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Long-term rotation and tillage effects on soil structure and crop yield

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Abstract

Tillage and rotation are fundamental factors influencing soil quality and thus the sustainability of cropping systems. Many studies have focused on the effects of either tillage or rotation, but few have quantified the long term integrated effects of both. We studied the issue using a 30-year old long-term rotation and tillage treatment experiment on a Canadian silt loam soil. Topsoil measurements were carried out for three different rotations: R1 (C-C-C-C) continuous corn (*Zea mays* L.), R6. (C-C-O(RC), B(RC)) corn, corn, oats (*Avena fatua* L.) and spring barley (*Hordeum vulgare* L.) and R8, (C-C-S-S) corn, corn, soybean (*Glycine max L*.), soybean. A red clover (*Trifolium pretense* L.) cover crop was under seeded in oats and spring barley in R6. In 2010, first year corn was grown in R6 and R8. The tillage treatments included no tillage, NT and mouldboard ploughing, MP. Topsoil structural quality was visually evaluated in early June and mid October. Minimal disturbed soil cores collected in early June were used for X-ray CT scanning and to quantify water content and porosity. Soil friability was determined on the soil samples using a drop shatter test. Crop yield was determined and correlated to the soil quality estimates. We found significant effect of both rotation and tillage on visual soil structure at both times of assessment. Poor soil structure was found for NT except when combined with a diverse crop rotation (R6). The soil core pore characteristics data also displayed a significant effect of tillage but only a weak insignificant effect of rotation. The drop shatter results were in accordance with the visual assessment data. Crop yield correlated significantly with the visual soil structure scores. We conclude that a diverse crop rotation was needed for an optimal performance of NT for the studied soil.

Keywords

visual soil structure evaluation, soil quality, tillage, rotation, X-ray CT, yield.

1. Introduction

Tillage and rotation are fundamental factors influencing soil quality, crop performance and thus the sustainability of cropping systems. Conservation tillage *per se* is considered one of the most effective management practices to obtain mutual benefits in terms of erosion control, carbon sequestration and reduced input of energy and labour. However, maintaining crop yields is a challenge when adopting conservation tillage in many traditional cereal-based cropping systems (Carter et al., 1994; Meyer-Aurich 2006; Morris et al., 2010). Decreased soil physical quality, in terms of excessive compaction of the untilled topsoil, is regarded as one of the primary reasons for yield reductions (e.g. Carter et al., 1991; Ball et al., 1994). This is especially problematic on weakly-structured soils in humid temperate climates (Munkholm et al., 2003). Many have suggested the use of controlled traffic and stimulated biological activity to mitigate the problem (Ehlers and Claupein, 1994; Munkholm et al., 2003). The latter is stimulated through the input of crop residues and the use of diverse rotations and cover crops – all such factors are included in the concept of conservation agriculture (CA), strongly promoted by FAO (www.fao.org/ag/ca). The CA concept is supported by numerous studies which usually include a limited number of factors. There is, however a shortage of studies, in which the long-term integrated effect of conservation, tillage, rotation and cover crops on soil quality have been evaluated.

Assessment of soil structure is challenging because soil is a very heterogeneous and complex medium. Visual soil evaluation methods have in recent years become a widespread tool for the integrative evaluation of soil structure as highlighted in this special issue. For topsoil structure evaluation, a number of methods are available such as the spade methods: VESS, Visual Evaluation of Soil Structure (Ball et al., 2007) and VSA, Visual Soil Assessment method (Shepherd, 2009) as well as the "le profil cultural" profile method (Manichon, 1987). In this study we applied the VESS method because it is takes account of a range of crucial properties (soil strength, porosity and roots and biological activity), integrates over a rather large volume, is fast and easy to use and integrates the evaluation of different aspects into a single number ranging from 1 (friable) to 5 (very compact). The numeric results, from the VESS test, allow statistical analysis of management effects and exploration of linear correlations to other factors, such as crop yield or quantitative soil physical properties. Visual soil evaluation methods are by nature, qualitative and operator dependent. A visual key in combination with text guide was developed to minimize the subjectivity when performing the VESS test. However, visual methods must be regarded as complementary to quantitative methods. In this study the VESS test was supplemented with quantification of porosity, soil friability, soil strength and detailed soil pore characteristics based on X-ray CT scanning imagery.

The objective of this study was to evaluate the cumulative effects of tillage and selected rotations on soil structure using the long-term rotation-tillage experiment at Elora Research Station (Meyer-Aurich et al. 2006). We hypothesized a positive effect of diverse rotation (including cover crop) on soil quality - especially under no tillage. A secondary objective was to link topsoil structure assessment to crop yield. We expected a positive correlation between crop yield and topsoil quality.

2. Materials and methods

2.1 The experiment

Samples were taken from the long-term rotation and tillage trial (initiated in 1980) at the University of Guelph’s Elora Research Station near Elora, Ontario, Canada (43°39’ N, 80°25’W). The soil is mapped as Woolwich silt loam and classified as a Grey Brown Luvisol (CSSC, 1998) or Albic Luvisol (WRB, 2006). The particulate size distribution is on average: 16, 44, 40 and 2.13 g $100g^{-1}$ of clay, silt, sand and organic carbon, respectively. The 30 year average rainfall (1970-2000) was 920 mm, and the average monthly temperatures for January, April and July are -7.6, 5.9 and 19.7°C, respectively (Table 1). The 2010 growing season had monthly temperatures similar to long term averages. Although annual precipitation in 2010 was lower than long term averages, rainfall received during the 2010 April-September growing season exceeded long term average precipitation and distribution was very good.

Table 1 around here

The experimental design is a randomized split plot with four replicates. The main plot treatment is rotation and the plot treatment is tillage. Seven four-course rotations are included in the trial. In this study we used rotation R1,(C-C-C-C) continuous corn (*Zea mays* L.), rotation R6, (C-C-O(RC), B(RC)) corn, corn, oats (*Avena fatua* L.) and spring barley (*Hordeum vulgare* L.) and rotation R8, (C-C-S-S) corn, corn, soybean (Glycine max *L*.), soybean. A red clover (*Trifolium pretense* L.) cover crop was underseeded in oats and spring barley in R6. In 2010, first year corn was grown in R6 and R8. The tillage treatments included no tillage (NT) and conventional tillage with mouldboard ploughing (MP). Mouldboard ploughing (20 cm) was carried out on November 18 2009. Secondary tillage in MP consisted of two passes of a field cultivator and packer within 1 day of crop seeding. The tillage plots are 7x17 m and 8 rows of corn were sown in each of the studied plots on May 7 2010. The corn crop was harvested at full maturity on October 19 and the yield was recorded.

