# Soil resistance to penetration under the dynamic and predictive perspective of restriction to crop yield

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## Abstract
Crop yield is related to soil compaction and water availability. In periods with scarcity of rains, water deficit to plant and soil resistance to root penetration are the main factors which cause yield loss. The way they affect biological processes in crops is already well understood; nevertheless, when and with what intensity they act are difficult questions to answer, above all in relation to resistance penetration, since studies do not duly consider its dynamic behavior. The declared hypothesis is that the time for the resistance penetration to reach a restrictive value is a consequence of the state of compaction and is related to plant response. The penetration resistance was estimated throughout the growing phase of the bean plant crop (*Phaseolus vulgaris*) as a function of soil moisture at different compaction levels (chisel plowed; no-till and no-till with additional compaction). The results obtained confirm the hypotheses of this study. Data showed that the time for the resistance to penetration to reach the value of 2 MP is different among the compaction levels and is directly related to the grain yield. Chisel plowing provides a significant increase in grain yield when the soil is high compacted. The analysis of time for the evolution of resistance to penetration at a critical value is a promising strategy with predictive potential for the effect of soil compaction on crops.

## Key Words
Compaction, no-till, bean crop, soil moisture.

## Introduction
The expansion of no-till system in the world has been accompanied by increasing use of agricultural machinery, whose continued traffic intensifies soil compaction, especially in inappropriate soil moisture conditions and can reduce crop production. Reductions in yield of bean greater than 50% were observed in the no-till when it was compacted by traffic (Collares 2005). Reduced production due to soil compaction has been reported in several other crops (Secco *et al.* 2005; Freddi *et al.* 2008). On the other hand, attempts to reduce soil compaction by plowing or chiseling not always were advantageous (Secco *et al.* 2004; Marcolan and Anghinoni 2006). Various physical properties have been related to crop response in the attempt to define critical physical limits. Using crop yield as a reference, Reinert *et al.* (2001) established restrictive values of soil bulk density as a function of the clay content. These levels have been refined with the association of studies of various other researchers who studied the physical quality of the soil by means of the least limit water range (LLWR) (Reichert *et al.* 2009), which associates information of critical aeration porosity and resistance to penetration. The great difficulty has been in establishing limits for these indicators which characterize a state of compaction which is harmful to crops. More than that, the greatest challenge has been in describing relations between one indicative piece of data and plant response, in a way that the relationship or model preserves the sensitivity between the cause and the effect in other situations of its application. The hypothesis is that values which indicate restriction from resistance to penetration occur at different times among the compaction levels, and there is a relationship between the grain yield of the bean plant and the time for resistance to penetration to reach restrictive conditions.

The objectives of this study are: (i) to generate equations of soil resistance to penetration as a function of soil moisture and estimate soil resistance to penetration during the bean plant growth period; (ii) quantify the period of time which passes for soil moisture to decrease from a moisture condition after rain or irrigation up to the moisture condition in which resistance to penetration reaches a critical value; (iii) relate grain yield with the period of time which passes for resistance to root penetration to reach a critical value.

## Methods
An experiment was implanted in the experimental area of the Soils Department of the Federal University of Santa Maria (29º 43' 14" S, 53º 42' 18" W), Rio Grande do Sul, Brazil. Soil at the location is classified as a typical Red Dystrophic Argisol, with a sandy loam surface texture with 150 g/kg of clay, 238 g/kg of silt, and 612 g/kg of sand, at the layer from 0 to 0.30 m. The area has been cultivated under no-till for 16 years.

In 12 experimental units (5 m long x 3 m width) distributed in four blocks, the treatments were randomized which consisted of three compaction levels: (1) soil under no-till along 16 years (NT), (2) soil under no-till along 16 years that received mechanical compaction (C-NT) and (3) soil under no-till along 16 years that was chisel plowed (CP). The C-NT was defined by means of the successive traffic of an agricultural tractor (approximate mass of 3.8 Mg), with a disk plow connected to increase the load on the soil. Four sequences of traffic were performed over the subplot, with parallel passing, at a distance from one another of half the width of the rear tractor tire. This operation was performed when the soil presented moisture of 0.14 kg/kg. The CP was defined by means of chisel plowing performed with a subsoiler, with shanks 0.5 m apart, to a depth of 0.25 m. Chisel plowing was performed when soil moisture was around 0.11 kg/kg. Compaction and chisel plowing were performed after chemical dissecation and spontaneous plant senescence present in the area (*glyphosate*, at a dose of 1,230 g.a.i./ha). Seeding of the beans, BRS Valente cultivar, was performed on January 30, 2008 (second crop), at a density of 280,000 seeds/ha.

