SOIL MOISTURE, PENETRATION RESISTANCE, AND LEAST LIMITING WATER RANGE FOR THREE SOIL MANAGEMENT SYSTEMS AND BLACK BEANS YIELD

J.M. Reichert, V.R. da Silva and D.J. Reinert
Soils Department, Federal University of Santa Maria, Santa Maria-RS, Brazil.

Abstract
Crop response to soil compaction depends on the interaction among crop, soil type, water content, and compaction degree. We determined the effects of soil management on penetration resistance (PR), bulk density (Bd), moisture (Θ), and root distribution, and to relate bean yield with the amount of days that soil moisture was outside the LLWR, on a sandy loam Hapludalf. Soil management systems were continuous no-tillage (NT) for 12 years, chisel tillage (ChT) of previous NT, and conventional tillage (CoT) of previous NT. Soil Bd at 5 cm depth was 1.72 Mg m^{-3} for NT, 1.65 Mg m^{-3} for ChT, and 1.52 Mg m^{-3} for CoT. The PR for 6-10 cm layer was greater than 2 MPa for NT, from 30 days after beans seeding until the end of the beans cycle. Roots concentrated mainly in the 5-15 cm layer for NT and were well distributed down to 25 cm depth for ChT, while no restriction to root growth was observed for CoT. The number of days in which the crop experienced soil water outside the LLWR was 18 days for NT, 19 days for CoT, and 13 days for ChT. Beans yield, however, was similar for the soil management systems.

Additional Keywords: soil-water-plant relationship, no-tillage, soil mechanical properties.

Introduction
Climatic variations affect dramatically beans yield and is sensitive to water stress during the growing season, mainly in reproductive periods. Beans roots have different tolerance to soil compaction, but plants respond to critical values restricting growth. In the literature it is not clear yet which soil property better relates to the critical limit of soil penetration resistance (PR) and crop yield. In the general, the value of 2 MPa is accepted as restrictive for root growth (Taylor *et al.,* 1966; Benjamin *et al.,* 2003). Crop response to soil compaction depends on the interaction among crop, soil type, water content, and compaction degree (Lipiec and Simota, 1994). In this context, soil moisture is the main factor and the Least Limiting Water Range (LLWR) relates soil moisture with aeration porosity (10%) and penetration resistance (2 MPa), which are both dependent upon the degree of soil compaction and represent the upper and lower limit of the LLWR (Silva *et al.,* 1994).

The hypothesis of this study was that soil plowing and/or chiseling reduces the degree of soil compaction and consequently, increases LLWR range. It implies that, plants would experience larger periods (days) of soil moisture between the upper and lower limit of the LLWR. The objectives were to determine the effect of plowing/chiseling to alleviate soil compaction changing soil bulk density, soil penetration resistance and root distribution, and to relate beans yield in three soil management systems with the amount of days that the soil moisture lied out the critical limits of the LLWR.

Materials and Methods
The experiment was located in the experimental site of the Soil Department of the Federal University of Santa Maria, Santa Maria, RS-Brazil, with an altitude of 95 m. The climate is "Cfa" according to Köppen classification. The experimental design was randomized blocks, with three soil management systems: no-tillage (NT); conventional tillage (CT), and chisel tillage (RT). Conventional tillage was done by disc plowing to 30 cm depth and disking. The chisel tillage consisted of a chisel with three shanks, operating at 30-cm depth. Soil tillage for both conditions was done about 15 days before seeding. The plowing and chiseling of the soil had as objective the reduction of the soil compaction degree, originated from the previous 5 -years of no-tillage. Black beans, var. FT-NOBRE, were seeded in November 23, 2001, at 0.45 m line spacing and starter fertilized with 400 kg ha^{-1} of 5-20-20 (N-P-K) formula.

The LLWR was determined in soil samples with preserved structure, following the methodology described by Silva *et al.* (1994). The upper limit of LLWR was the water content at field capacity ($\theta_{0.01}$) or air filled porosity of 10% (θ_{ar}), while the lower limit was the water content at –1.5 MPa ($\theta_{1,5}$) matric potential or the water content where soil resistance reached 2 MPa (θ_{PR}). Values of LLWR for different density values for this soil type are presented in Figure 1.