2.2 Visual evaluation of soil structure

Topsoil structural quality was visually evaluated according to the Visual Soil Structure Evaluation (VESS) method described by Ball et al. (2007) and further refined by Guimaraes et al. (2011). The topsoil (0-20 cm) is evaluated according to aggregation, porosity and root growth and graded on a scale from Sq1 to Sq5 where 1 is best. Two assessments were carried out per plot in R1, R6 and R8, i.e. 48 observation points. The soil was sampled in the centre of the plot between rows 2 and 3 and rows 6 and 7 to avoid traffic zones. The evaluation was carried out on June 4 2010 when the corn was in the 6 leaf tip stage and repeated just before harvest on October 18 2010. The average gravimetric water content was 26% and 29%, respectively at testing in June and October. This corresponds to a matric potential around field water capacity at assessment according to soil water retention data from the Elora site (Parkin, unpublished data).

2.3. Penetration resistance

Penetration resistance was measured, at approximately field capacity, with a RIMIK cone penetrometer (Agridry Rimik, Toowoomba, Queensland, Australia) to a depth of 50 cm on May 21 2010. All measurements employed a 20.27 mm diameter, 30^{o} semi-angle cone. Penetration resistance was recorded at each 25 mm increment. Five determinations were made per tillage plot in all the studied rotations, i.e. 2(tillage) x 3(rotations) x 4(blocks) x 5(replicates) =120 determinations.

2.4 Soil core sampling

Two minimally disturbed soil cores (Ø=6.4 cm, height=8.0 cm) were taken at 10-20 cm depth in R1 and R6 on May 28 2010. In all, 32 samples were taken. The samples were taken at the same location as for VESS test. Immediately after sampling, the samples were stored in a refrigerator at 5°C until CT scanning. The samples were also stored in the refrigerator between X-ray CT scanning and the drop shatter test. The CT images from two samples were lost and data analyses were, therefore, carried out on a total of 30 samples. Samples were weighed before CT scanning and the drop shatter test, (field moist) condition and in air-dry condition after drop shatter and in oven dry condition (105°C, 24h) after sieving. This allowed us to calculate total porosity and air-filled porosity at sampling, ε_a, as well as bulk density when assuming a particle density of 2.65 g cm^{-3}.

2.5 Drop shatter test

Soil fragmentation behaviour was evaluated by a drop shatter test modified from the methods described by Hadas and Wolf (1984) and Schjønning et al. (2002). The field sampled undisturbed cores were gently pressed out of the tubes and dropped from 2.0 m height onto a concrete floor. The soil was subsequently air-dried and passed through a nest of sieves with the openings of 19, 9.2, 4, 2 and 1 mm. The amount of material in each size class was recorded. Based on the aggregate size distribution data, the geometric mean diameter (GMD) and the approximate specific surface area (m^2 kg^{-1}) (Hadas and Wolf, 1983) were calculated.

2.6 CT scanning, binary thresholding and image analysis

The top 40 mm of the soil core samples were scanned using an EVS (now GE Medical, London, Canada) microCT scanner, model MS8X-130. The samples were scanned at 120 kV, 170 mA and with a 3500 millisecond integration time, generating an axial sequence of X-ray attenuation imagery. For each soil sample, a region of interest (ROI) of 36m x 36mm x 36 mm, extended isometrically from the centroid of the image. The final reconstructed image had voxel size of 60 µm. Please consult Munkholm et al. (2011) for more details on the scanning procedure and image reconstruction. The open source software programme ImageJ was used for binary thresholding and image analysis (Rasband, 2005). Binary imaging was carried out using the standardized and automated thresholding procedure developed by Elliott and Heck (2007) and as detailed by Munkholm et al. (2011). General pore characteristics in the 3D images were generated for each ROI using the ImageJ *3D object counter* plug-in (Bolte and Cordelires, 2006). This plug-in determines total void volume (pixel^3), mean void volume and number of pores. In this study, a minimum pore volume filter of 3 voxels was used. A skeleton reconstruction was also performed for each sample to determine branching of the pores, average length of the pores and maximum pore length. In this study the plug-in provided by BoneJ (Doube et al., 2010) was used outlined by Munkholm et al. (2011). This skeletonised binary stack was then put through the *analyze skeleton* plug-in within the BoneJ plug-in. This provided a summary of number, length (mean, maximum and total) and junction of branches in each ROI.

2.7 Statistical analysis

All statistical analyses were carried out using SAS (Version 9.2, SAS Institute, Cary, NC) (SAS, 2005). We used PROC INSIGHT to test data for normality. The pore characteristics derived from X-ray CT imagery were log-transformed to yield normality. All other data were best fitted by a normal distribution. Averages were calculated for each plot and used in the calculation of mean and standard error. The averages were used as input in general linear models for test of treatment effects. For this purpose we used PROC GLM in SAS.

3. Results

3.1 Visual soil structure evaluation, penetration resistance and crop yield

Significant effects of both tillage and rotation were found for the VESS Sq scores (Figure 1). There was a strong effect of tillage (MP<NT) at both times of assessment (i.e. P<0.001 and 0.002 for the tillage effect at early and late season assessment, respectively). The average Sq scores increased for both tillage treatments from June to October that is from 1.5 to 1.9 for MP and from 2.2 to 2.4 for NT. This means that the difference between tillage treatments decreased slightly from, 0.7 Sq units in May to 0.5 Sq units in October. The effect of rotation was in both cases significant at P=0.05 level and the lowest Sq scores was found for the diverse rotation, R6 in comparison with the continuous corn (R1) or corn-soybean rotations (R8). The mean Sq score for R6 was approximately 1.5 at both times of assessment whereas the Sq scores for R1 and R8 increased from c. 2.0 in June to c. 2.4 in October. No significant interactions, between tillage and rotation, were observed at any time of assessment. However, there was almost a significant interaction between tillage and rotation for the June sampling (P=0.10). Highest values were recorded for the R1-NT treatment with a Sq score of 2.8 in October and lowest for R6-MP where Sq=1.3 at both times of assessment.

