soja em rotação com o arroz irrigado pode ser prejudicado. Assim, é fundamental identificar alternativas como sistemas de preparo do solo e de semeadura que proporcionem maior rendimento de grãos de soja em áreas de várzea, além de identificar se há diferenças no rendimento de grãos entre as áreas de corte e aterro, para auxiliar no manejo da cultura nessas áreas. Em função disso, o trabalho teve por objetivo avaliar a influência de sistemas de preparo de solo, de semeadura e de locais (corte e aterro) sobre rendimento de grãos de soja em área de várzea sistematizada.

MATERIAL E MÉTODOS

O experimento foi realizado nas safras de 2013/14 e 2014/15 na área experimental de várzea sistematizada da Universidade Federal de Santa Maria (UFSM), em solo classificado como Planossolo Háplico Eutrófico arênico, pertencente à unidade de mapeamento Vacacaí (EMBRAPA, 2013). Na safra de 2013/14, o experimento foi realizado em área que na safra anterior havia a cultura da soja e, na safra de 2014/15, havia a cultura do arroz irrigado anteriormente à realização do experimento. Os valores dos seguintes atributos físico-químicos do solo, aos 60 dias antes da semeadura, correspondiam a: argila = 25 a 26%; pH $_{\text{água}}$ = 5,4 a 5,4; P = 18 a 15,3mg dm^{-3}; K = 60 a 44mg dm^{-3}; Ca = 5,3 a 8,3cmol$_c$ dm^{-3}; Mg = 2,4 a 3,1cmol$_c$ dm^{-3} e M.O. = 2,0 a 2,0%, nas safras 2013/14 e 2014/15, respectivamente. Esses resultados foram obtidos em análises no laboratório de análises de solo (LAS) da UFSM conforme metodologia de TEDESCO et al. (1995).

O delineamento experimental foi o de blocos ao acaso, com quatro repetições. O arranjo dos fatores foi em parcelas subdivididas. A sistematização da área foi realizada há quinze anos, com profundidade de corte máxima de 30cm. A parcela principal foi composta pelos locais: área de corte (A1) e área de aterro (A2). As subparcelas foram os sistemas de preparo do solo e de semeadura: com escarificação do solo e semeadura utilizando disco duplo na semeadora (D1); sem escarificação do solo e semeadura utilizando haste sulcadora na semeadora (D2); sem escarificação do solo e semeadura utilizando disco duplo na semeadora (D3).

A escarificação do solo foi realizada aos 45 e 19 dias antes da semeadura, na safra de 2013/14 e 2014/15, respectivamente, na profundidade de 25cm. A profundidade de trabalho da haste sulcadora e do disco duplo desencontrado no solo foi aproximadamente de 18 e 10cm, respectivamente. A semeadura foi realizada no dia 7 e 14 de novembro de 2013 e 2014, respectivamente, utilizando uma semeadora adubadora pantográfica. Devido a uma precipitação pluvial de 245mm distribuídos em quatro dias, iniciando aos dois dias após a semeadura, o experimento foi ressemeado no dia 26 de novembro de 2013 (safra 2013/14). A cultivar de soja utilizada foi a BMX Tornado, que possui hábito de crescimento indeterminado. Foram distribuídas 26 sementes por m^{-2}. O espaçamento entre linhas foi de 0,5m.

A adubação de semeadura foi de 30kg ha^{-1} de nitrogênio (N), 60kg ha^{-1} de P_2O_5 e 60kg ha^{-1} de K_2O. Em função da ressemeadura, utilizaram-se mais 10kg ha^{-1} de N, 20kg ha^{-1} de P_2O_5 e 20kg ha^{-1} de K_2O (safra 2013/14). Na safra de 2014/15, essa adubação foi de 13N, 54kg ha^{-1} de P_2O_5 e 86kg ha^{-1} de K_2O. Optou-se pela utilização de N na semeadura, pois os alagamentos frequentes e a presença de camada compactada poderiam limitar o conteúdo de oxigênio do solo e, consequentemente, a nodulação. Além disso, não há informação suficiente na literatura sobre o uso ou não de fertilizantes nitrogenados na semeadura da cultura da soja para o ambiente de várzea. Os demais tratos culturais foram realizados conforme as recomendações técnicas para cultura (EMBRAPA, 2012).

Aos 10 dias antes da semeadura, realizou-se avaliação da resistência do solo à penetração, para caracterizar a profundidade da camada compactada na área. Essa avaliação também foi realizada aos 2 e 15 dias após a semeadura, na linha de cultivo, visando identificar o efeito do rompimento de parte dessa camada, em cada sistema, nas safras de 2013/14 e 2014/15, respectivamente. Essa avaliação foi na profundidade de até 30cm, utilizando penetrômetro digital da marca Falcker, modelo PLG 1020. A densidade do solo e a porosidade foram realizadas 10 dias antes da semeadura, na camada de 0-10 e de 10-20cm, conforme métodos descritos pela EMBRAPA (1997). A densidade do solo foi obtida pelo método do anel volumétrico. A porosidade total (Pt) foi calculada a partir da densidade do solo (Ds) e a macroporosidade foi calculada pela diferença entre a porosidade total e a microporosidade.

Avaliaram-se os seguintes atributos das amostras de solo: pH $_{\text{água}}$; cálcio (Ca); magnésio (Mg); Sat Bases; matéria orgânica (M.O.); enxofre (S); fósforo (P); CTC pH7; potássio (K); cobre (Cu); Zinco (Zn) e boro (B) conforme TEDESCO et al. (1995). As amostras foram coletadas nas áreas de corte e aterro, no estádio R2 da soja, segundo escala de FEHR & CAVINESS (1977). As coletas foram realizadas com pá de corte, na camada de 0-20cm e na entrelinha de semeadura. Para amostragem do solo, foram utilizadas 12 repetições em cada local, na safra de 2013/14 e quatro repetições, na safra de 2014/15. Nas plantas, avaliaram-se os teores dos nutrientes N; P; K; Ca; Mg; e S no estádio R2, segundo escala de FERHR & CAVINESS (1977). Coletou-se o terceiro trifólio completamente expandindo, da haste principal, do ápice para a base, de 15 plantas consecutivas em cada parcela. As amostras foram encaminhadas para o laboratório de Ecologia Florestal da UFSM para análise dos nutrientes, conforme metodologia de TEDESCO et al. (1995) e MIYAZAWA et al. (1999).

Os parâmetros avaliados foram submetidos ao teste das pressuposições do modelo matemático (normalidade e homogeneidade das variâncias). A análise da variância dos dados dos experimentos foi realizada com teste F. As médias dos locais (área de corte e aterro), quando significativas, foram comparadas pelo teste t bilateral, a 5% de probabilidade de erro; e as médias dos sistemas de preparo do solo e de semeadura foram comparadas pelo teste Tukey, utilizando esse mesmo nível de probabilidade de erro.

RESULTADOS E DISCUSSÃO

O solo da área em que foi realizado o experimento tinha valores limitantes (<10%) de macroporos e elevada relação de micromacroporos, até os 20cm de profundidade (Tabela 1). Além disso, os valores de densidade do solo eram elevados (superior a 1,65g cm^{-3}), principalmente na área de corte e na camada de 10-20cm nas safras de 2013/14 e 2014/15.

As áreas de corte e de aterro da camada de 8-17cm na safra de 2013/14 (Figuras 1A, B) e dos 5-17cm da safra de 2014/15 (Figuras 1 C, D) tiveram valores de resistência do solo à penetração maior que 2,0MPa. Na área de corte, registraram-se valores médios de 0,8 e 0,3MPa superiores à área de aterro, na safra de 2013/14 e 2014/15, respectivamente, nessa camada de solo. Isso pode estar relacionado aos valores mais acentuados de densidade do solo, pois ORTIGARA et al. (2014) encontraram aumento exponencial e positivo da resistência à penetração, com o aumento dos valores de densidade do solo.

Os sistemas de preparo do solo e de semeadura, em ambos os locais e safras, responderam de forma diferenciada quanto à redução da resistência do solo à penetração na linha de semeadura. O sistema com escarificação do solo utilizando o disco duplo no momento da semeadura e a semeadura utilizando haste sulcadora reduziram os valores de resistência do solo à penetração a valores menores que 1,5MPa, até os 15cm de profundidade. Já a semeadura com disco duplo, em área sem escarificação do solo, proporcionou menor redução da resistência, mantendo a camada compactada na linha de semeadura, visto que a resistência à penetração tem sido amplamente utilizada em avaliações do estado de compactação dos solos (FLORES et al., 2007). De acordo com TAYLOR et al. (1966), valores de resistência à penetração do solo maior de 2,0MPa são considerados limitantes ao crescimento e desenvolvimento do sistema radicular das plantas. O menor efeito do disco duplo está associado a pouca ação em profundidade desse sistema no solo, que foi de aproximadamente 10cm, em comparação aos 25 e 18cm para a escarificação e haste sulcadora na semeadora, respectivamente.