For purposes of characterization of the compaction levels, porosity and soil bulk density were measured at 5 DAS, corresponding to 20 and 13 days after the operations of chisel plowing and compacting respectively. Soil samples were collected with their structure preserved in metallic rings of 0.06 m diameter by 0.05 m height in the layers of 0-0.1; 0.1-0.2; 0.2-0.4 m. The soil resistance to penetration (PR) was determined at 23, 25, 26, 35 and 36 DAS, with a manual penetrometer with electronic data storage and a conical point with a 30º angle of penetration. Determinations of the PR were used to generate PR regression equations as a function of the soil moisture. These equations were used to estimate the daily PR throughout the crop cycle based on the moisture data measured with TDR. The time which passed until the PR reached the value of 2 MPa ($Days_{[PR<2MPa]}$) was calculated by means of the estimates of PR throughout the crop cycle. The measurement $Days_{[PR<2MPa]}$ was quantified in the period from 33 to 52 DAS, when the rainfall had practically ceased. Time zero was considered when the soil moisture was near field capacity (33 DAS, Figure 3). The intensity of PR was also quantified, measured by the difference between the maximum values of PR in the period analyzed minus the value of 2 MPa ($\Delta PR_{[PRmax-2MPa]}$). The value of 2 MPa was chosen as the critical value, due to its generalized use by most researchers.

**Results**

Changes in soil moisture were greatest from 32 to 52 DAS due to extremely low rainfall. Soil moisture variations were more pronounced at the layer ranging from surface to the depth where the effects of different levels of compaction were observed, especially in the 0-0.10 m layer, both within and among levels of compaction. However, the moisture measured 24 hours after significant rainfall ($\theta_{24h}$), which occurred at 14 and 33 DAS, was not significantly affected by the levels of compaction. As of 33 DAS, soil moisture in CP was always less than in the other compaction levels, mainly in the layer from 0-0.10 m. As the $\theta_{24h}$ was similar in the different compaction levels, which confers a similar quantity of water in the profile, the more accentuated reduction of soil moisture in the CP must be associated with a greater depth of the root system of the crop, which allowed greater access and, consequently, greater water extraction of soil. In the C-NT, greater soil moisture indicates less access to water by the crop, limited by the high PR. The PR profile of the C-NT at 36 DAS (Figure 1), two days after a period of intense rainfall, and considering 2 MPa as restrictive, clearly indicates that the PR must have limited crop growth even when the soil had elevated moisture. The PR profile of the C-NT shows the occurrence of PR greater than 2 MPa in the layer from 0-0.10 and near this value in the layer from 0.10-0.20. This indicates that the first factor to limit crop growth was the moisture in the CP, and the PR in the PDC. In the PD, moisture and PR must have affected in conjunction, but both at lesser intensities and with non-additive effects.

The time which passed for the PR to reach the value of 2 MPa, or the time in which it remained above this value, to the extent that soil moisture decreased, was different among the compaction levels, as well as among the soil layers (Figure 2). The time which passed for the PR to reach the value of 2 MPa ($Days_{[PR<2MPa]}$) was on mean 2 and 7 days for the C-NT and PD, respectively, in the 0-0,10 m layer and 3, 4 and 13 days for the C-NT, NT and CP respectively in the 0.15-0.25 m layer. The intensity of the PR measured by the difference between the maximum value of the PR in the period analyzed minus the value of 2 MPa ($\Delta PR_{[PRmax-2MPa]}$) was on mean 0.5 and 1.0 MPa for the NT and the C-NT respectively, in the 0-0.10 m layer and 0.4, 1.2 and 1.4 MPa for the CP, NT and C-NT respectively in the 0.15-0.25 m layer. At the time in which the estimated PR was equal to 2 MPa, the soil moisture was in the domain of the functions of the estimate of PR. Soil moisture which corresponds to the lower limit of the domain of the functions occurred at the time indicated by the dotted vertical line (Figure 2).