Figure 1 around here

The penetration resistance data revealed significant effect of treatments in the topsoil at 5-20 cm depth (Figure 2). No tillage produced higher penetration resistances than the MP treatment. The highest values in the topsoil was recorded for R1-NT (max. 1.5 MPa) and lowest for R6-MP (max. 1.1 MPa). Strong effect of tillage was also found for the penetration resistance data when averaged across 0-20 cm and 10-20 cm depth (Table 2). Notice, that the interaction between tillage and rotation was almost significant (P=0.08) for the 10-20 cm data. Smallest difference between MP and NT was recorded for R8 and largest for R1. There was no significant difference between the treatments below 20 cm depth.

Figure 2 around here

The corn yield was, in general, high (i.e. 90-120 hkg ha^{-1}) and there were significant effects of tillage, rotation and interaction between tillage and rotation (Table 2). The MP treatment produced higher yields than NT – on average 109 and 104 hkg ha^{-1} for MP and NT, respectively. Larger differences were obtained between the rotations, i.e. 96, 117 and 107 for R1, R6 and R8, respectively. Notice that for R6 there was no significant difference in yield between MP and NT whereas this was found for both R1 and R8 (i.e. c. 10 hkg ha^{-1} higher yields were found for MP).

Table 2 around here

3.2 Bulk soil characteristics from soil cores

Bulk density, BD, at 10-20 cm depth differed markedly between tillage treatments (i.e. 1.46 and 1.28 g cm^{-3} for NT and MP, respectively) (Table 3). There was no significant effect of rotation or interaction between rotation and tillage. However, there was a slight tendency to lower BD for R6 than for R1 (P=0.15). The water content at sampling was on average 24 g 100 g^{-1}. The drop shatter test revealed significant effects of both tillage and rotation when expressed as surface area produced. Almost significant effects (P=0.07) were also found when expressed as GMD (Table 3). A larger surface area (i.e. smaller fragments) was produced for R6 vs. R1 and for MP vs. NT. The largest surface area (1.11 m^2 kg^{-1}) was produced for R6-MP and lowest (0.53 m^2 kg^{-1}) for R1-NT. The total porosity data was a mirror image of the BD results with significantly higher values obtained for MP than NT (Figure 3a). The air-filled porosity at sampling results followed in line with those for total porosity, i.e. MP>NT and no significant effect of rotation (Figure 3b). The MP treatment had an average air-filled pore space at sampling (i.e. around field capacity) of 20.3 m^3 m^{-3} and NT 10.8 m^3 m^{-3}.

Table 3 and figure 3 around here

3.3 Soil pore characteristics from microCT imagery

The void volume identified in the microCT imagery, Por_{CT}, varied between 2.4 and 8.2 m^3 m^{-3} for the different treatments (Figure 3c). There was only a significant effect of tillage on Por_{CT} (MP>NT). The surface area results displayed similar trends as the Por_{CT} results. Markedly higher average values were obtained for MP than for NT (i.e. 3.4 and 1.4 cm^2 cm^{-3}, respectively) (Figure 4a). The number of pores showed a geometric mean of 71 per cm^3 and this parameter was not sensitive to management (Figure 4b). For the data obtained on the skeletonised images (Figure 4c, d, e) the geometric mean values were 117, 279 and 198 per cm^3 for junctions, branches and end points, respectively. Higher values were in general obtained for MP than for NT although the differences were only significant for junctions and branches (Figure 4).

Figure 4 around here

4. Discussion

4.1. Management effects on physical soil quality

The VESS results confirmed our hypothesis of a positive effect of diverse rotation and cover crops on soil quality – especially under no tillage. The poorest structure was observed for the R1-NT treatment in October (Sq=2.8) and best for R6-MP in May and October (Sq=1.3). It has to be emphasized that all treatment averages were characterized as either good (Sq=1-2) or fair (Sq=2-3) according to the threshold values suggested by Ball et al. (2007). Therefore, the soil was assessed as favourable to crop production in all treatments. However, poor soil structures (Sq>3) were found in some individual R1-NT plots with Sq 3.8 as the highest recorded. A good soil structure (i.e. Sq scores 1-2) was recorded for R6-MP, R6-NT at both times of sampling and for R1-MP and R8-MP for the May sampling. Our results are in good agreement with previous visual assessments from the trial (Mueller et al., 2009b) when applying other visual methods. They also found a positive effect of tillage on topsoil structure and showed a better structure for continuous alfalfa than for continuous corn.

The quantitative soil core and penetration resistance data supported the VESS results in terms of a clear effect of tillage. That is, the lowest penetration resistance and highest air-filled and total porosity were found for MP in the topsoil layer (0-20 cm). The soil core data were taken in the zone with most pronounced differences between tillage treatments according to the penetration resistance results (Figure 2). Soil core data showed, in most cases, a weak and insignificant effect of rotation. The drop shatter test, in contrast to the other examinations, showed a significant effect of rotation when data were expressed as surface area produced. However, the general trend was similar to the VESS results with R6 having more favourable physical properties than R1. The VESS results were linearly correlated to the soil pore data and showed the best correlation to ε_a, air-filled porosity at sampling (R^2=0.59***). Significant negative linear correlations were also found to log porosity CT imagery (R^2=0.49**), total porosity (R^2=0.47**), log number of junctions (R^2=0.30*) and there was almost significant negative correlation to log number of branches (R^2=0.24). Visible macroporosity is one of the key parameters evaluated when applying the VESS test and our results confirmed a strong influence of macroporosity on the VESS scores. Apparently, pore complexity, quantified by number of junctions and branches, also influenced the VESS scores, i.e. better scores for soil soils with a more complex macropore organization.

Result from the drop shatter test yields information on friability (Munkholm, 2011). Friability has been proposed as an indicator of the suitability of a given soil for no tillage (Macks et al., 1996). Our data indicate that the diverse rotation R6 promoted best suitability for no-tillage.

It is noticeable, that topsoil structural quality generally decreased from June till October for R1 and R8 and not R6. The largest decrease was found for MP (i.e. the Sq scores increased by c. 0.5 and 0.2 for MP and NT, respectively). Our study clearly suggests that growing corn *per se* may not improve topsoil structural quality. Introducing a double crop of rye between two crops of corn may result in improved soil quality as shown by Liesch et al. (2011).

To summarize, our results indicate that the diverse R6 rotation resulted in a good topsoil structure irrespective of tillage method. Thus, an optimal topsoil structure was achieved through the combination of a diverse rotation and no tillage. For continuous corn (R1) and corn-soybean (R8) poorer soil structure was observed especially for NT. This is in correspondence with results from numerous other studies (e.g. Braim et al., 1992; Ball et al., 2007; Munkholm et al., 2003, 2008).