De acordo com os resultados dos atributos físico-químicos do solo quando as plantas estavam em R2 (Tabela 1), a faixa de interpretação dos teores de Cu, Zn, B, Ca, Mg e S é alto, e médio, para o K, em ambas as safras e locais, com exceção do B, que estava médio na safra 2013/14. Os teores de P do solo, nas safras 2013/14 e 2014/15, estavam muito alto e médio, respectivamente. De maneira geral, os teores dos nutrientes Ca, Mg, S, P, K, Cu e Zn (safra 2013/14), B e P (safra 2014/15) da área de aterro foram superiores, em relação à área de corte. Segundo MARCHEZAN et al. (2001), o processo de sistematização causa desuniformidade nas características físico-químicas do solo entre as áreas de corte e aterro, principalmente nos primeiros anos de cultivo nessas áreas.

Em relação aos resultados apresentados na tabela 2, não houve interação entre os fatores de estudo. A análise dos teores de macrocronutrientes no tecido foliar das plantas em R2, na safra de 2013/14, indicou maior teor de Ca na área de aterro e de N na área de corte. Entre os sistemas de preparo e de semeadura, verificaram-se maiores teores de Mg e de S nos sistemas com haste sulcadora e com escarificação do solo. Na safra de 2014/15, verificou-se maior teor de Ca e de Mg no tecido foliar da área de corte, em relação à área de aterro, não ocorrendo diferenças com os demais macronutrientes. A análise foliar indicou maior teor dos macronutrientes no sistema com escarificação do solo, seguido com semeadura utilizando haste sulcadora, que proporcionou maior teor de N, Ca e de Mg, em comparação ao disco duplo.

O menor teor de alguns nutrientes verificado no tecido foliar da área de aterro pode estar associado ao efeito de diluição, em função da maior massa seca das plantas nesse local que foi 21,3 e 17,0mg planta^{-1}, em comparação as das área de corte, que foi de 20,5 e 16,7mg planta^{-1}, nas safras 2013/14 e 2014/15, respectivamente (resultados não apresentados).

A maior redução da camada compactada do solo na linha de semeadura para o sistema com escarificação e semeadura utilizando haste sulcadora, em comparação ao disco duplo, como indicam os resultados de resistência à penetração, podem explicar o maior teor de macronutrientes do tecido foliar dos dois primeiros sistemas. DRESCHER et al. (2011), avaliando efeito do disco duplo e da haste sulcadora, verificaram que esse último é eficiente em aumentar a macroporosidade e diminuir a microporosidade e a densidade do solo, o que pode explicar os resultados encontrados. Em trabalho realizado por SOUZA et al. (2012), o aumento da compactação do solo reduziu o acúmulo de N, P, K, Ca, Mg e de S das plantas de soja. Com o aumento da compactação, ocorre aumento da resistência mecânica ao crescimento das raízes, limitação da aeração e da disponibilidade de água e nutrientes (GOEDERT et al., 2002).

Na safra 2013/14, os teores de macronutrientes das plantas no estádio R2 são adequados para o desenvolvimento das plantas de soja (CQFSRS/SC, 2004). No entanto, na safra 2014/15, somente o teor de K do sistema com escarificação e de Ca e de Mg, para os três sistemas, foram adequados.

Apesar da área de aterro, de forma geral, ser caracterizada por melhor fertilidade química, isso não se refletiu no rendimento de grão nas duas safras avaliadas. Uma hipótese para isso é a distribuição regular das chuvas que, associado à adubação realizada para o nível de rendimento obtido, atendeu às necessidades da planta em ambas as áreas. Os sistemas com escarificação do solo e haste sulcadora proporcionaram maior rendimento de grãos em comparação ao disco duplo em área sem escarificação do solo. Esses sistemas tiveram rendimento de 9 e 12%, respectivamente, superior ao disco duplo (safra 2013/14) e 10 e 22%, respectivamente, superior ao disco duplo (safra 2014/15). Isso está relacionado à maior redução da resistência à penetração do solo por esses sistemas na linha de semeadura, o que contribui para maior teor de macronutrientes do tecido foliar das plantas. Segundo DRESCHER et al. (2012), a compactação do solo afeta a disponibilidade de água e de nutrientes para as plantas, reduzindo a fotossíntese, o crescimento e o rendimento de grão da cultura. Contribuindo com o estudo, REICHERT et al. (2008) encontraram que 65% da variação na produtividade de grãos de soja é atribuída a atributos químicos do solo e físicos, como a resistência à penetração.

Para todos os sistemas, o rendimento de grãos foi elevado, devido à boa disponibilidade de água proporcionada pelas precipitações pluviais, que foi de 305; 98; 140; 123; 242; e 116mm (safra 2013/14) e 65; 323; 189; 89; 145 e 131mm (safra 2014/15) nos meses de novembro, dezembro, janeiro, fevereiro, março e abril, respectivamente. Isso contribuiu para que todas as práticas de manejo expressassem seu potencial de resposta, pois disponibilidade de água é fundamental para obtenção de elevado rendimento (MIAO et al., 2012). Assim, restrições físicas do solo, como a presença de uma camada compactada próxima à superfície do solo, interferem nos teores foliares de macronutrientes das plantas e no rendimento de grão de soja, em área de várzea.

CONCLUSÃO

O sistema de preparo do solo com escarificação e a semeadura utilizando haste sulcadora na semeadora proporcionam maior rendimento de grão de soja, em área de várzea, que contém camada compactada próxima à superfície do solo. Não há diferenças entre áreas de corte e aterro, em sistematização realizada há quinze anos.

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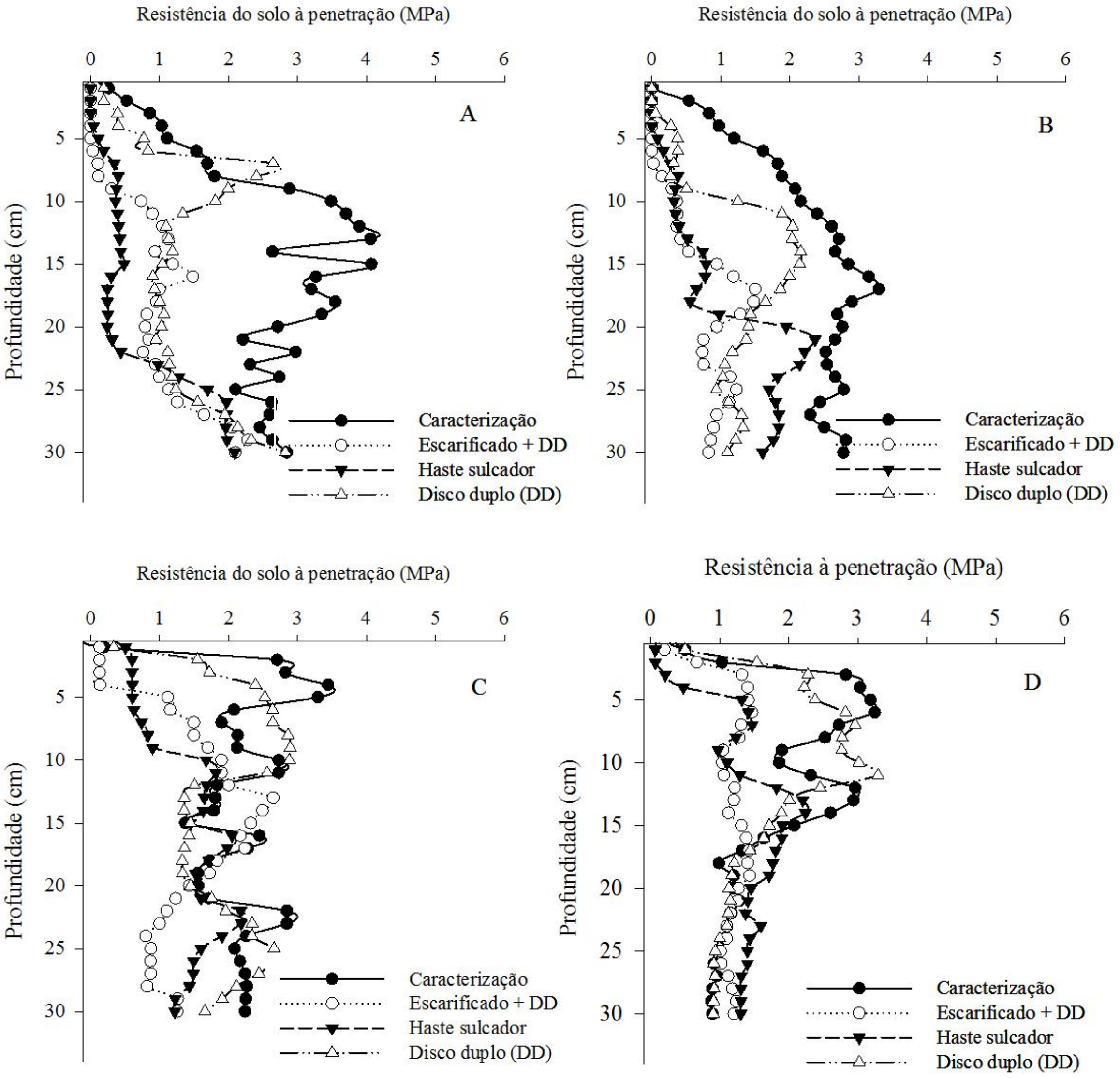