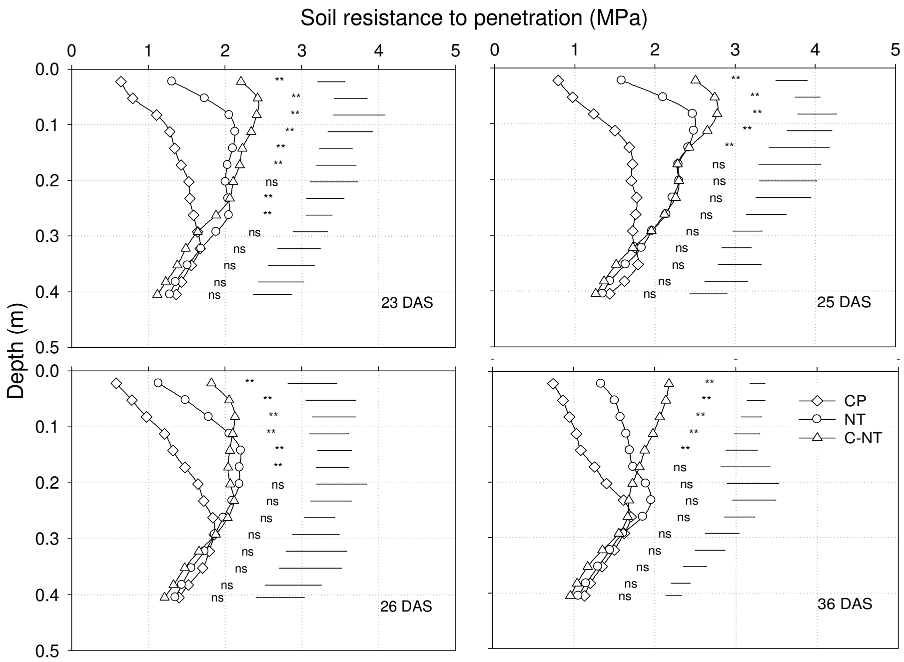


**Figure 1. Soil resistance to penetration measured at different days after seeding (DAS). The horizontal lines represent the least significant difference of the Tukey test at 0.05 and compare the means of the treatments in each layer. CP = chisel plowed; NT = no-till; C-NT = compacted no-till; * = significant; ns = not significant.**

Therefore, one verifies that the $\Delta PR_{[PRmax-2MPa]}$ calculated is the result of extrapolations of the functions to values beyond the interval over which they were generated. Nevertheless, the lower limit of moisture of the domain of the general function in the 0-0.10 m layer was 0.07 $cm^3/cm^3$, less than the moisture of the wilting point (0.09 $cm^3/cm^3$), and the best adjustment of the PR as a function of moisture was the linear. Thus, one expects that in the 0.15-0.25 m layer, if the soil moisture used for the adjustment of the function had decreased as in the 0-0.10 m layer, the linear model would be that which would best adjust a function to the data.

Therefore, the extrapolation used in this study may be considered as an acceptable risk. Comparison of the values of $Days_{[PR<2MPa]}$ with the PR profile at 36 DAS, two days after a period of intense rainfall, shows that the PR in the C-NT had reached the value of 2 MPa, while in NT it would take some days; however, it would not be possible to foresee how many days it would delay. For the 0.15-0.25 m layer, one would also expect that the value of 2 MPa would first occur in the C-NT and NT and then in the CP. Knowledge of the increase of the PR as a function of the daily rate of soil water extraction requires sequential or strategic measurements which allow one to foresee the evolution of the PR and the occurrence of levels which are critical to the plants. The strategy used in this study has potential for this purpose.

The average grain yield was greater in the CP and in the NT (2,807 e 2,791 kg/ha, respectively) which differed from the C-NT (2,254 kg/ha) by the Tukey test at 0.05 (Figure 3). Many studies have shown that when compaction is induced by intense traffic, crops decrease yield in relation to no-till. However, when no-till is compared with soil mobilization, whether by chisel plowing, moldboard plowing or disking, crop response has been varied. At times the yields are greater in mobilized soil, and other times in no-till, or without a difference between soil management systems. In this study, the bean plant grain yield showed that chisel plowing was not a beneficial option compared to the NT; however, it may significantly increase the yield when soil compaction is high (C-NT).