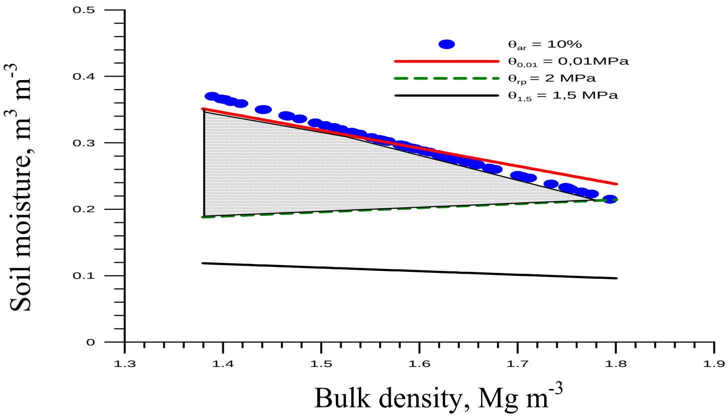

Figure 1. Least limiting water range (LLWR) for Hapludalf soil (adapted from Silva, 2003).

Soil moisture was determined with TDR (Trase System), at four depths (0-5 cm, 5-10 cm, 10-20 cm, and 20-30 cm), using sensors with 23 cm rods transversely inserted inside in the soil at each depth increment, during the whole beans cycle. Soil penetration resistance (PR) was determined from the soil surface down to 40 cm depth at 1.5 cm depth increments, with a handheld penetrographer (Rimik CP 20), with a 30° conical tip and 12.83 mm of cone base diameter. Root distribution was evaluated when the beans crop was at reproductive stage, around 35 days after the seeding. Crop yield was measured when the plants reached physiologic maturation.

Results and Discussion

Bulk density and soil penetration resistance

Bulk density (Bd) in the 0 to 5 cm layer was 1.53 Mg m^{-3} for no-tillage, 1.45 Mg m^{-3} for conventional tillage, and 1.35 Mg m^{-3} for chisel tillage. In 5 to 10 cm layer, for the conventional tillage Bd was 1.48 Mg m^{-3}, while for no-tillage it was 1.72 Mg m^{-3}. Soil plowing was efficient in reducing Bd at 7.5 cm depth, which usually is the soil depth with higher degree of soil compaction under no-tillage conditions (Hakansson *et al.,* 1988). Although soil plowing decreased Bd, several factors as soil structure breakdown, absence of soil surface residues, raindrop impact, and wetting/drying cycles contributed to rapid soil recompaction. The PR was greater for no-tillage than for conventional or chisel tillage.

The lowest values of soil moisture during the beans cycle were observed during January, providing a high degree of strength that disabled the determination of PR. Among several soil properties that influence PR values, moisture is the most highly variable during the crop cycle. Therefore, isolated determinations of PR do not detect possible limitations of high PR to crop growth. During whole beans cycle, low PR were verified in the 3-5 cm layer, mainly in the first 10 days after the beans were sown (Figure 2). During all crop cycle, no-tillage presented greater PR than conventional or chisel tillage, but always below to 1.5 MPa.

For the 6-10 cm layer, no-tillage presented PR values of 1.5 MPa in the first days after seeding, while the other two soil management systems had PR around 0.5 MPa. From 30 to 60 days after sowing, no-tillage presented PR of 2 Mpa (Figure 2), considered critical for roots growth (Taylor *et al.,* 1966). However, root growth was fast and in the first 10 days after seeding the roots already surpassed the depth of 10 cm (visual observation). The greatest variation in PR occurred for the 12-20 cm depth due to variations in soil moisture, with PR above 2.5 MPa for the three soil management systems. In the layer of 21-30 cm small variations were observed among the soil management systems. Restrictions to root growth due to high PR (above 2 MPa) during beans cycle were observed in the 6-10 cm depth, starting from 30 days after seeding for no-tillage. In the depth from 12 to 20 cm, PR above 2 MPa were observed in all soil management systems, with alternating periods with PR below 2 MPa when soil moisture increased, permitting root growth to deeper soil.

At beans reproductive stage, roots in conventional tillage presented greater distribution in width and depth than in no-tillage and chisel tillage. In no-tillage, the roots concentrated at the 5-15 cm layer, but some roots surpassed the compacted layer and grew to depths deeper than 30 cm. In the conventional tillage no restrictions to root growth were observed, with roots distributed around all sides of the plant, occupying the whole soil volume. In chisel tillage, roots were concentrated until 25 cm depth.