Figura 1 - Resistência do solo à penetração aos 10 dias antes da semeadura (caracterização das áreas) e aos dois dias após a semeadura nos diferentes sistemas de preparo do solo e de semeadura na área de corte (A) e na área de aterro (B) para safra de 2013/14; aos 15 dias após semeadura na safra de 2014/15 na área de corte (C) e aterro (D). Santa Maria, RS, 2015. A umidade volumétrica média do solo na camada de 0 a 20cm de profundidade, no momento da avaliação de caracterização da área, e nos sistemas Escarificado + DD; Haste sulcadora e Disco duplo (DD) foram de 31; 32; 32 e 35% (safra 2013/14) e 28; 30; 25 e 34% (safra 2014/15), respectivamente.

Tabela 1 - Densidade do solo (Ds), porosidade total (Pt), microporos (Mi), macroporos (Ma) e relação Mi/Ma, na área de corte (AC) e aterro (AA), em duas camadas do solo e atributos químicos do solo da área de corte e de aterro, no estádio R2, nas safras de 2013/14 e 2014/15. Santa Maria, RS. 2015.

Local	Camada (cm)	Ds (g cm^{-3})	Pt (%)	Mi (%)	Ma (%)	Mi/Ma	
	------------------------------------- Safra 2013/14 -------------------------------------						
AC	0 -10	1,52	48	39	9	4:1	
	10 - 20	1,67	43	35	8	5:1	
AA	0 -10	1,40	52	41	11	4:1	
	10 - 20	1,66	43	35	9	4:1	
	------------------------------------- Safra 2014/15 -------------------------------------						
AC	0 -10	1,61	39	34	5	7:1	
	10 - 20	1,70	37	32	5	5:1	
AA	0 -10	1,56	37	30	6	5:1	
	10 - 20	1,62	33	31	7	4:1	
Local	pH água 1:1	Ca	Mg	Sat Al	Sat Bases	MO	S
		----- cmol$_c$ dm^{-3} ----		-------------- % ------------			mg dm^{-3}
	------------------------------------- Safra 2013/14 -------------------------------------						
AC	5,3	8,1	3,5	1,7	79,1	1,4	10,5
AA	5,1	8,5	3,6	2,0	76,3	1,8	18,2
	------------------------------------- Safra 2014/15 -------------------------------------						
AC	5,8	8,8	3,9	0,0	81,9	1,5	23
AA	5,3	6,6	2,8	3,0	63,7	1,8	10
Local	P mg dm^{-3}	CTCpH7c mol$_c$ dm^{-3}	K	Cu	Zn	B	
			--------------- mg dm^{-3} ----------------				
	------------------------------------- Safra 2013/14 -------------------------------------						
AC	11,1	14,8	55,0	1,3	0,6	0,2	
AA	27,8	16,1	70,0	1,4	1,1	0,2	
	------------------------------------- Safra 2014/15 -------------------------------------						
AC	6,0	15,7	76,0	1,8	1,1	0,4	
AA	10,9	15,1	72,0	1,7	1,0	0,5	

Tabela 2 - Teor de macronutrientes do tecido foliar das plantas de soja no estádio R2 e rendimento de grão, em função dos sistemas de preparo do solo e de semeadura na área de corte (AC) e aterro (AA), nas safras de 2013/14 e 2014/15. Santa Maria, RS. 2015.

Sistemas^{1}	Macronutrientes ($g\ kg^{-1}$)					
	N	P	K	Ca	Mg	S
	---------------------------------- Safra 2013/14 ----------------------------------					
DD	49,19 ^{ns}	3,62 ^{ns}	19,87 ^{ns}	9,14 ^{ns}	5,39 b*	2,53 b
HS	55,33	4,07	16,88	9,44	5,86 a	2,85 ab
E + DD	52,75	3,87	21,04	9,27	5,88 a	2,92 a
Local						
AC	55,79**	3,87 ^{ns}	18,08 ^{ns}	9,08**	5,56 ^{ns}	2,79 ^{ns}
AA	49,05	3,80	20,44	9,48	5,86	2,73
Média	52,42	3,84	19,26	9,28	5,71	2,76
CV%	10,31	9,97	19,43	4,64	7,62	8,57
Sistemas	------------------------------ Safra 2014/15 ------------------------------					
DD	31,81 c	1,84 b	15,01 ab	7,48 c	3,29 c	1,49 b
HS	33,95 b	1,91 b	12,66 b	8,03 b	3,48 b	1,57 b
E + DD	36,18 a	2,26 a	18,06 a	8,47 a	3,65 a	1,48 a
Local						
AC	34,09 ^{ns}	1,95 ^{ns}	14,98 ^{ns}	8,13**	3,59**	1,52 ^{ns}
AA	33,87	2,06	15,51	7,85	3,36	1,50
Média	33,98	2,00	15,24	7,99	3,47	1,51
CV%	3,9	5,51	14,04	2,75	2,19	2,12
Sistemas	------------------------- Rendimento de grão kg ha^{-1} --------------------					
	--- Safra 2013/14 ---	--- Safra 2014/15 ---				
DD	3980 b	3754 c				
HS	4451 a	4111 b				
E + DD	4350 a	4564 a				
Local						
AC	4146 ^{ns}	4083 ^{ns}				
AA	4375	4203				
Média	4260	4143				
CV%	6,64	3,68				

DD = Disco duplo; HS = Haste sulcadora; E + DD = Escarificado + Disco duplo.

AC = Área de corte; AA = Área de aterro.

[1] Sistemas de preparo do solo e de semeadura.

^{ns} Não significativo em nível $P \leq 0,05$ na coluna.

*Médias não seguidas da mesma letra minúscula na coluna diferem entre si pelo teste Tukey em nível de 5% de probabilidade de erro.

** Diferença significativa entre os locais pelo teste t bilateral em nível de 5% de probabilidade de erro.

3.6 ARTIGO 6

EFFECT OF DEEP TILLAGE AND GYPSUM AMENDMENT ON FULLY, DEFICIT AND DRYLAND FURROW IRRIGATED SOYBEANS ROTATED WITH RICE

Abstract

A major limitation to soybean yield is the availability of water for crop production; however, water available for irrigation is declining in many of the crop growing regions. The objectives of this study were to validate and or refine current allowable deficit recommendation for evapotranspiration (ET) based irrigation scheduling for furrow irrigated soybeans and to examine the effects of deep tillage and gypsum amendment on yields and water use efficiency. This experiment was conducted in Stuttgart, Arkansas, in 2015 at University of Arkansas, Rice Research and Extension Center (silt-loam with a pan). The soil management treatments were (deep tillage, deep tillage/gypsum application, gypsum, and conventional). Irrigation treatments (fully irrigated, +1 deficit, +2 deficit, and non-irrigated), were replicated three times within each soil treatment. Increases in soybean yields above 10% (2015), were observed in the deep tillage treatments. No yield benefits were observed in the gypsum amendment treatments. The +1 deficit resulted in reduction of irrigation water used and can be used in conjunction with deep tillage to obtain similar yield responses as fully irrigated treatments. In conventional treatments reduction in yield was observed at all levels of irrigation deficit except for fully irrigated treatments, indicating that conventional soil management practices should follow Arkansas allowable deficit recommendation for ET based irrigation scheduling as a maximum allowable deficit to prevent yield loss.

Introduction

Crop Irrigation is the largest component of human freshwater use (Haddeland et al., 2014). According to Morison et al. (2008), agriculture accounts for 80-90% of all freshwater used by humans worldwide.

Soybean [*Glycine max* (L.) Merrill] is one of the most important leguminous plants in the world. The United State accounts for 38% of global soybean production (Grassini et al., 2015). In 2014, 33,872,623 hectares were planted in the United States of which 3.87% was in the state of Arkansas (USDA, 2015a). The average seed yield for the state is 3363 kg ha^{-1} (USDA, 2015a). In Arkansas 82% of the area planted in 2014 was irrigated (USDA, 2015b). However, water available for irrigation is declining in the main growing regions. The increase of irrigated agriculture, climate change, water supply limits, and continued population growth has increased the demand for measures controlling irrigation water usage (Ward and Velazquez, 2008).