4.2. Corn yield and correlation to soil structure

The corn yield was very high in 2010 (107 hkg ha^{-1}) in comparison with the average for first year corn of c. 82 hkg ha^{-1} observed for the years 1982-2001 (Meyer-Aurich, 2006) and c. 79 hkg ha^{-1} found in 2005 (Mueller et al., 2009b). The high yield level was a result of close to optimal growing conditions during the cropping season, i.e. a warm summer without marked periods of too dry or wet conditions. Despite this, we observed a significant effect of intensive tillage, rotation and the interaction between tillage and rotation on crop yield. This is in agreement with previous observations from the experiment (Meyer-Aurich, 2006; Mueller et al., 2009b). Interestingly, the relative differences were much larger in 2010 than for 1982-2001 and 2005. The yield benefit of a diverse rotation (R6) as compared to continuous corn no till (R1-NT) was 28% and 13% for 2010 and 1982-2001, respectively. Yield benefits from growing first-year corn in a corn-soybean rotation (R8) relative to continuous corn R1-NT were 7-11%, 10-14% and 10-23%, for 1982-2001 (Meyer-Aurich et al., 2006), 2005 (Mueller et al., 2009b) and 2010 (this study), respectively. For

R8, the largest yield benefit was found for the ploughed treatment in 2010 and this corresponds with previous results from the experimented (Meyer-Aurich et al., 2006; Mueller et al., 2009b).

Our experimental results indicate a rather good correlation between topsoil structure and crop yield as shown in Figure 5. Corn yields decreased linearly with increasing VESS Sq values (R^2=0.35**). Weaker correlations were found withthe quantitative soil physical properties (data not shown). The relatively good agreement between visual methods and crop yield is in agreement with previous studies (Mueller et al., 2009a; Mueller et al. (this issue); Giarola et al. (this issue). In general quantitative physical data were not very sensitive to rotation effect. Apparently, the VESS method was better able to detect differences between rotations – most likely because a range of crucial factors were taken into account (e.g. root growth) and because a relatively large volume of soil was evaluated.

Figure 5 around here

The profound effect of rotation and especially tillage on yield was rathersurprising when considering the excellent growing conditions in 2010 when soil water content was expected to be within the least limiting water range for root growth during almost the entire growing season. Structure affects crop yield through a complex of root-based mechanisms including those that are moisture related. Many examples of this exist. For example a negative effect of mechanical impedance on leaf growth and nitrogen uptake have been found even when nutrients and water were in plentiful supply (Young et al., 1997; Bingham et al., 2010).Also under conditions with no nutrient and water restrictions, Munkholm et al. (2008) found impeded early season growth for winter wheat under no tillage as compared to ploughing. They related the difference to poorer structural quality (more compact) under no tillage. Enhanced plant root exudation with increasing soil mechanical impedance has been widely reported (Barber and Gunn, 1974; Boeuf-Tremblay et al. 1995; Iijima et al., 2000). Finally, soil structure effects on root characteristics may alter plant growth through root biochemical signaling affects on above ground processes as discussed in the comprehensive review by Passioura (2002).

5. Conclusions

- The visual soil structure evaluation supported the hypothesized positive effect of diverse rotation (including cover crop) on soil quality - especially under no tillage. For no tillage, optimal soil structure was only found in diverse R6 rotation that included a cover crop.

- The quantitative physical properties confirmed the positive effect of intensive tillage on soil structure but showed in general a weak and insignificant effect of rotation.
- Crop yield correlated significantly with the visual soil structure scores.

We conclude that a diverse crop rotation was needed for an optimal performance of NT for the studied soil. Therefore our study supports the idea behind the conservation agriculture concept, i.e. sustainability is promoted when conservation tillage is combined with crop rotation, cover crops and residue management.

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References

Ball,B.C., Lang,R.W., Robertson,E.A.G., Franklin,M.F., 1994. Crop performance and soil conditions on imperfectly drained loams after 20-25 years of conventional tillage or direct drilling. Soil Tillage Res. 31, 97-118.

Ball, B.C., Batey, T., Munkholm, L.J., 2007. Field assessment of soil structural quality - a development of the Peerlkamp test. Soil Use Manage. 23, 329-337.

Barber, D.A., Gunn, K.B., 1974. The effect of mechanical forces on the exudation of organic substances by the roots of cereal plants grown under sterile conditions. New Phytol. 73, 39-45.

Bingham,I.J., Bengough,A.G., Rees,R.M., 2010. Soil compaction-N interactions in barley: Root growth and tissue composition. Soil Tillage Res. 106, 241-246.

Boeuf-Tremblay, V., Plantureux,S., Guckert, A., 1995. Influence of mechanical impedance on root exudation of maize seedlings at two developmental stages. Plant Soil 172, 279-287.

Bolte, S., Cordelières, F. P., 2006. A guided tour into subcellular colocalization analysis in light microscopy, J. Microscopy. 224, 213-232.

Braim, M.A., Chaney, K., Hodgson, D.R., 1992. Effects of simplified cultivation on the growth and yield of spring barley on a sandy loam soil .2. Soil physical-properties and root-growth - root -shoot relationships, inflow rates of nitrogen - water-use. Soil Tillage Res. 22, 173-187.

Carter, M.R., 1991. Evaluation of shallow tillage for spring cereals on a fine sandy loam. 2. Soil physical, chemical and biological properties. Soil Tillage Res. 21, 37-52.

Carter, M.R., 1994. A review of conservation tillage strategies for humid temperate regions. Soil .Tillage Res. 31, 289-301.

CSSC, 1998. The Canadian System of Soil Classification, third ed.

Doube, M., Kłosowski, M.M., Arganda-Carreras, I., Cordelières, F, Dougherty, R.P., Jackson, J., Schmid, B., Hutchinson, J.R., Shefelbine, S.J., 2010. BoneJ: free and extensible bone image analysis in ImageJ, Bone, 47, 1076-1079.

Ehlers, W., Claupein, W., 1994. Approaches toward conservation tillage in Germany. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems, Lewis Publishers, pp. 141-165.

Elliot, T.R., Heck, R.J., 2007. A comparison of optical and X-ray CT technique for void analysis in soil thin section. Geoderma 141, 60-70.

Elliot, T.R., Heck, R.J., 2007. A comparison of optical and X-ray CT technique for void analysis in soil thin section. Geoderma 141, 60-70.

