PLANT RESPONSE TO MECHANICAL RESISTANCE
AND AIR-FILLED POROSITY OF SOILS UNDER
CONVENTIONAL AND NO-TILLAGE SYSTEM

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ABSTRACT: Roots may respond to restrictive soil physical conditions and send signals to shoots to control plant growth. Soil mechanical resistance and aeration can be managed to improve the soil physical conditions for plant growth by using different tillage systems. The objective of this study was to quantify the influence of no-tillage and conventional-tillage systems on plant response to soil mechanical resistance and aeration. The study was carried out on a farm, cultivated with corn, with a side-by-side comparison of no-tillage and conventional-tillage systems. Thirty-two paired sampling sites were located along two transects, located one in each treatment. Soil water content, bulk density, and plant growth were measured in each treatment. Based on the soil water and bulk density measurements, the air-filled porosity values were computed for each treatment. Soil water contents and bulk density values were converted to soil mechanical resistance by using the soil resistance curve. Plant growth varied positively with soil air-filled porosity, and negatively with soil mechanical resistance in both tillage systems. However, the decrease rates/increase rates were dependent on the tillage system. The no-tillage system somehow improved the soil physical conditions for the plants, especially when they were more restrictive, allowing them to attain greater values of growth.

Key words: plant growth, plant height, soil physical properties, tillage system

INTRODUCTION

Plant growth may be altered by a number of stress factors that are encountered by roots in their environment. Several researches have shown that soil mechanical resistance is one of the most important stress factors since it may control plant growth by reducing root elongation rate (Taylor & Ratliff, 1969; Boone & Veen, 1982; Veen & Boone, 1990; Matererecha & Mloza-Banda, 1997; Zou et al., 2001). However, little is known about how soil me-
Mechanical resistance may affect leaf and stem growth (Masle & Passiouara, 1987; Masle, 1990; Karunatilake et al., 2000; Passiouara, 2002). Another stress factor, the soil air-filled porosity, may also cause detrimental effects on plant growth (Voorhees et al., 1975; Drew, 1990; He et al., 1996; Grischko & Glick, 2001; Zou et al., 2001). As the total air-filled porosity decreases to 10% or less, the oxygen diffusion rate into the soil is inhibited, causing injury to roots and their inability to function (Engelhaar & Yoneyama, 2000).

Pore size distribution and pore continuity play an important role in root growth by directly determining the soil volume filled with air and water, and indirectly the soil resistance. Furthermore, pore size distribution and pore continuity determine the ability to transport oxygen throughout the soil to the roots (Lipiec & Hatano, 2003). A favorable environment to plant growth may be obtained by reducing the soil stress factors. To this end, farmers have used many mechanical modification methods, usually known as tillage. Several papers have been published to highlight the influence of the tillage system on soil physical properties (Pagliai et al., 1995; Azooz et al., 1996; Ball-Coelho et al., 1998; Arshad et al., 1999).

Despite the benefits of tillage for crop establishment and production, the effects of different tillage systems on the relationships between soil mechanical resistance as well as aeration and plant growth remain almost unknown (Silva & Kay, 1997). The objective of this study was to quantify the influence of both no-tillage and conventional-tillage systems on plant response to soil mechanical resistance and aeration.

**MATERIAL AND METHODS**

Field studies were conducted in 1991, 1992 and 1993 on a private farm located near Clinton, Ontario, Canada. The farmer had maintained a field scale side-by-side comparison of no-tillage (NT) and conventional-tillage (CT) system, defined here as moldboard plowing in fall followed by cultivation in spring. A corn-soybean-wheat rotation had been used for 11 years on the site, which was only cultivated with corn during the experiment.

The comparison, in the form of a strip, crossed soils with a wide range in soil texture (from 58 to 374 g kg\(^{-1}\) of clay) and organic carbon content (from 9 to 39 g kg\(^{-1}\)). Thirty-two plots (6 m long by 4.5 m wide) were established along parallel transects about 500 m length in each of the two tillage treatment to incorporate the systematic variation in soil texture and carbon content. Corn (hybrid 'Pioneer Brand 3751') was sown to a population of 67,000 plants ha\(^{-1}\) about two weeks after emergence.

Plant growth and soil water content were simultaneously measured in each tillage treatment in 1992 and 1993, whereas soil bulk density was determined for all years. The 1992 and 1993 growing season were characterized as wet and dry, respectively. Details on the climate, soil properties, and crop management are given in Silva & Kay (1997).