The results of this study confirm the hypothesis that the indicative values of restriction of resistance to penetration (2 MPa) occur at different times among distinct levels of compaction. The PR of 2 MPa occurred at 33 and 40 DAS in the C-NT and NT respectively (0-0.10m layer), and at 37 DAS in the C-NT and NT and at 47 DAS, in the CP (0.15-0.25 m layer). The hypothesis that there is a relationship between grain yield and the time for the PR to reach a restrictive value was also confirmed. Thus, temporal analysis of the PR may be a good study strategy of the effect of soil compaction on crops. In addition, this strategy presents PR predictive potential and may come to be a good guiding instrument for making decisions in regard to physical soil management.

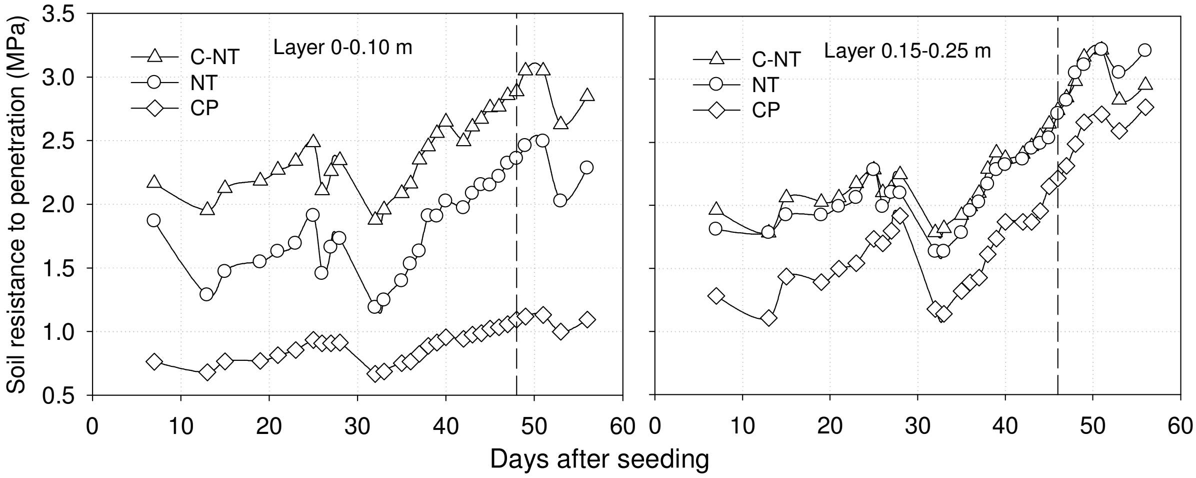


**Figure 2. Variation of the soil resistance to penetration at different compaction levels. The vertical line indicates the time at which the soil moisture (Figure 3) decreased beyond the domain of the soil resistance to penetration estimate functions. CP = chisel plowed; NT = no-till; C-NT = compacted no-till.**

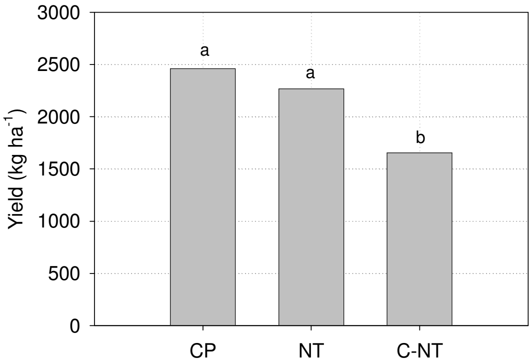


**Figure 3. Average yield of bean plant crop. Columns followed by the same letter do not differ statistically by the Tukey test at 0.05 probability of error. CP = chisel plowed; NT = no-till; C-NT = compacted no-till.**

## Conclusion

The time for resistance to penetration to reach the value of 2 MPa is affected by the state of compaction. In soils with a high state of compaction, plants suffer restriction to growth earlier and with greater intensity through resistance to root penetration than through water deficit. In contrast, in mobilized soils or not very compacted soils, resistance to penetration is much less important than water deficit. The analysis of time for the evolution of resistance to penetration to a critical value is a promising strategy and has predictive potential regarding the effect of soil compaction on crops.

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