FAO, 2011. Conservation agriculture. Avaiable at http://www.fao.org/ag/ca/ (accessed 31. August 2011).

Giarola,N.B., da Silva,A.P., Tormena,C.A., Guimaraes,R.L., Ball, B.C., On the visual evaluation of soil structure: The Brazilian experience in oxisols under no-tillage. Soil Tillage Res. (submitted to this issue).

Guimarães, R.M.L., Ball, B.C., Tormena, C.A., 2011. Improvements in the visual evaluation of soil structure. Soil Use Manage. 27, 395-403.

Hadas, A., Wolf, D., 1983. Energy efficiency in tilling dry clod-forming soils. Soil Tillage Res. 3, 47-59.

Hadas, A. and Wolf, D., 1984. Refinement and re-evaluation of the drop-shatter soil fragmentation method. Soil Tillage Res. 4: 237-249.

Iijima, M., Griffiths, B, Bengough, G., 2000. Sloughing of cap cells and carbon exudation from maize seedling roots in compacted sand. New Phytol. 145:477-482.

Liesch, A.M., Krueger, E.S., Ochsner, T.E., 2011. Soil structure and physical properties under rye-corn silage double-cropping systems. Soil Sci.Soc.Am.J. 75, 1307-1314.

Macks, S.P., Murphy, B.W., Cresswell, H.P., Koen, T.B., 1996. Soil friability in relation to management history and suitability for direct drilling. Aust. J. Soil Res. 34, 343-360.

Manichon, H. 1987. Observation morphologique de l'état structural et mise en evidence d'effects du compactage des horizons travaillés. In: Monnier, G., Goss, M.J. (eds.). Soil compaction and regeneration. Balkema, Rotterdam, the Netherlands, pp. 35-52.

Meteorological Services Canada. 2011. Canadian climate normals: 1971–2000.Available at www.climate.weatheroffice.ec.gc.ca/climate_normals (accessed 30. Aug. 2011). Environment Canada, Ottawa, ON.

Meyer-Aurich, A., Janovicek, K., Deen, W., Weersink, A., 2006. Impact of tillage and rotation on yield and economic performance in corn-based cropping systems. Agron. J., 98, 1204-1212.

Morris, N.L., Miller, P.C.H., Orson, J.H., Froud-Williams, R.J., 2005. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment--A review. Soil Tillage Res. 108, 1-15.

Mueller, L., Kay, B.D., Hu, C., Li, Y., Schindler, U., Behrendt, A., Shepherd, T.G., Ball, B.C., 2009a. Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany: Part I: Comparing visual methods and linking them with soil physical data and grain yield of cereals. Soil Tillage Res. 103, 178-187.

Mueller,L., Kay,B.D., Deen,B., Hu,C., Zhang,Y., Wolff,M., Eulenstein,F., Schindler,U., 2009b. Visual assessment of soil structure: Part II. Implications of tillage, rotation and traffic on sites in Canada, China and Germany. Soil Tillage Res. 103, 188-196.

Mueller, L., Schindler, U., Ball, B.C., Munkholm, L.J., Hennings, V., Smolentseva, E., Rukhovic, O., Lukin, S., Hu, C., Shepherd, G. Evaluation of Soil Structure in the Framework of an Overall Soil Quality Rating. Soil Tillage Res. (submitted to this issue).

Munkholm, L.J., 2011. Soil friability: A review of the concept, assessment and effects of soil properties and management. Geoderma (In Press).

Munkholm, L.J., Heck, R., Deen, B. Soil friability assessment from micro-CT derived images on undisturbed field moist soil cores Geoderma (Submitted).

Munkholm, L.J., Schjønning, P., Rasmussen, K.J., Tanderup,K., 2003. Spatial and temporal effects of direct drilling on soil structure in the seedling environment. Soil Tillage Res. 71, 163-173.

Munkholm, L.J., Hansen, E.M., Olesen, J.E., 2008. The effect of tillage intensity on soil structure and winter wheat root/shoot growth. Soil Use Manage. 24, 392-400.

Passioura, J.B., 2002. 'Soil conditions and plant growth'. Plant Cell Env. 25, 311-318.

Rasband, W., 2005. ImageJ. National Institute of Health, Bethesda MD.

SAS Institute, 2005. SAS Institute, SAS/STAT™ Software: Language reference and concepts Release 9.1.3, SAS Institute, Cary, NC.

Schjønning, P., Elmholt, S., Munkholm, L.J., Debosz, K., 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. Agric. Ecosyst. Env. 88, 195-214.

Shepherd, T.G., 2009. Visual soil assessment. Volume 1. Field guide for pastoral grazing and cropping on flat and rolling country. Second edition. Horizons Regional Council, Palmerston North, New Zealand, 119p.

WRB, 2006. World reference base for soil resources 2006. Food and Agriculture Organization of United Nations, Rome.

Young, I.M., Montagu, K., Conroy,J., Bengough, A.G., 1997. Mechanical impedance of root growth directly reduces leaf elongation rates of cereals. New Phytol. 135:613-619.

Table 1- Average monthly temperature and monthly total precipitation, Elora, Ontario, Canada for 2008, 2009, 2010.

	Temperature (°C)				Precipitation (mm)			
	2008	2009	2010	30-yr Av.*	2008	2009	2010	30-yr Av.*
January	-4.7	-11.7	-7.2	-7.6	98.5	66.1	27.2	56.4
February	-8.6	-6.1	-5.8	-6.9	57.4	82	24.4	50.8
March	-5.2	-0.7	2.2	-1.3	85.5	72.7	41.3	72.1
April	7.5	6.1	8.7	5.9	64.6	106.2	47.5	78.3
May	9.8	11.4	13.8	12.3	86.1	79.3	99.9	79.9
June	17.6	15.8	16.8	16.9	81.6	69.2	184.1	76
July	19.1	16.5	20.2	19.7	131.3	79.5	89.4	88.5
August	17.2	17.8	19.4	18.6	120.7	92.1	12.1	95.9
September	14.8	14.5	14.0	14.1	119.3	53.7	117.8	92.1
October	7.2	6.8	8.3	7.9	68.4	91.5	52.6	69.2
November	0.7	4.6	3.0	2.4	103.1	37.3	50.8	86.3
December	-5.5	-4.5	-6.1	-4	100.4	65.8	21.1	77.7

*Source: Meteorological Services Canada, 2011.