**Soil Measurements**

A total of two hundred and fifty six (2 tillage treatments \(x \) 32 plots \(x \) 4 replications) undisturbed cores (5 cm diameter by 2.5 cm length) were taken in 1991 from the surface layer (5-7.5 cm), where the effects of the tillage system would be more pronounced, to determine the soil resistance curve. A pedotransfer function was developed to relate soil resistance to penetration (SR) with clay content (CLAY), organic carbon (OC), and bulk density (D\(_b\)) for each treatment. Details on this procedure are given in Silva & Kay (1997). The SR model expressed in terms of soil properties was:

\[
\ln \text{SR} = \ln (c + d \ln \theta + e \ln D_b) \quad (1)
\]

where: \(\text{SR} = \) soil resistance (MPa); \(\theta = \) volumetric water content (cm\(^3\) cm\(^{-3}\)); \(D_b = \) bulk density (g cm\(^{-3}\)); \(c, d, \) and \(e = \) constants. The value of these constants can be obtained by using the following equations:

\[
\begin{align*}
\ln c &= -3.673 - 0.145 \text{ CLAY} + 0.765 \text{ OC}, \\
\ln d &= -0.481 - 0.124 \text{ CLAY} + 0.208 \text{ OC}, \\
\ln e &= 3.852 + 0.096 \text{ CLAY}
\end{align*}
\]

where: CLAY = clay content (%); OC = organic carbon content (g kg\(^{-1}\)).

During the experimental periods of 1992 and 1993, four undisturbed cores (5 cm diameter by 2.5 cm length) were taken from the 5-7.5 cm deep in the row and interrow positions in each plot of each tillage treatment for the D\(_b\) measurements. The earliest D\(_b\) measurement was made at the 6-leaf stage and the latest at harvest. These individual values were averaged for each plot.

The soil water content was measured daily, in 1992 and 1993, using the time domain reflectometry (TDR) technique over the 0-0.2 m depth in the row and interrow positions. The soil water content was measured in each tillage treatment for the D\(_b\) measurements. The earliest D\(_b\) measurement was made at the 6-leaf stage and the latest at harvest. These individual values were averaged for each plot.

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The averaged D\(_b\) values and the averaged water content values, measured in the dry growing season, were used to calculate (equation 1) the SR values to be related to plant growth.

The averaged D\(_b\) values and the averaged water content values, measured in the dry growing season, were used to estimate the air-filled porosity values. These values were computed for each treatment as \(\theta_{sat} - \theta_{air}\), where \(\theta_{sat}\) is the soil saturation water content (equal to the total
Porosity obtained from the D₄ and particle density values, and ρₒ is the observed soil water content. The air-filled porosity values were related to plant growth.

**Plant growth versus air filled porosity**

The plant growth was obtained from the plant height measurements. The plant height was measured with a ruler as the distance from the soil surface to the tip of the extended youngest leaf that corresponded to the number 12 ± 1. The measurements were carried out in 1992, on Julian days 197, 198, and 202, on 3 randomly selected plants in each plot of the two tillage treatments. The plant growth (PG) between successive days was calculated as:

\[ \text{PG}_{\text{day}n-\text{day}m} = \text{height}_{\text{day}n} - \text{height}_{\text{day}m} \]

The PG measurements of the 3 plants were averaged for each day-plot combination. The average variability (expressed in terms of coefficient of variability ± error) across the field was: CV (PG) = 5 ± 4%. CV (SLG) across the field was: CV (SLG) = 8 ± 4%. The SLG measurements of the 3 plants were averaged for each day-plot combination. The average variability (expressed in terms of coefficient of variability ± error) across the field (all plots) was: CV (SLG) = 7 ± 3%.

In order to assess the relationship between PG and air-filled porosity (AFP) it was necessary to match both measurements with respect to time and plot of each tillage treatment. Therefore for PG_{dayn-1}, the AFP was estimated as the interpolated AFP at day 197.5. Similarly the PG_{dty-200} was paired with the interpolated AFP at day 200. Thus, for both treatments a total of 128 pair of values were used to the analysis.

**Plant growth versus soil resistance**

The plant growth was obtained from the plant height measurements by using the methodology shown in the preceding item. The determinations were carried out in 1993, on Julian days 199, 200, 201, 202, 203, and 204. The PG measurements of the 3 plants were averaged in each day-plot combination. The average variability (expressed in terms of coefficient of variability ± error) across the field was: CV (PG) = 5 ± 3%; CV (PG) = 7 ± 4%; CV (SLG) = 8 ± 4%; CV (PG) = 7 ± 4%.

The relationship between PG and SR was established by pairing the measurements as follows: (PG\_{\text{day}n-\text{day}m}, (PG\_{\text{day}n-\text{day}m}), (SLG\_{\text{day}n-\text{day}m}), (SLG\_{\text{day}n-\text{day}m}), (SLG\_{\text{day}n-\text{day}m})), (SLG\_{\text{day}n-\text{day}m})). The SR values at the refereed days were obtained by interpolation of the values calculated with equation 1.