The reliance of irrigated crops on groundwater has caused many shallow aquifers to decline over the past century by several hundred feet. The projections suggest that by 2050, there will be demand for about 8634 million cubic meters per year of groundwater that cannot be met with groundwater supplies in east Arkansas (Arkansas Natural Resource Commission, 2014). The general trend in Arkansas's long-term water-level change is that the groundwater levels are declining in response to continued withdrawals at a rate which is not sustainable (Arkansas Natural Resource Commission, 2015). At the same time global populations continue to rise, increasing crop production demand. In turn, soybean production systems face the dilemma of maintaining or increasing yields with less water available to irrigate.

A major limitation to soybean production is the availability of water. The water demand of soybean lies in the range 550 to 800 mm over the course of a growing cycle

(Chavarria et al., 2015). Research has shown that water stress is most detrimental to soybean yield during reproductive growth stages (Doss et al., 1974; Sionit and Kramer, 1977; Torrion et al., 2014). Furthermore, Purcell and Specht (2004) state that water deficit is the most common abiotic stressor reducing soybean yields. Heatherly and Spurlock (1993) have shown that delays in irrigation initiation, scheduling, and termination can limit soybean yields.

Arkansas soils have very low organic matter (OM) due to the tillage practices and climate. The lack of organic matter plus the high proportion of silt in Arkansas's silt loam soils (up to 70% silt) increase the propensity for soil sealing (the formation of soil crust), which can significantly affect seedling emergence, but it also impairs the inherent hydraulic conductivity of silt loams. According to Borselli et al. (1996), numerous papers have shown the effectiveness of gypsum additions in reducing crust formation on sodic or generally non-acid soils. Miller (1987), found that gypsum delayed initiation of runoff compared with control, and increased water infiltration. Research by Zondoná et al. (2015), gypsum increased soybean and corn yield.

Also due to tillage practices Arkansas soils have high soil compaction levels. Soil compaction is prevalent in soil systems where tillage occurs and can limit yield potential. The presence of a compacted layer in the sub-surface is also a factor limiting the soybean yield. Kirnak et al. (2013), has shown that high soil compaction can result in yield losses up to 45%. Compaction influences the hydraulic conductivity and infiltration, soil temperature and aeration (Borges et al., 2004). Soil compaction is characterized by increased bulk density and soil total porosity and macroporosity reduction (Drescher et al., 2011).

Studies have shown that deep tillage increases water infiltration, internal drainage and aeration, thus, increases rooting depth (Strudley et al., 2008). In many sugarcane growing regions deep tillage is thought to be vital to obtaining high crop yields (Yang and Quintero, 1995). A significant amount of time and resources have been devoted to improve water use efficiency (WUE) in order to conserve water available for urban and the environmental uses, while maintaining high yield potential. Therefore, the optimization of current irrigation and soil management practices, is imperative for the sustainability of soybean production systems.

The objective of this study was to evaluate the current irrigation scheduling recommendations for soybeans on a silt loam soil with a pan. The Arkansas Irrigation Scheduler (AIS) is a computer program was developed in the late 1980 and early 1990's and has been used by farmers since that time to schedule irrigation on all crops in Arkansas (Calhoon et al., 1990; Tacker et al., 1996). The scheduler is a computer program that predicts evapotranspiration using a pan-referenced temperature equation method, crop coefficients calibrated to the region, and soil type and irrigation type based deficits. Deficits change according to crop coefficients referenced to emergence dates. No adjustment is made for soil amendments or other soil treatments such as deep tillage. Earlier unpublished work in 2013 had found that the AIS program and alfalfa referenced atmometer provided the same irrigation schedule, so atmometers were used in subsequent years for simplicity. For this study the base deficit for furrow irrigated silt loam soil with a pan was adjusted before the crop coefficient applied for the respective growth stage to determine the irrigation trigger for +1 and +2 irrigation treatments. Fully irrigated treatments followed the current irrigation scheduling recommendations. Thus the study was designed to evaluate the current conventional irrigation recommendations and the interaction of soil treatments (deep tillage, deep tillage with gypsum application, conventional with gypsum application and conventional alone). The resultant information will be use to validate and, if needed, modify current, recommended, irrigation practices .

Materials and Methods

Plot design and treatments

The field was divided into four blocks, each block received one of the following soil treatments: deep tillage, deep tillage with gypsum application, gypsum application, and conventional (standard tillage practices in Arkansas). These blocks were further divided into 8 row plots with 30 inch row spacing, 6 row plots with 30 inch row spacing. Irrigation was scheduled by tracking evapotranspiration (ET) losses through the use of an atmometers (ETgage Company, Loveland CO). Plots were irrigated with one of four different irrigation deficit: fully irrigated (Arkansas recommend allowable deficit; 100% ET), +1 deficit (recommended deficit plus 25.4 mm; 160% ET), +2 deficit (recommended deficit plus 50.8 mm; 220% ET), and non-irrigated each having 3 replicates randomly assigned within each soil treatment block. Note fully irrigated was scheduled in accordance with Arkansas irrigation scheduling using an atmometer (Henry et al., 2015) recommendations for furrow irrigated soybeans grown on silt-loam with a pan soils. The +1 deficit is adding 25.4 mm to the recommended allowable deficit and likewise for +2 deficits is adding 50.8 mm.

Rice Research and Extension Center site specifics

This experiment was conducted in an experimental field at Rice Research and Extension Center, Stuttgart, Arkansas (silt-loam with a pan). The deep tillage consisted of inserting the implement 40 cm deep, 1 m apart on 05 May 2014 with a 5 shank no-till soil management system ripper (John Deere; Moline, IL). Plots were planted with soybean cultivar Progeny 4900 on 6 June 2015. The soybeans emerged 16 June 2015. Gypsum was applied on 6 June 2015 at 2472 kg ha^{-1} using a MagnaSpread 1039 Single Axle Fertilizer Lime Spreader (Katyas Corporation; Cornelia, GA) Cultural practices (fertilizer and weed control) were in accordance with current University of Arkansas’ recommendations. Field was harvested on 13 and 14 October 2015, the middle 4 rows were harvested for each plot.

Cone penetration resistance

Cone penetration resistance was measured using a FieldScout Soil Compaction Meter SC900 (Spectrum Technologies inc., Aurora, Illinois) in the spring of 2014, just prior to tillage. Two cone resistance readings were taken on top of the bed and two in the furrow in four different plots within each soil treatment (Conventional and Deep tillage) block at five different locations down the row (from top to bottom of the field). Readings were taken from the top of the bed and the middle of the furrow at 40 different locations across and down the conventional treatment and 40 across and down the deep tillage treatment block (total of 160 probes with readings occurring 2.5 cm from 0 to 45cm deep). Average resistance was calculated for each depth across all measuring locations for the readings on the bed and in the furrow.

Water use, soil tension, and weather data

Water use was monitored using iron MD30E propeller flowmeters (McCrometer; Hemet, CA). Soil tension was monitored using a 975 Irromesh wireless node base data logging systems (Irrometer, Riverside, Ca), attached to watermark sensors 200SS (Irrometer, Riverside, Ca) placed at three different depths (15.2, 45.7, and 76.2 cm). Temperature sensors were also installed at a depth of 22.9 cm to correct soil tension readings. Weather data was monitored using a H21-001 Hobo data logger equipped with onset sensors as found in U30-NRC weather station starter kit (Onset computer corporation; Bourne, MA) located 10 m from the experimental field.

Root and shoot growth and nodulation

Five plants were collected from each plot during the R3 growth stage. In the field a soil monolith of 40 x 40 x 20 cm (length, width and depth) was collected containing five plants (shoot plus root), in order to conduct root, shoot, and nodulation evaluations. The sample was carried to the laboratory were shoots were separated from roots. For each plant, the plant height was measured with a graduated ruler and the number of nodes was counted. The soil was washed from the roots, nodules were removed from each plant and counted. Lastly the nodules, roots, and shoots of the five plants were dried in forced-air oven at 65 ° C until a constant mass was obtained (ie weighed the same across a 24 hour period). Then plant material was weighed using a digital balance and dry mass was recorded.

Canopy temperature, canopy minus air temperature, stomatal conductance

The canopy temperatures were measured with Fluke a Ti25 Thermal Imager (FLUKE Corporation, Everett, Washington). Readings were taken at ten different locations within each fully irrigated and non-irrigated plots across all the soil treatment blocks. Air temperature was recorded at the start and finish of data collection to obtain an average air temperature for the duration data collection. Average canopy temperatures were calculated for each of the treatments. Canopy temperature values were also subtracted from the air temperature at the time of assessment, and values were averaged according to irrigation treatment as well as soil treatment.