Table 2. Effect of rotation and tillage on penetration resistance (May sampling) and yield of the corn crop. R1-MP: continuous corn, mouldboard ploughed, R1-NT: continuous corn, no tillage; R6-MP: R6. Diverse rotation, mouldboard ploughed; R6-NT: Diverse rotation, no tillage; R8-MP: corn-soybean rotation, mouldboard ploughed; R8-NT: corn-soybean rotation, no tillage.

Treatment	Penetration resistance		Crop yield
	0-20 cm	10-20 cm	
	MPa		Hkg ha^{-1}
R1-NT	1,1a	1.5a	91d
R1-MP	0.8b	1.0c	101c
R6-NT	1.0a	1.3b	119a
R6-MP	0.7b	0.9c	115ab
R8-NT	1.0a	1.3b	101c
R8-MP	0.8b	1.1c	112b
Rotation	NS	NS	**(p=0.005)
Tillage	***(p<0.0001)	***(p<0.0002)	**(p=0.002)
Rotation*Tillage	NS	NS(p=0.08)	**(p=0.002)

Table 3. Bulk density, water content and drop shatter data for the core samples taken late May 2010. R1-MP: continuous corn, mouldboard ploughed, R1-NT: continuous corn, no tillage; R6-MP: R6. Diverse rotation, mouldboard ploughed; R6-NT: Diverse rotation, no tillage.

Treatment	Soil core		Drop shatter test	
	Bulk density	Water content at sampling	GMD	Surface area
	g cm^{-3}	g 100 g^{-1}	mm	m^2 kg^{-1}
R1-NT	1.48a	23.9a	14.6a	0.53c
R1-MP	1.31b	24.6a	10.6ab	0.73bc
R6-NT	1.43a	23.7a	8.2b	0.83b
R6-MP	1.25b	23.8a	6.5b	1.11a
Rotation	NS	NS	NS (p=0.07)	*(p=0.04)
Tillage	***(p=0.0009)	NS	NS	* (p=0.02)
Rotation*Tillage	NS	NS	NS	NS

Figure captions

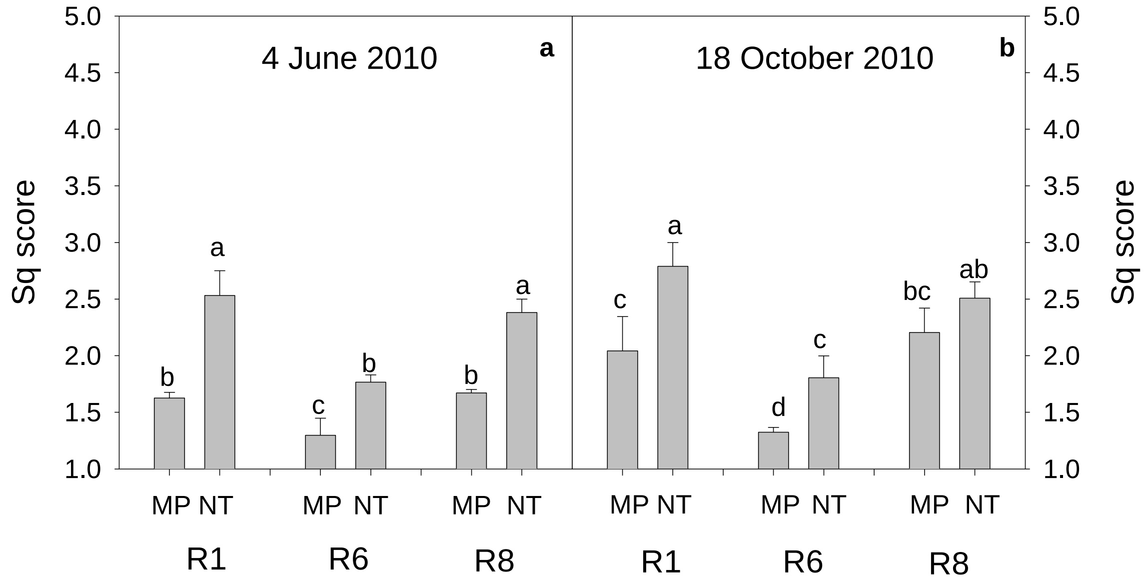
Figure 1.Visual Soil Structure Evaluation Sq score for 0-20 cm depth at the beginning and the end of the 2010 growing season. Corn was grown in all treatments. Bars indicate +/-1 standard error of mean. Figures with the same letter within each time of sampling are not significantly different at $P<0.05$ level. R1: continuous corn; R6: diverse rotation; R8: corn-soybean rotation; MP: mouldboard ploughed; NT: no tillage.

Figure 2. Penetration resistance determined in the field at a water content around field capacity at 0-45 cm depth. R1-MP: continuous corn, mouldboard ploughed, R1-NT: continuous corn, no tillage; R6-MP: R6. Diverse rotation, mouldboard ploughed; R6-NT: Diverse rotation, no tillage; R8-MP: corn-soybean rotation, mouldboard ploughed; R8-NT: corn-soybean rotation, no tillage. Bars indicate +/-1 standard error of mean.

Figure 3. Total porosity, air-filled porosity at sampling, ε_a, on soil cores and porosity determined from the CT imagery. Bars indicate +/-1 standard error of mean. Figures with the same letter for each parameter are not significantly different at $P<0.05$ level. R1: continuous corn; R6: diverse rotation; MP: mouldboard ploughed; NT: no tillage.

Figure 4. Pore characteristics from CT imagery. Bars indicate +/-1 standard error of mean. Figures with the same letter for each parameter are not significantly different at $P<0.05$ level. R1: continuous corn; R6: diverse rotation; MP: mouldboard ploughed; NT: no tillage.

Figure 5. Correlation between corn yield and Sq score (June assessment).