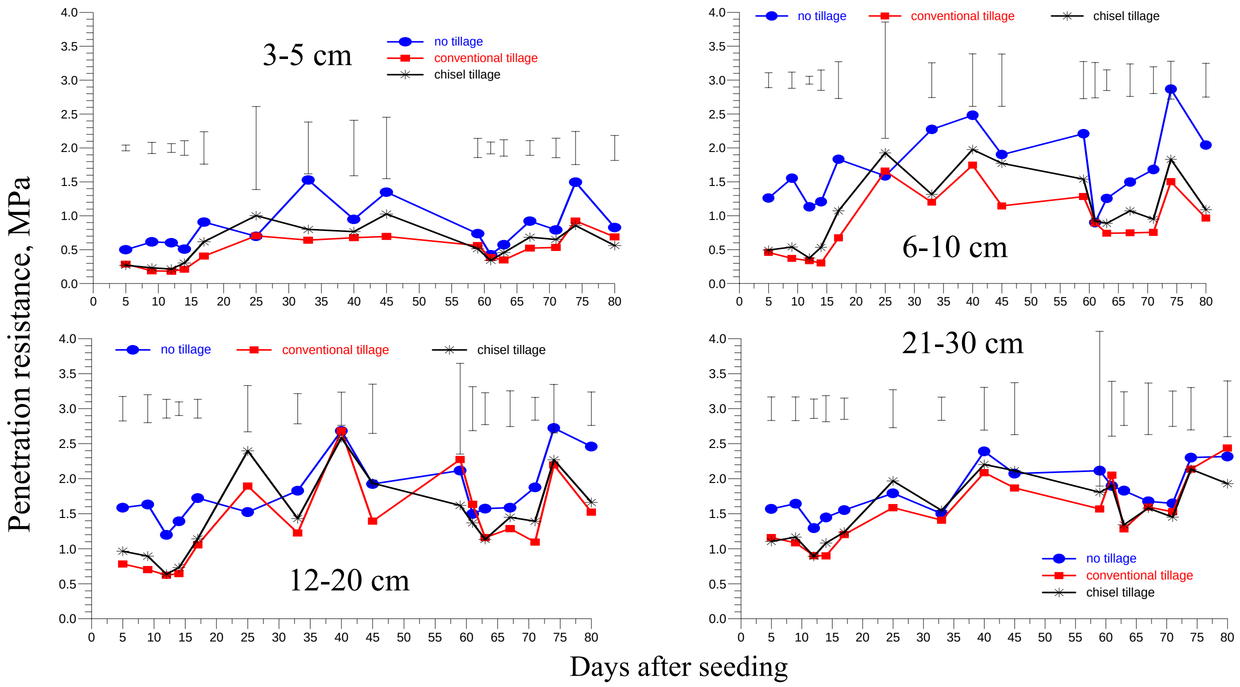

Figure 2. Soil penetration resistance during the beans cycle for three soil management systems, at four depths. Vertical lines compare treatments in each available day with LSD (5%).

Soil moisture, LLWR and beans yield

The upper and lower limit of LLWR for this soil was considered the soil moisture where the soil physical conditions are optimum for plants growth and productivity (Silva *et al.,* 1994). The lower limit refers to the soil moisture where the PR was superior to 2 MPa, or soil moisture in the potential of -1.5 MPa. While the upper limit refers to the soil moisture when the porosity of aeration was of 10% or the soil moisture in the potential of -0.01 MPa. Differences between the upper and lower limits of LLWR were of 0.155 m^3 m^{-3} of water for chisel tillage, of 0.110 m^3 m^{-3} for conventional tillage and of 0.107 m^3 m^{-3} for no-tillage.

From November 28, 2001 until December 7, 2001, soil moisture was outside the LLWR limits for all depths in no-tillage (Figure 3a), while from December 7, 2001 to January 21, 2002 only 0-5 and 5-10 layers shown soil moisture lesser than lower limit of LLWR. However, in depths from 10-20 cm and from 20-30 cm, soil moisture was adequate for beans growth until January 3, 2002. From this date until January 21, 2002 plants grew with soil moisture lesser than the lower limit of LLWR in the 0-30 cm layer. Irrigations were done during that period to alleviate the plant water stress.