Five plants from each plot stomatal conductance were measured using a Leaf Porometer SC -1 (Decagon Devices inc., Pullman, Washington), at the third expanded trifoliate. These measurements were conducted 1 day prior to irrigation (-1 day), during irrigation (0 day), and three days after irrigation (3 days) during the R5 growth stage in the 2015 season.

Statistical analysis

Harvest weights were corrected with a 12% moisture correction, using the measure grain moisture from each plot. The measured outcomes were tested by the assumptions of the mathematical model (normality and homogeneity of variance). The analysis of variance of the experimental data was performed using the F-test. The factor means, when significant, were compared by Tukey's test at 5% probability.

Results and Discussion

Cone penetration resistance

The soil penetration resistance is used as an indicator of the degree of soil compaction (Beulter and Centurion, 2004). According to the soil penetration resistance readings, the deep tillage treatments had less resistance compared to the conventional treatment indicating that deep tillage had a positive effect on compaction (Fig. 1A, B). Soil compaction is associated with increases in soil density and penetration resistance, as well as reduction in soil macroporosity and total soil porosity (Valadão et al., 2015). Ramos et al. (2015) suggests that the critical level of soil penetration resistance is 2.0 MPa. According to the soil penetration resistance readings in this study, higher resistance, greater than 2 MPa, was recorded at a depth of 7 to 15 cm, indicating the presence of a compaction layer in the conventional treatments (Fig. 1A, B). This critical resistance was not observed in the deep tillage treatments indicating the compaction layer was disrupted in this soil management system and that the effects of deep tillage persisted for more than one season.

The soil penetration resistance values were lower s on the bed (Fig. 1A) than in the furrow (Fig. 1B), this was expected because the deep tillage shank passes were on the center of the bed.

The compaction observed in the conventional treatments as well as increased levels of soil penetration resistance in the furrows across treatments, could potentially have an effect on soil air and water holding capabilities as well as plant growth. Compaction can affect the soil-air-water relationship, limiting root growth and development (Cardoso et al., 2006), which may compromise yield potential.

Water use, rainfall and soil moisture data

The total water applied to the fully irrigated treatment was 457 mm of irrigation and the +1 deficit and +2 deficit treatments received 200 to 256 mm less, respectively (Table 1). The fully irrigated treatment required 7 irrigations, 3 and 4 less irrigations were required for the +1 deficit and +2 deficit treatments, respectively (Table 1). For the three seasons the water use efficiency (WUE) was higher to for the +1 deficit and +2 deficit than fully irrigated treatments.

Root and shoot growth and nodulation

There were no interaction effects observed between soil and irrigation treatments with respects to plant height, nodes per plant, shoot dry mass, root dry mass, nodules per plant, and nodules' dry mass (Table 2).

Larger plant height measurements and more nodes per plant were observed in the deep tillage treatment. Gypsum amendment in conjunction with deep tillage and conventional systems seemed to have no effect on plant height and little to no effect on nodes per plant. No significant differences were observed in shoot dry mass and root dry mass with respects to soil treatment. More nodules per plant were observed in the conventional and deep tillage with gypsum treatments, likewise higher nodules' dry mass per plant were observed in these treatments. However, the results are a little convoluted making it difficult to make clear conclusions on the combination of deep tillage and gypsum, deep tillage, as well as gypsum amendments, treatment effects on nodulation (Table 2).

The largest negative effect of all variables in table 2 was seen in the non-irrigated treatment. Plants grown in the fully irrigated treatment had more nodules, nodules' dry mass, and shoots dry mass. No significant difference was found in plant height, nodes per plant, and root dry mass between fully irrigated, +1, and +2 deficit treatment groups. However, when looking at just the irrigated treatments the data suggests: no difference exists in root dry matter between irrigated treatments; no difference in plant height exists between fully irrigated and +1 deficit; and as irrigation deficit increased reductions were observed in nodes per plant, shoot dry mass, nodules per plant, and nodules' dry mass (Table 2).

Decrease in photosynthetic rate may be related to diffusive factors (stomatal) or metabolic factors (non-stomatal) when a water deficit develops in the field more slowly, damages to soybean vegetative growth may occur (Chavarria et al., 2015). Therefore the plants in the +1 and +2 and non- irrigated treatments may have experienced varying photosynthetic rates as a direct effect of the irrigation treatment. The reduction in plant growth (plant height, nodes by plants, shoot dry mass) observed in the non-irrigated treatment was likely associated with a reduction in photosynthetic reactions as a result of diffusive factors (stomatal) due to water stress. According to Chaves and Oliveira (2004), a moderate water stress applied to soybean caused a decrease in photosynthesis due to a decrease in CO_2 diffusion from the atmosphere to the carboxylation site, as a result of stomatal closing to reduce water loss. Furthermore water stressed conditions cause an imbalance between the capture of energy and metabolism, which result in decreases in photochemical reaction and increased energy dissipation (Lawlor and Tezara, 2009). Also, water stress influences plant nutrition and the establishment of plant organs and function (Prudent et al., 2015).

In this study when comparing fully irrigated to +1, +2, and non-irrigated treatments, a reduction in number of nodules per plant was observed as well 20, 35, and 60%, respectively. Similarly, Prudent et al. (2015) showed that water stress conditions drastically reduced the number of nodules produced by ~55% at harvest. King and Purcell (2001) also found that water stress can inhibits nodule formation as well as symbiotic N_2 fixation, by decreasing nodule size and by reducing nodule-specific activity. Water stress contributes to a decrease in nitrogen fixation and consequently decreases in photosynthetic rates (Chavarria et al., 2015). Furthermore symbiotic N_2 fixation, has been shown to be the metabolic process most susceptible to water stress in soybean plants (King et al., 2014). Therefore one may speculate that as irrigation deficit was increased in this study reductions in levels of nitrogen fixation across irrigation treatments may have occurred. The possible reduction in the metabolic nitrogen fixation (non-stomatal) across the irrigation treatments may have contributed to reductions in photosynthetic rates as well. Therefore reduction in plant growth associated with water stress in this study is likely to be a result of a reduction in photosynthetic rate from both diffusive factors (stomatal) and reduction in the metabolic nitrogen fixation (non-stomatal).

Effects of irrigation on canopy temperature, canopy minus air temperature, stomatal conductance

Comparison between fully irrigated and non-irrigated treatment were made in order to evaluate the effect of irrigation treatment on canopy temperature, stomatal conductance, and canopy air temperature difference one day prior to irrigation event (-1 day), during an irrigation event (0 day), and three days after irrigation (3 days).

As one would expect, the data indicates that plants in the fully irrigated treatments experienced less water stress than the non-irrigated plots. Lower canopy temperatures, lower differences between canopy and air temperature and higher stomatal conductance were observed in the full irrigated plots relative to the non-irrigated plots (Fig. 3A, 3B, and 3C respectively). In the non-irrigated plots, an average 2°C temperature increase was recorded relative to the fully irrigated treatment pre and post irrigation event (Fig. 3A). Irrigation shows to have reduced the difference between canopy and air temperature. Canopy to air temperature difference for the fully irrigated treatment was on average ~4°C lower than the non-irrigated treatments pre and post irrigation event (Fig. 3B). Stomatal conductance difference for the fully irrigated treatment was 0.44 mmol m^{-2} s^{-1} higher than non-irrigated treatment pre irrigation and 0.32 post irrigation (Fig. 3C).

Effects of soil treatments on canopy temperature, canopy minus air temperature, stomatal conductance

One day before irrigation (-1) the deep tillage and deep tillage + gypsum treatment showed lower canopy temperature, about 1°C less than the conventional and conventional + gypsum (Fig. 3D) ($p = 0.0011$). About a 0.5°C decrease in this difference was observed after an irrigation event ($p = 0.0289$). Furthermore, the canopy to air temperature difference in the deep tillage and deep tillage + gypsum treatments was ~2°C lower before ($p = 0.0012$) and 1°C lower after irrigation ($p = 0.0297$)., than the conventional and conventional + gypsum (Fig. 3E). The reduction in differences, between treatments with deep tillage and treatments without deep tillage, in both canopy temperatures and the canopy to air temperature difference indicate that the irrigation effect on canopy temperatures minimized the soil treatment effect on canopy temperatures. No soil treatment effect on level of stomatal conductance was observed post irrigation (Fig. 3 F).