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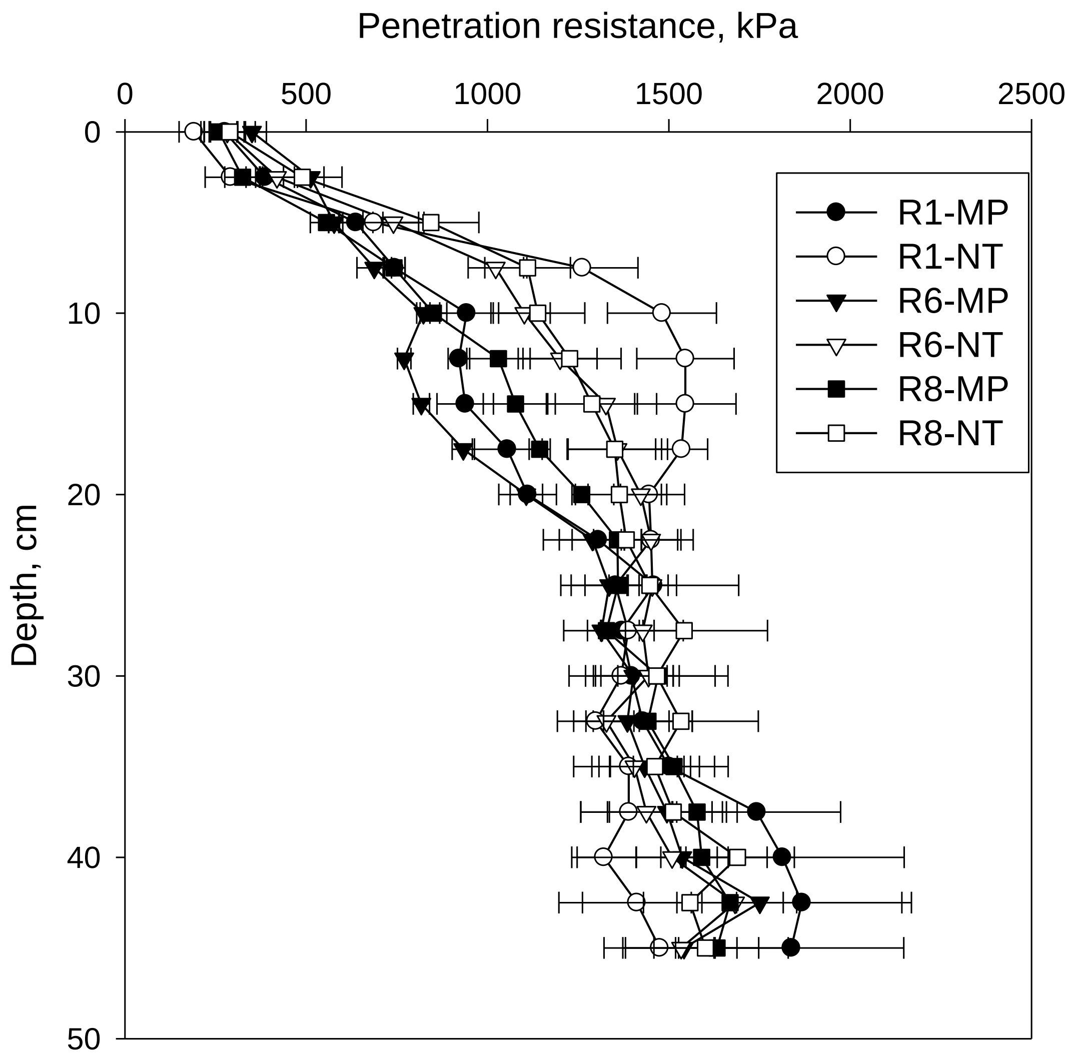

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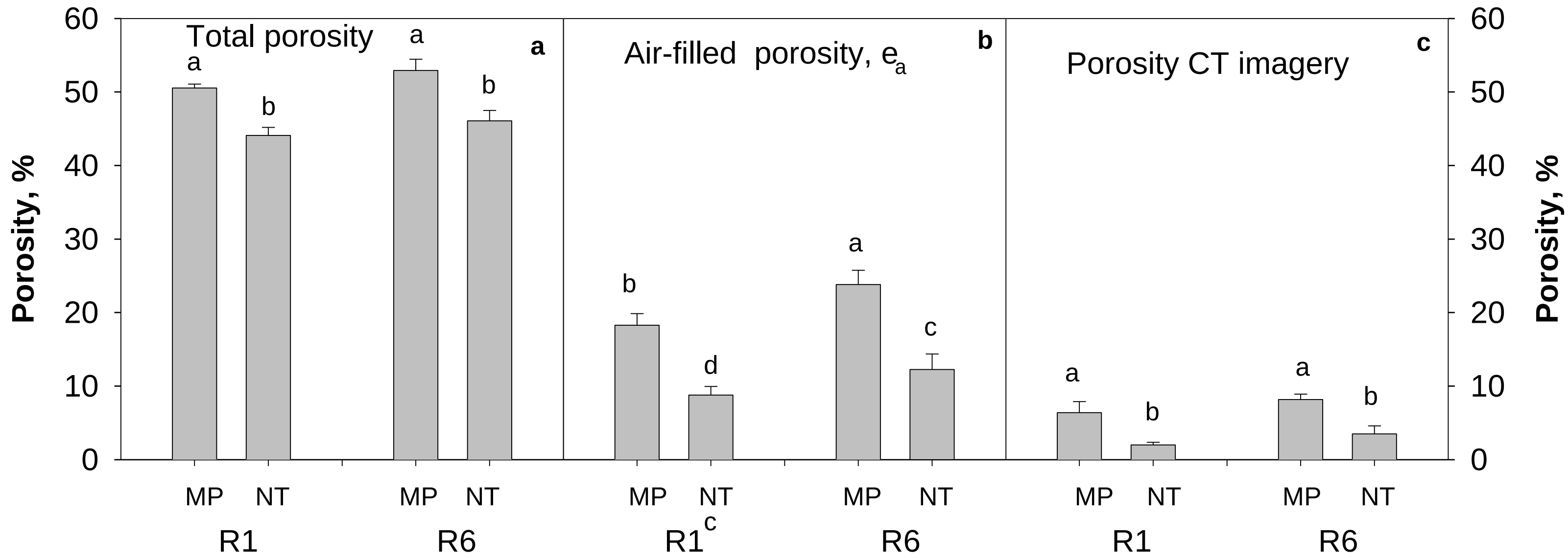