For conventional tillage, the 0-5 cm and 5-10 cm layers presented soil moisture below the ideal conditions for plant growth on December 7, 2001, while the layers from 10-20 cm and 20-30 cm stayed in between the LLWR critical limits on January 2, 2002 (Figure 3b). For chisel tillage, the period in which soil moisture was outside of the LLWR was from January 8, 2002 until January 21, 2002 (Figure 3c). The bean plant cultivated under chisel tillage grew with soil moisture between the upper and lower limits of LLWR three days more than for no-tillage and four days more than for conventional tillage.

No differences in beans yield for the three soil management systems were observed, indicating that number of days in which soil moisture was outside the LLWR was not enough to affect the beans yield. However, Silva and Kay (1996) verified that initial corn plant growth was correlated positively with LLWR and negatively with the frequency of days that soil moisture was out of the limits of LLWR, but they did not analyze crop yield. A regression of wheat yield to LLWR gave an r^2 of 0.76, but the LLWR was a poorer indicator of plant productivity when low soil moisture limited the expression of the potential crop production (Benjamin *et al.,* 2003).

Conclusions

Plowing the soil reduced the bulk density and soil penetration resistance throughout the beans cycle. No-tillage had lesser root density than chisel and conventional tillage. Soil management reduced the bulk density and increased the amplitude of soil moisture inside of the LLWR. The soil moisture stayed inside of the LLWR longer in chisel tillage. The number of days in which the beans crop grew with soil moisture smaller then the LLWR lower limit, for the three soil management, did not induce difference in beans yield.

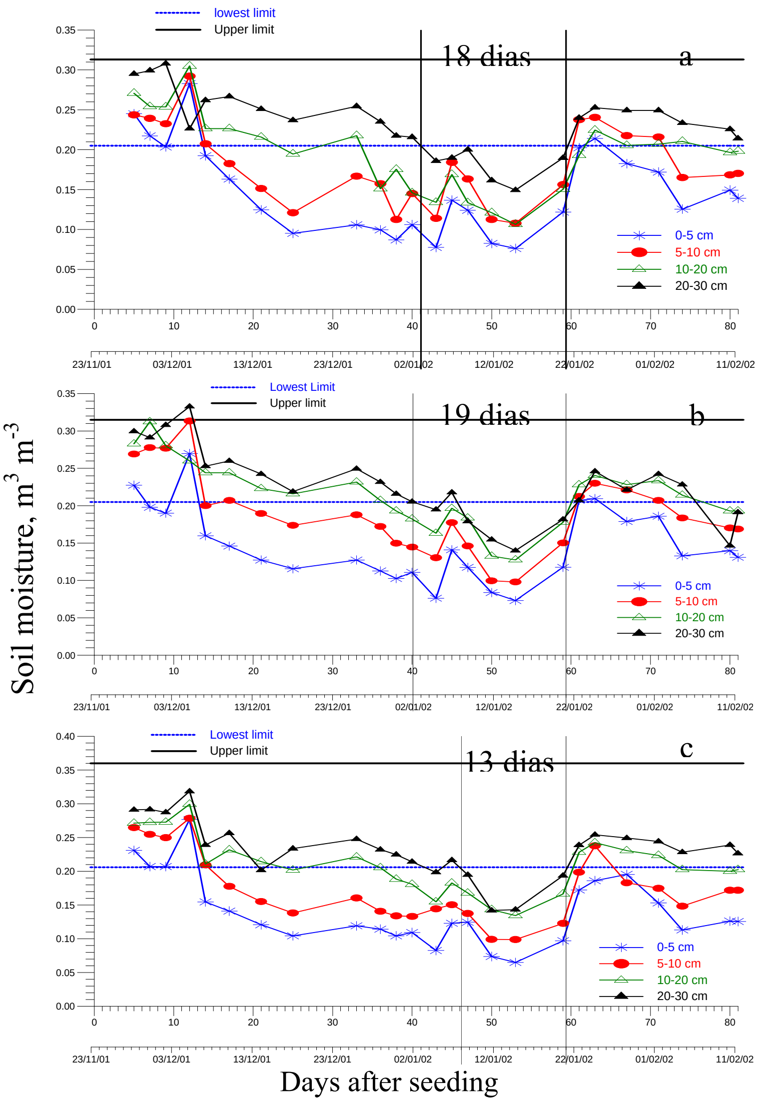

Figure 3. Soil moisture during beans cycle, at four depths, for (a) no-tillage, (b) conventional tillage, and (c) chisel tillage.

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