Solar radiation absorption causes canopy temperatures to increases; however when the solar energy is used for water evaporation through the stomata, the surface of the leaf is cooled (Dejonge et al., 2015). Under water stress free conditions, the water transpired by plants evaporates and cools the leaves; in water stressed conditions, transpiration and subsequent evaporation is restricted causing leaf temperature increases (González-Dugo et al., 2006). In this study, plants in the fully irrigated treatment had a lower canopy temperature than those in the non-irrigated treatment, which indicates that plants in the non-irrigated treatment experience higher levels of water stress. The higher canopy temperatures observed from plants in the non-irrigated treatment was likely due to reduction in transpiration and evaporation through the leaf in response to water stress. Water stressed plants will reduce transpiration as a result restricting evaporation at the surface of the leaf, which will typically cause higher canopy temperatures relative to non-stressed plants (Throssell et al., 1987; González-Dugo et al., 2006; Dejonge et al., 2015).

The difference between canopy and air temperature, has often been used to quantify water stress (Throssell et al., 1987; DeJonge et al., 2015). Higher differences between canopy temperatures and air temperature indicate higher levels of water stress (Throssell et al., 1987; Dugo-Gonzalez et al., 2006; DeJonge et al., 2015). Plants in the non-irrigated treatment expressed consistently higher canopy to air temperature differences than plants in the fully irrigated, indicating that the non-irrigated plants experiences high levels of water stress. Three days after the irrigation event canopy temperatures lower than that of the air temperature were observed in the fully irrigated treatment, indicating that plants were experiencing little to no restrictions on transpiration and therefore, water stress at that time. On the contrary, plants in the non-irrigated treatment continued to show a higher level of water stress (remaining ~4°C higher).

The importance of practicing irrigation in agriculture is evident from the observed decrease in canopy temperatures of plants in the irrigated treatment. Irrigating crops helps prevent restrictions to transpiration and thermoregulation. According to Zhang et al. (2015), the use of irrigation has two important effects on adaptive corn and soybean yields in the Central United States, is reducing dry conditions and extreme heat impacts.

Differences found in Canopy temperatures suggest that the use of deep tillage can be used as management tool in minimizing the water stress in areas with soil compaction; one day before the irrigation event plants in treatments with deep tillage had lower canopy temperature and less variation between canopy and air temperature. According to Strudley et al. (2008), deep tillage increases water infiltration, internal drainage and aeration in the soil, in turn increases rooting depth, intensity, and development. Jabro et al. (2015), deep tillage often provides healthier soil physical conditions that promote a more favorable soil environment for plant growth relative to no tillage system.

Seeds yield

Interaction was detected between the soil and the irrigation treatments in relation to seed yield (Table 3). Again deep tillage and deep tillage + gypsum treatments produced higher grain yields. Within all irrigation treatments, the deep tillage treatment produced 10, 15, 18 and 15% more yield than conventional in the fully irrigated, +1 deficit, +2 deficit and non-irrigated, respectively (Table 3). The only clear difference in yield between the deep tillage + gypsum treatment and the conventional + gypsum was that within the +1 deficit plots, deep tillage + gypsum treatment yielded 17% more grain than the conventional + gypsum (Table 3). There were no differences for the other irrigation treatments and the gypsum in each irrigation treatment. Again no effect on yield was observed as a result of the gypsum amendment. Within all irrigation treatments, no clear differences in yields was found between deep tillage and deep tillage + gypsum treatments or between conventional and conventional + gypsum treatments (Table 3).

Within all soil treatments the fully irrigated treatment resulted in higher yields than all other irrigation treatments, and the non-irrigated treatment resulted in lower seed yields than all other irrigation treatments. With exception of the deep tillage + gypsum soil treatment, no difference in yields detected between the +1 and +2 deficit treatments (Table 3).

Yield discussion

Deep tillage provides healthier soil physical conditions (Jabro et al., 2015), which makes soils more favorable for plant growth. In this study an overall soil penetration resistance reduction was observed in the soils treated with deep tillage relative to the conventionally treated soils. According Jabro et al. (2015), deep tillage practices induce greater soil loosening, disturbance, and manipulation intern lowering soil penetration resistance and creating more soil macropores. The penetration resistance reduction in the deep tillage treatment was extremely evident at a depth of 7 to 15 cm indicating that deep tillage also caused a disruption in the compaction layer observed in the conventionally treated soil (Fig. 2). The higher yields observed in the deep tillage treatment are associated with, the overall reduction in penetration as well as the disruption of the compaction layer at 7-15 cm in the soil subsurface. In addition it has been noted that deep tillage practices cause a reduction in soil compaction, which increases water infiltration, internal drainage, and aeration in the soil (Strudley et al., 2008; Jabro et al., 2015), which are all important for obtaining higher soybean yield. Therefore one may speculate that the deep tillage treated soils in this study had higher infiltration, internal drainage, and aeration, which contributed to greater plant yields and overall plant growth. Furthermore the compaction layer present in the soil sub-surface of the conventional treatment was a limiting factor to soybean yield in this study. According Beulter and Centurion (2004), noted that compaction layers caused decrease in the root density, root dry matter and reduction in soybean yield. Overall seed yield increased as the allowable deficit got smaller in the irrigation treatments. The irrigation effects on soybean yield are likely a result of increases in stomatal conductance, shoot dry mass, root dry mass, as well as reduction in canopy temperature, observed in the lower deficit irrigation treatments. Furthermore nodules per plant and nodules dry mass increased as deficit was decreased and was the highest in the fully irrigated treatment. According to Brandelero et al. (2009), nodulation is a determining factor in seed yield and is correlated 40% with grain production. Therefore the higher number of nodules per plant and nodule dry mass observed for plants in the wetter irrigation treatments (highest in the fully irrigated treatment) is likely the greatest contributor to the increase in soybean yields observed among the irrigation treatments.

Inversely, the lower seed yield in the higher deficit irrigation treatments were likely associated with a decrease in photosynthesis due to water stress, evident from the higher canopy temperatures and lower stomatal conductance observed in the non-irrigated treatment. According to Carbo et al. (2005), water stress, induced by controlled watering, caused a progressive and concomitant decrease in net photosynthesis. Doss et al. (1974), examined effects on seed yield in response to water stress at several stages of soybean growth, and found that yield reductions in treatments that experienced water stress, at any portion of the season treatments that experiences water stress all season.

Summary

Increases in yields associated with deep tillage practices were observed across all three years of this study. Production systems that suffer from yield loss as a result of a compaction layer present in the soil sub-surface may consider deep tillage practices. This study has shown that deep tillage can be a beneficial management tool to combat the negative consequences of a compaction layers in soybean production. In addition, this study suggests that using deep tillage can allow for more effective water use and may lead to reduction in water use in soybean production systems. The use of gypsum amendment or associate combined deep tillage gypsum did not show effects on grain production in the soil type examined in this study. More studies on various soil types are needed to determine applicability and any potential effects on soybean yields.

The use of irrigation is a recommended practice for maximizing soybean yields. Irrigation practices combat the negative consequences of water stress experiences by the plants throughout the course of the growing season. In this study reducing the allowable water deficit induced greater crop growth, nodulation, and resulted in higher-yielding soybeans. As the irrigation deficit was increased the soybean seed yield decreased. However, with in deep tillage treatments no difference in seed yield was observed between the +1 deficit and the fully irrigated irrigation treatments. Furthermore the +1 deficit was associated with a reduction in water use, suggesting that when deep tillage practices are being used in soybean production systems with compaction layers, greater allowable deficits can be employed in scheduling soybean irrigation. As a result applying deep tillage practices in soybean production systems with similar soil conditions can lead to a reduction in water use and associated cost with that water use by using an increased deficit. However in similar soybean production systems in Arkansas not using deep tillage to combat compaction should follow current Arkansas scheduling recommendation for ET based irrigation scheduling as a maximum allowable deficit to prevent yield loss.