**Statistical Analysis**

Nonlinear regression analysis (SAS, 1991) was used to evaluate the relationship between SLG and both air-filled porosity and soil resistance.

**RESULTS AND DISCUSSION**

The results for the relationship between plant growth (PG) and air-filled porosity (AFP) for both tillage treatments are given in Table 1. PG was positively and non-linearly related to AFP. The relationship was significant (P < 0.0001) in both tillage treatments. Both models’ parameters were higher in the conventional-tillage (CT) than in the no-tillage (NT) system. The model accounted for 55% of the PG variability in the NT and 65% in the CT. The observed data and the fitted function are given in Figure 1 for both tillage treatments. There was no sudden critical limit of 0.10 m⁻³/AFP below which PG became quickly inhibited. Moreover there was an AFP range from about 0.05 m⁻³ to 0.15 m⁻³ in which PG increased with increasing AFP, and over which PG changed from affected to unaffected, for both tillage treatments. The decreasing slopes of the curves indicate that the PG sensitivity to aeration decreases as AFP increases. Similar results were found by Voorhees et al. (1975) and Zou et al. (2001) for root growth.

![Figure 1 - Plant growth (PG) variation with air-filled porosity (AFP) for the no-tillage (NT) and conventional-tillage (CT) system.](image)
The tillage effect on PG depended on the magnitude of AFP. In most of the AFP range, PG was higher in the NT than in the CT. However, the magnitude of tillage effect on PG increased as AFP decreased. At relatively high AFP the tillage effect was reversed. This behavior may be related to the differences on soil pore size distribution, which in turn are induced by the tillage systems. According to Pagliai et al. (1995) and Ball-Coelho et al. (1998), the NT system seems to lead to an increase in the water storage pores as well as in the largest transmission pores. Thus, the NT system may increase the water holding capacity, and simultaneously allow better water and air movement. The presence of the large scale pores may be responsible for the interaction tillage-AFP:PG; i.e. the highest PG at low AFP in the soil under NT.

The decrease in PG due to low oxygen availability have been reported by Drew (1990), He et al. (1996), and Grichko & Glick (2001). These authors found that hypoxia (partial O2 deficiency) promoted ethylene biosynthesis by roots. Another hormonal message to the shoots originated in the roots is abscisic acid (ABA). Plants respond to these hormones with epinasty, stem hypertrophy, inhibition of stem and root growth, and leaf abscission. He et al. (1996) determined that hypoxia promoted aerenchyma formation on corn as a consequence of the elevated levels of ethylene on roots. These authors mentioned that roots subject to mechanical stress also exhibit an increase on ethylene levels, and that the two stresses acting together cause a synergistic promotion of ethylene biosynthesis. Voorhees et al. (1975) indicated that root sensitivity to air-filled porosity decreased with increasing soil aeration, probably due to the fact that as soil dries, the soil mechanical impedance becomes more limiting to root growth.

The relationship between PG and soil resistance (SR) was also non-linear, and it was described by the model given in Table 2. Plant growth was negatively and significantly \( P < 0.0001 \) related to SR in both tillage treatments. Both regression parameters were significantly \( P < 0.01 \) higher in the NT than in the CT. The observed data and the fitted function are given in Figure 2 for both tillage treatments. The model accounted for 43% of the PG variability in the NT and 75% in the CT.

Similarly to the air-filled porosity model, there was an interaction between tillage and SR on PG. Across the entire SR range the PG in the NT treatment was higher than in the CT. However, the magnitude of the effect increased with increasing soil resistance.

Vreeland et al. (1992) found reduction in corn shoot elongation at high soil mechanical resistance. Van & Rainbolt (1993) also observed a negative relationship between corn growth and bulk density and soil resistance. Bristow & Abrecht (1989) and Vreeland et al. (1992) reported a negative relationship between corn shoot elongation and soil resistance. Moreover, Masle & Passioura (1987) and Passioura & Gardner (1990) observed a decrease in wheat shoot growth due to increase in soil resistance in experimental conditions with non-limiting conditions associated with water, nutrients and carbon supply. Plants may respond to unfavorable soil conditions by controlling their development, therefore making more carbon available for root growth. This may probably be a mechanism to increase the chance for roots to overcome the adverse soil condition as suggested by Masle et al. (1990). Researchers have suggested that a hormonal message is originated from the roots in soils with high soil resistance and sent to the leaf causing the reduction on shoot and leaf growth (Passioura, 2002).