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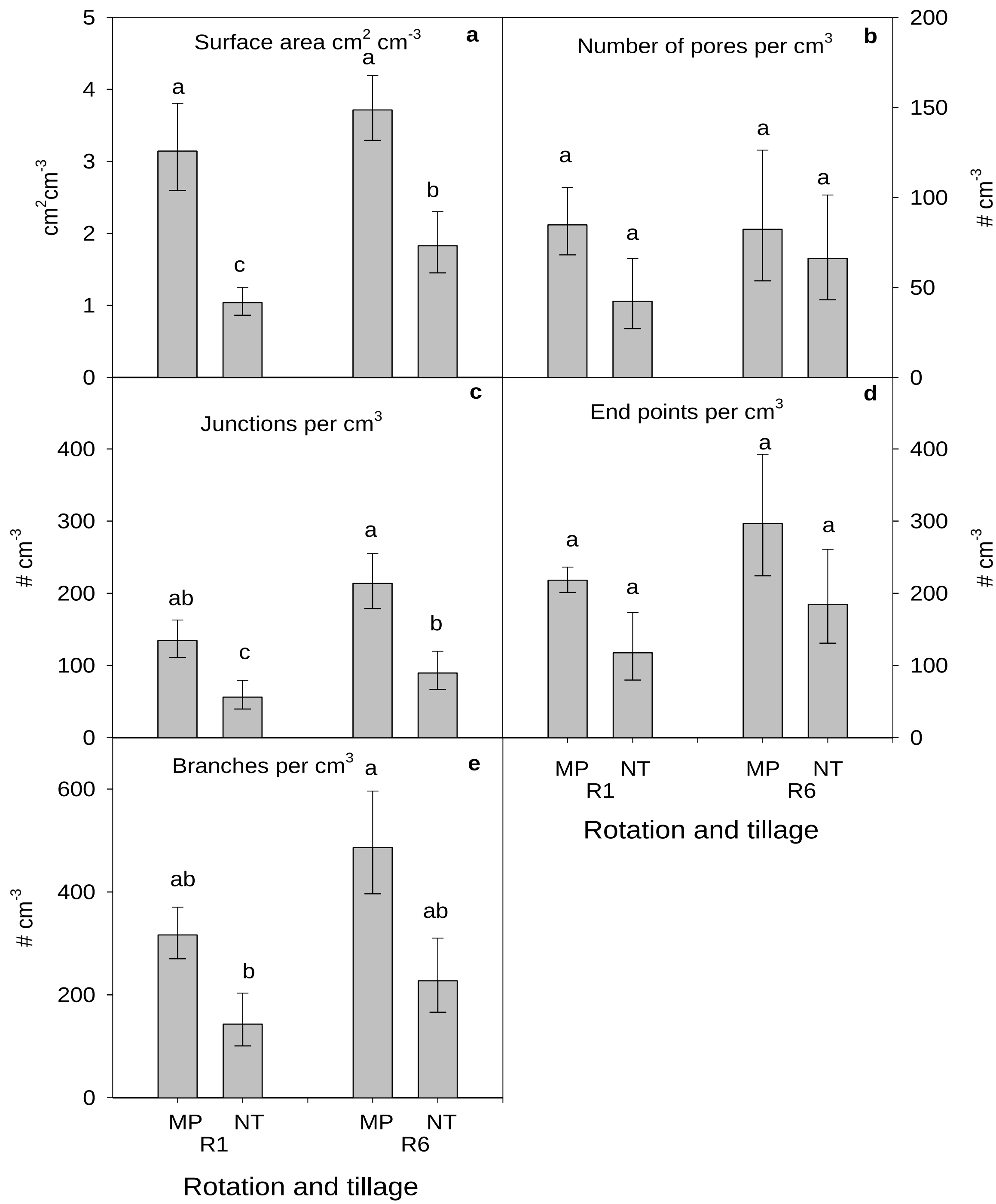
Surface area cm2 cm-3
a
cm2cm-3
Number of pores per cm3
b
cm-3
Junctions per cm3
c
End points per cm3
d
Branches per cm3
e
cm-3
MP NT MP NT
R1 R6
Rotation and tillage

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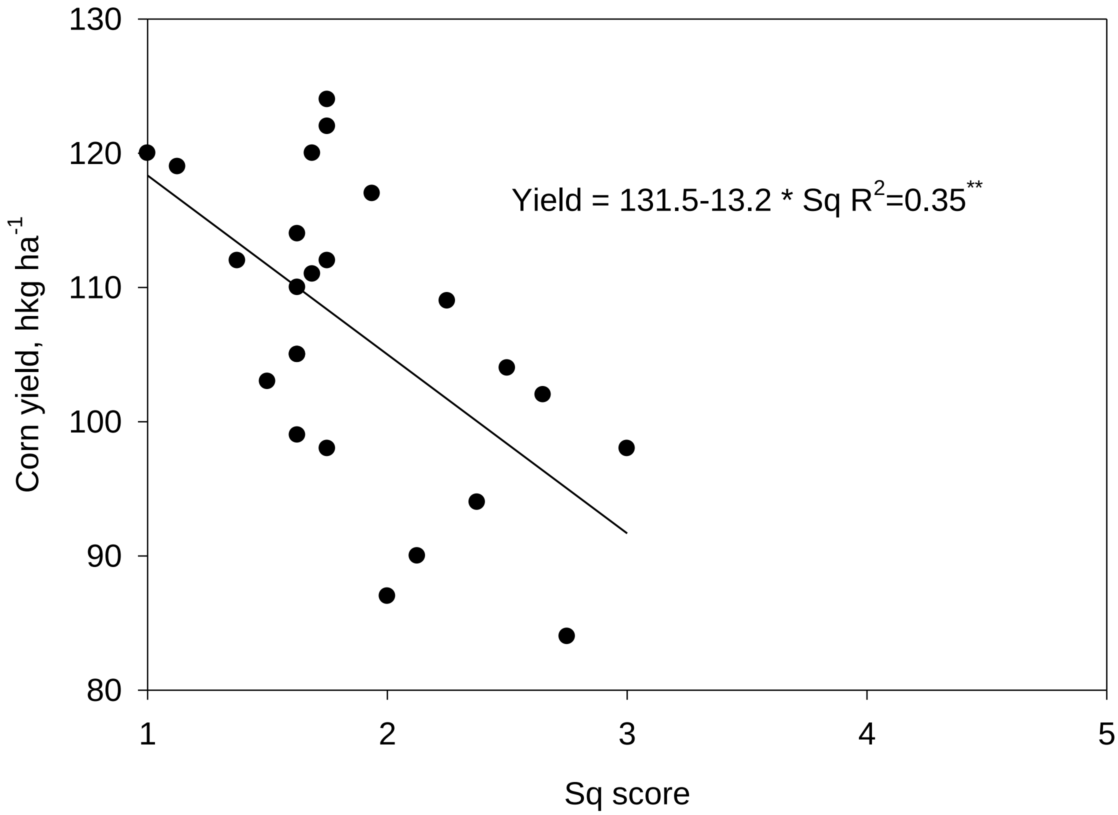

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