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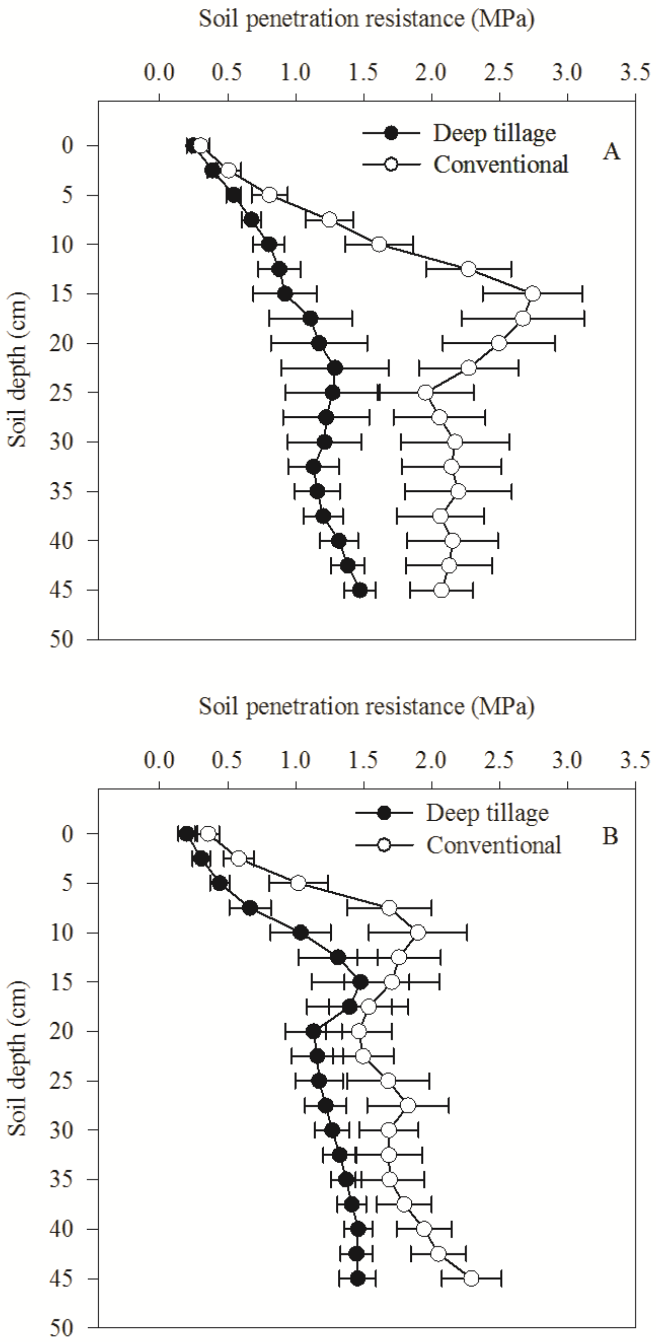

Fig. 1. Average soil penetration resistance (MPa) bed (A) and furrow (B) carried after harvest. Stuttgart, 2015. Error bars indicate two standard errors around the mean of measured values or 95% confidence interval.

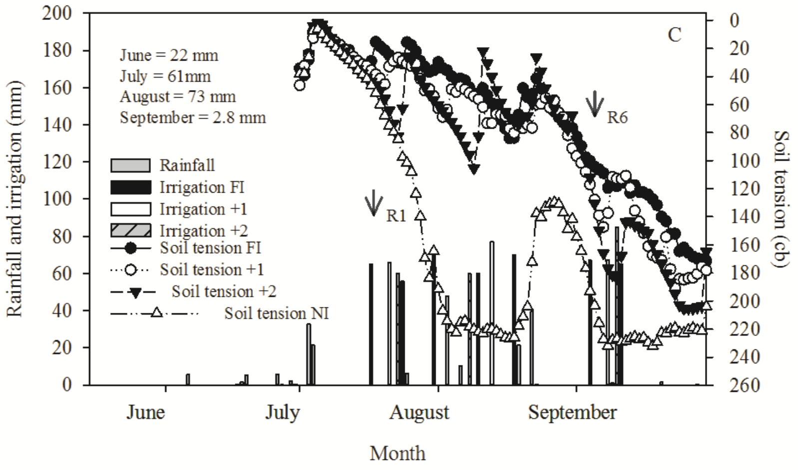

Fig. 2. Rainfall, irrigation and average soil tension across the three depths monitored for the 2013 season (A), 2014 season (B) and 2015 season (C). Stuttgart, 2015. FI = Fully irrigated; NI = non-irrigated. R1 and R6 growth stage according Fehr and Caviness (1977). 2014 season equipment soil tension failed.

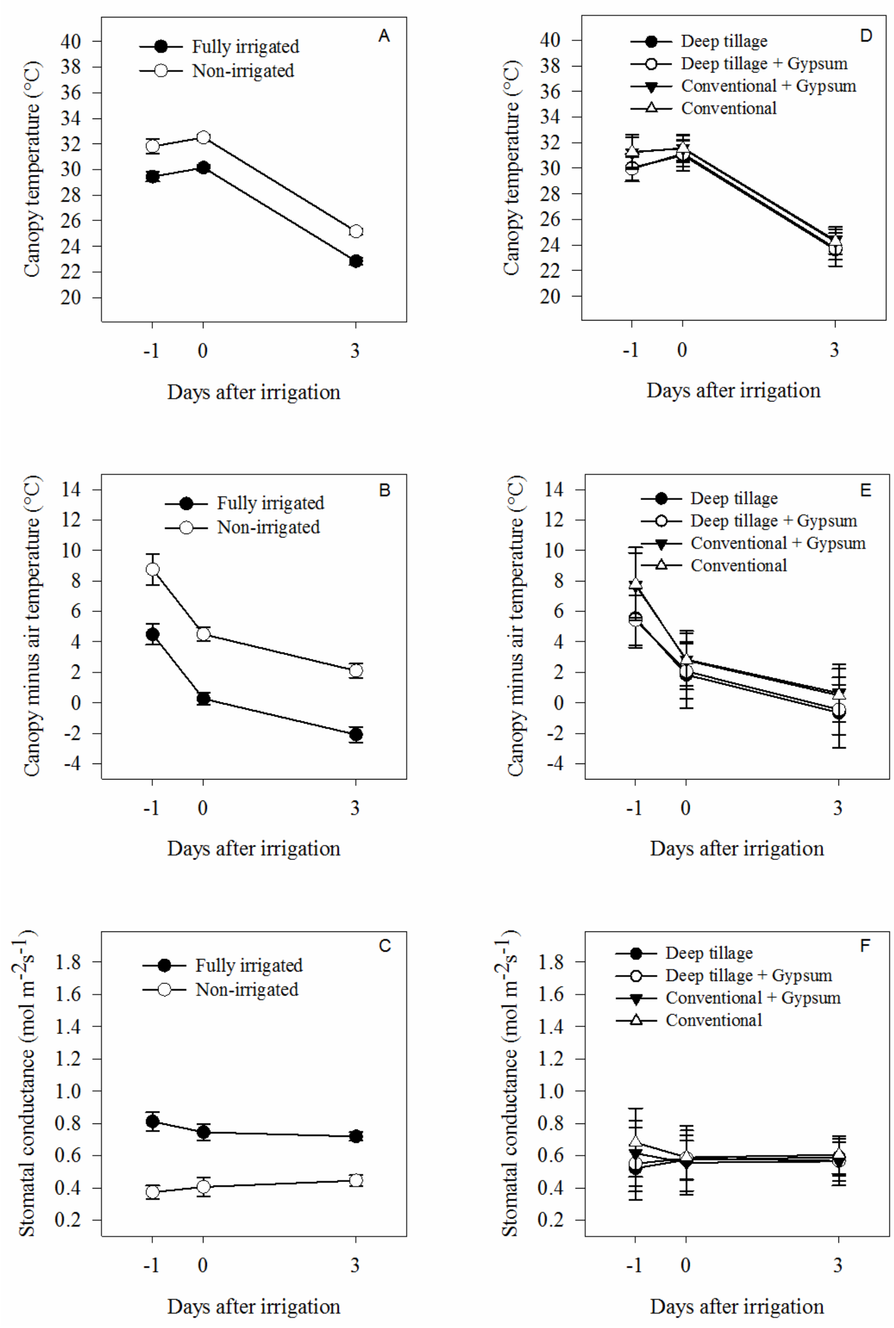

Fig. 3. Canopy temperature (A), canopy minus air temperature (B), stomatal conductance (C) to the irrigation and soil treatment, in R5 growth stage according Fehr and Caviness (1977). 2015 season. Stuttgart, 2015. Error bars indicate two standard errors around the mean of measured values or 95% confidence interval.

Table 1. Irrigation date, number of irrigation (NI), total water applied (TWA), water use efficiency (WUE) to 2015 season. Stuttgart, 2015

Treatment	Irrigation date	NI	TWA (mm)	WUE (Kg mm^{-1})
Fully irrigated	07/17; 07/24; 07/31; 08/10; 08/18; 09/04; 09/11	07	457	8.2
+1 deficit	07/21; 08/03; 08/13; 09/08	04	257	12.3
+2 Deficit	07/24; 08/10; 09/10	03	201	14.7
Non-irrigated	-	-	-	-

Table 2. Plant height (PH), nodes by soybean plants (N), shoot dry mass (SDM), root dry mass (RDM), nodules by soybean plants, nodules dry mass (NDM) in R3 growth stage. 2015 season. Stuttgart, 2015.