Both relationships, i.e., (PG) vs (AFP and SR) indicated that plant growth does not stop even at values beyond the ones considered critical with respect to AFP

| Variable | NT Parameter estimate | Standard error | t | Prob>|t| | CT Parameter estimate | Standard error | t | Prob>|t| | NT-CT t | Prob>|t| |
|----------|-----------------------|----------------|---|--------|----------------------|----------------|---|--------|----------|-------------------|----------------|---|--------|----------|-------------------|
| \( \gamma \) | 7.39 | 0.06 | 123.17 | 0.0001 | 7.07 | 0.05 | 141.20 | 0.0001 | 4.10 | 0.0001 |
| \( \lambda \) | -0.18 | 0.02 | -9.00 | 0.0001 | -0.25 | 0.01 | -25.00 | 0.0000 | 3.13 | 0.0027 |

Figure 2 - Plant growth (PG) variation with soil resistance (SR) for the no-tillage (NT) and conventional-tillage (CT) system.
(0.10 cm$^{-3}$) and SR (2 MPa). The 2 MPa critical limit was set to root growth (Taylor et al., 1966) and may not be adequate for shoot and leaf growth. However, the shoot growth sensitivity to soil resistance has been demonstrated by Masle & Passiourea (1987), who concluded that growth of roots was less affected than that of shoots.

It may be argued that the AFP and SR data were taken at the surface layer (0-0.2 m), and thereby the PG may be also associated with soil conditions of deeper soil layers. This is indeed a limitation of our data. However, our results may be supported by the findings of Saab & Sharp (1989) with wheat. In split-root experiments, they observed that the exposure of a relatively small part of a plant root system to a dry soil significantly reduced plant growth. Therefore, plant growth may be restricted by the most limiting soil layer regardless of how adequate the rest of the soil profile is. In addition, during the experiment trenches were open up to 1 m depth in 4 sites across the field. The overall observation was that the vast majority of the root system was greater under the CT than the NT. Moreover, for a given level of stress, such as high SR or low AFP, the plant response was greater in the NT treatment than the CT. The results may be related to the presence of soil biopores in the NT system as it was earlier mentioned. Ehlers et al. (1983) observed a negative linear relationship between soil resistance and root growth. Moreover, the limiting penetration resistance for root growth was 3.6 MPa in the tilled Ap-horizon and 4.9 MPa in the uniltled Ap-horizon. They argue that this behavior may be due to the pores created by the soil fauna, which represent rooting pathways of low soil mechanical resistance. In fact, soil structure has a major impact on how root growth, and consequently PG, relates to SR, and the more common available techniques for measuring matrix soil properties do not take into account these large scale pores.

The biopores are normally beyond the range measured by standard techniques used to measure pore size distribution. Shipitalo & Protz (1987) applied micromorphometric analyses to evaluate the effects of tillage on the porosity of soils planted with corn. They observed that Ap horizons of soils under NT had approximately half of the macroporosity of soils under CT. Karunatilake et al. (2000) also found higher leaf biomass production in NT. They have mentioned that the numerous failure zones associated with the well-structured soil in NT helped to overcome the higher soil mechanical resistance observed in this system.

These biopores may be particularly important when the soil matrix has poor physical conditions such as high SR. Under these circumstances root growth may be strictly dependent on the presence of the biopores since by using these biopores roots can bypass the zones of high mechanical impedance (Lipiec & Hatano, 2003). The biopores may then be related with the observed interaction tillage-SR:PG, i.e., the highest PG at high SR in the soil under NT.

One important implication of the influence of the tillage system on the soil physical condition, i.e. on soil mechanical resistance and aeration, is that the presence of large scale pores in soils under NT would lead to the increase on the SR and the decrease on the AFP critical values. The continuous PG variation with either AFP or SR suggests that the adoption of critical values for air-filled porosity (10%) or soil resistance (2 MPa) may have a limited value. Specifically for this study 10% AFP would correspond to a relative PG (PG maximum PG) of 80% and 75%, for NT and CT, respectively. Soil resistance of 2 MPa would imply in a relative PG of 69% for the NT and 65% for the CT.

For the specific cases of air-filled porosity and soil resistance it may be more realistic to look forward to limits based on relative plant growth. Instead of search for limits associated with growth/no growth or yield/no yield, it would be more appropriate to tie the critical limits with the percentage of reduction of a given plant response.

CONCLUSIONS

Plant growth was dependent on the soil physical properties and on the tillage system. The plant height increased with increasing air-filled porosity in a wet year, and decreased with increasing soil mechanical resistance in a dry year for both tillage systems. However, the tillage systems modified differently the soil physical conditions to plant growth since the increase rates/decrease rates of plant growth changed with them. Continus long-term no-tillage system promoted higher plant growth at greater values of soil mechanical resistance and lower values of soil air-filled porosity than that reached for the plants in the conventional-tillage system.

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