Soil treatment	PH (cm)	Nodes ($plant^{-1}$)	SDM (g $plant^{-1}$)	RDM (g $plant^{-1}$)	Nodules ($plant^{-1}$)	NDM (mg $plant^{-1}$)
Deep tillage (DT)	68.5 a*	16.4 a	15.5 a	2.7 a	34.2 b	173.2 b
DT + Gypsum (G)	67.5 ab	16.3 ab	15.5 a	2.6 a	46.5 ab	271.4 a
Conventional + G	63.8 ab	15.7 b	15.5 a	2.6 a	45.0 b	244.1 ab
Conventional	58.6 b	16.0 ab	16.7 a	2.9 a	58.1 a	288.3 a
Irrigation treatment						
Fully irrigated	69.8 a	17.0 a	18.9 a	2.7 ab	64.4 a	335.6 a
+1 deficit	69.2 a	16.5 a	17.5 ab	3.0 a	51.6 ab	267.5 ab
+2 Deficit	66.8 a	16.3 a	15.2 b	2.8 a	41.8 b	237.7 b
Non-irrigated	52.6 b	14.6 b	11.7 c	2.3 b	26.0 c	136.2 c
Mean	64.6	16.1	15.8	2.7	45.9	244.2
CV%	12.9	3.8	14.4	15.7	25.6	35.5

*means not followed by the same letter in the column differ by Tukey's test at 5% probability.

Table 3. Seeds yield to the irrigation and soil treatment. 2015 season, Stuttgart, 2015.

Soil treatment	Irrigation treatment			
	Fully irrigated	+1 deficit	+2 deficit	Non-irrigated
	Seeds yield (kg ha^{-1})			
Deep tillage	3897.3 Aa[*]	3357.0 Ba	3262.3 Ba	1656.3 Ca
Deep tillage + Gypsum (G)	3778.0 Aab	3318.6 Ba	2972.6 Cb	1470.0 Dab
Conventional + G	3781.0 Aab	2754.3 Bb	2926.0 Bbc	1331.3 Cb
Conventional	3524.6 Ab	2854.0 Bb	2674.3 Bc	1406.3 Cab
Mean	2810.2			
CV%	4.71			

[*] means followed by the same lowercase letter in the column and the same uppercase letter in the row, does not differ by Tukey's test at 5% probability.

4 DISCUSSÃO

As áreas de várzeas cultivadas com arroz irrigado possuem uma camada adensada (compactada) na camada subsuperficial do solo. A região de maior adensamento se encontra na camada de 05 - 15 cm de profundidade. As características físicas naturais dos solos de várzeas (BAMBERG et al., 2009), associado algumas práticas de preparo da área, como exemplo da sistematização para aquelas áreas sistematizadas (NUNES et al. 2002), gradagens e aplainamento, principalmente com teor inadequado de umidade do solo, que são práticas comumente utilizadas para o cultivo do arroz irrigado, favorecem o adensamento do solo na camada subsuperficial. Em função disso, há redução principalmente na quantidade de macroporos (DRESCHER et al., 2011), que possuem função importante na aeração do solo e também na drenagem do excesso de água. Dessa forma, a capacidade de infiltração de água dos solos que possuem uma camada adensada principalmente na camada subsuperficial, a exemplo dos solos de várzeas, é reduzida.

A utilização de um sistema de implantação que utiliza escarificação do solo na profundidade que esta situada a camadada de maior adensamento é uma prática de manejo benéfica que promove uma redução da densidade do solo e dos valores de resistência à penetração. Essa prática resulta em aumento da aeração do solo e também da infiltração de água, sendo uma alternativa de manejo eficiente objetivando-se melhoria das condições físicas do solo. Outra alterntiva de manejo está associada aos mecanismos da semeadoura. O uso do mecanismo haste sulcadora na semeadora de forma isolada ou associada a outro sistema, como o sistema em microcamalhão também proporciona benefícios nas características físicas do solo principalmente na região de atuação do mecanismo na linha de semeadura. Os mecanismos disco duplo e disco ondulado que são utilizados para a semeadura de soja por parte de grande parte dos agricultores possuem menor efeito de redução da camada adensada na região de atuação do mecanismo, mantendo as características físicas da área.

Em função disso, ao se utilizar um sistema sem escarificação do solo e semeadura com os mecanismos disco duplo ou disco ondulado na semeadura da soja em áreas de várzeas que possuem uma camada adensada próxima à superfície do solo, ocorrem menor crescimento e desenvolvimento das raízes das plantas de soja, devido menor efeito desses mecanismos nas melhorias das propriedades físicas do solo. Esse efeito pode ser ainda mais acentuado quando se utiliza semeadoras com massa insuficiente para promover uma maior penetração dos mecanismos no solo.

O aumento da resistência do solo à penetração acima dos níveis críticos é um dos limitantes do cresimento e desenvolvimento do sistema radicular (BOTTA et al., 2010); BORTOLUZZI et al., 2014). A presença de uma camada compactada além de interferir no cresimento e desenvolvimento das raizes, limita a exploração do sistema radicular em profundidade. Com isso, mais de 90% do sistema radicular concentra-se na camada de 0 - 10 cm. Assim, em sistemas que utilizam escarificação do solo ou uso de mecanismos que melhoram as características físicas do solo na linha de semeadura, a exemplo da haste sulcadora é verificado aumento do crescimento das raízes (massa seca e volume) e do seu desenvolvimento (número de pontas de raiz).

Em função disso, as plantas de soja estão menos predispostas à ocorrência de estresses tanto em épocas de excesso como de déficit hídrico. No entanto, maiores problemas podem ocorrer em plantas que possuem menor crescimento radicular, sendo a deficiência de oxigênio no solo uma das principais causas (CARDOSO et al., 2006). No tecido foliar das plantas é observado um aumento na concentração de peróxido de hidrogênio, aumento da peroxidação de lipídios e da atividade da superoxido dismutase em função dos estresses. Já quando são utilizados sistemas com escarificação do solo e uso de um mecanismo como a haste sulcadora, seja ela utilizada de forma isolada na semeadora ou associada ao sistema em microcamalhão os estresses nas plantas ocorrem em menor proporção pelas melhorias das características físicas do solo. Associado a isso, em função das restrições físicas do solo, a nodulação da soja é afetada em número e em massa seca, interferindo também a concentração de nutrientes no tecido foliar.

Diante disso, em função dos inúmeros fatores que podem interferir no rendimento de grãos de soja, a camada compactada que comumente é encontrada em áreas de várzea, por interferir na qualidade física do solo e nas relações solo-ar-água, limita o crescimento radicular, a nodulação, favorecendo a ocorrência de estresses e plantas com menor aporte nutricional. Com isso, o rendimento de grãos de soja é reduzido em mais de 10%, podendo essa redução de rendimento ser mais expressiva em épocas déficit ou excesso hídrico.

Associado aos sistemas de implantação e de semeadura, a irrigação é uma tecnologia que pode minimizar os efeitos da camada compactada e do déficit hídrico. O efeito positivo da irrigação é evidenciado pelo maior crescimento de raízes, menores estresses oxidativos e aumento do número e massa seca de nódulos, o que proporciona em ganhos de mais 5% de rendimento, quando a mesma é realizada em condições de umidade do solo abaixo de 60% da capacidade de campo.

Em áreas que utilizam alguma prática de redução da camada compactada do solo, a exemplo da escarificação do solo, dependendo do nível de adensamento do solo, profundidade em que se encontra a camada adensada, pode-se ocorrer um aumento da tolerância das plantas a épocas de falta de chuva, podendo-se com isso reduzir o número de irrigações. No entanto, mais estudos precisam ser realizados para verificar o efeito da escarificação do solo sobre a redução do número de irrigações.

Assim, é necessário proporcionar às plantas de soja condições físicas favoráveis do solo, visando atingir tetos produtivos elevados. A escarificação do solo, e uso da haste sulcadora na semeadora de forma isolada ou associada no sistema em microcamalhão são alternativas que contribuem significativamente para o aumento do rendimento de grãos de soja cultivada em áreas de várzeas.

5 CONCLUSÕES

O sistema de implantação com escarificação do solo e a semeadura utilizando haste sulcadora e em microcamalhão com haste sulcadora reduzem a densidade do solo na linha de semeadura, aumentando a porosidade total, o percentual de macroporos e a capacidade de infiltração e armazenamento de água no solo.

O uso da escarificação do solo e haste sulcadora na semeadora promove maior crescimento de raízes de soja em áreas de várzea.

Há menores estresses oxidativos em plantas de soja em sistemas que proporcionam melhorias nos atributos físicos do solo, como o sistema com escarificação do solo e o sistema com semeadura utilizando a haste sulcadora.

Os sistemas com escarificação do solo e uso de haste sulcadora na semeadora proporcionam maiores teores de nutrientes no tecido foliar em soja.

Há maior rendimento de grãos de soja quando utilizado os sistemas com escarificação do solo e semeadura em microcamalhão e com haste sulcadora, comparado à semeadura sem escarificação do solo utilizando disco duplo e disco ondulado na semeadora em área que apresenta camada compactada próxima à superfície do solo.

A irrigação minimiza os estresses oxidativos nas plantas em épocas de déficit hídrico, promovendo maior crescimento de raízes, nodulação e rendimento de grãos de soja em áreas de várzea.

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