Influences of degree of compactness and matric water tension on some important plant growth factors

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Abstract

The degree of compactness (D) has been defined earlier as the dry bulk density of a soil in percent of a reference bulk density obtained by a standardized uniaxial compression test on large samples at a stress of 200 kPa. It was primarily aimed for use in annually disturbed soil layers. Field experiments have demonstrated its usefulness for characterizing the state of compactness from a crop production point of view, but knowledge is lacking regarding the relation between D and various plant growth factors. While the bulk density or porosity optimal for crop growth has varied considerably between soils, the optimal D-value has been virtually independent of soil texture. This led to a hypothesis that critical limits of penetration resistance (3 MPa) and air-filled porosity (10%, v/v) are similarly related to the D-value in most soils. With the objective to test this hypothesis, the positions of these limits as functions of the D-value and the matric water tension were studied in four soils with clay content ranging from 70 to 220 g kg\textsuperscript{-1}. In all of them, the positions of the critical limits were similar. The higher the D-value, the more limited was the tension range offering adequate conditions for crop growth, the higher was the water tension (the lower the water content) at which aeration became critical, and the lower was the water tension (the higher the water content) at which penetration resistance became critical. The effects of critical soil conditions were reflected in increased stomatal resistance of plants grown in soil with a high D-value. The results provide basic information for modeling the relationships between soil compactness and plant growth. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Soil compaction; Degree of compactness; Aeration; Penetration resistance; Matric water tension; Stomatal behavior

1. Introduction

Dry bulk density and total porosity are the most frequently used parameters to characterize the state of compactness of a soil, e.g. the plough layer, from a crop production point of view. However, when using these parameters, crop response curves and optimum values are different for different soils. To overcome this problem, efforts have been made to find a parameter that results in crop response curves and optimum values that are similar for all soils. This has mainly been made by relating the bulk density to some reference bulk density obtained by a standardized compaction test. Pidgeon and Souine (1977), Carter

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(1990) and da Silva et al. (1994) used a standard Proctor test for this purpose.

In Swedish research, the degree-of-compactness concept (Eriksson et al., 1974; Häkansson, 1990) was introduced for use in soil layers annually disturbed by tillage. The degree of compactness \( D \) was defined as the dry bulk density of a soil in percent of a reference dry bulk density of the same soil obtained by a standardized uniaxial compression test at a stress of 200 kPa. Häkansson (1990) used this parameter in an extensive series of field experiments in a wide range of soils with spring barley as a common test crop. In mineral soils, with clay contents ranging between 20 and 600 g kg\(^{-1}\), he got the same mean optimal \( D \)-value in the plough layer (about 87) independent of soil textural composition. Similar results have been obtained in Norway (Riley, 1983) and Poland (Lipiec et al., 1991).

Since the degree of compactness influences crop growth similarly in most soils, it was hypothesized that it also influences the most decisive compaction-dependent growth factors similarly. The factors usually identified as the most critical in overcompacted soils are aeration and penetration resistance (Allmaras et al., 1988; Häkansson et al., 1988; Boone and Veen, 1994).

The main objective of the present study was to investigate to what extent this hypothesis holds true for soils with various textures. Therefore, the effects of the degree of compactness and matric water tension on air-filled porosity and penetration resistance were studied in soils with textural compositions from loamy sand to clay loam. Emphasis was on whether an air-filled porosity of 10% (v/v) and a penetration resistance of 3 MPa were similarly related to the \( D \)-value and the matric water tension in the soils studied. From the literature it can be derived that these values often represent critical limits of soil aeration and rootability, respectively (Gliníski and Stepniewski, 1985; Boone et al., 1986; Allmaras et al., 1988; Boone, 1988; Bengough and Mullins, 1990). Among others, they can affect plant growth and crop yield through changes of stomatal resistance (Sojka, 1992; Lipiec et al., 1996). Therefore, the interactive effects of different \( D \)-values and rainfalls during the growing season on stomatal behavior were also investigated.

### 2. Materials and methods

#### 2.1. Field experiments

Field experiments with various compaction treatments were carried out in four Polish soils: loamy sand (Leptic Podzol), light loam (Leptic Podzol), silty loam (Orthic Luvisol), and clay loam (Leptic Podzol) in the Lublin region (Table 1) using a randomized complete block design with four replicates. The experimental fields had been mouldboard-ploughed to about 25 cm depth in the preceding autumn. Five compaction treatments with four replicates were applied by tractors in the spring using a range of combinations of tractor weights, ground pressures and number of passes. Soon afterwards, the degree of compactness in the 5–25 cm layer was determined with the technique described by Häkansson (1990) using a measuring frame of \( 0.707 \times 0.707 \) m\(^2\). The \( D \)-values in various sites and treatments ranged between 78 and 101. Barley (Hordeum vulgare L.), oats (Avena sativa L.) and wheat (Triticum aestivum L.) were grown as test crops. Experimental methods and crop responses were described in greater detail by Lipiec et al. (1991).

### Table 1

Particle size distribution and content of organic matter in the experimental soils

<table>
<thead>
<tr>
<th>Soil</th>
<th>Particle size (µm) distribution (g kg(^{-1}))</th>
<th>Organic matter (g kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000–100</td>
<td>100–50</td>
</tr>
<tr>
<td>1. Loamy sand</td>
<td>660</td>
<td>120</td>
</tr>
<tr>
<td>2. Light loam</td>
<td>580</td>
<td>90</td>
</tr>
<tr>
<td>3. Silty loam</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>4. Clay loam</td>
<td>160</td>
<td>140</td>
</tr>
</tbody>
</table>
2.2. Penetration resistance and air-filled porosity

Penetration resistance was measured in the field with a recording constant rate cone penetrometer (cone semiangle 30°, cross-section 1 cm²) (Walczak et al., 1973). The measurements were done at various times during the growing season at a range of soil water contents between field capacity and wilting percentage. Each measurement was made to a depth of 40 cm in six replicates per plot. Mean values for the plough layer (5–25 cm) were obtained from the penetration resistance curves using planimetry. At the same time, soil cores of 100 cm³ were taken (six replicates per plot) close to the points of penetrometer measurements to determine soil water content, water characteristic curve and porosity. The data were processed to show the mean penetration resistance in the 5–25 cm layer as a function of the degree of compactness and matric water tension. Soil water content was converted into matric tension using the water characteristic curve. For various matric tensions, the air-filled porosities were calculated from the water contents and porosities obtained in the core samples.

2.3. Stained pores

In another experiment on the silty loam with similar treatments, 50 mm of water followed by 30 mm of 0.1% methylene blue solution was infiltrated from the soil surface on delimited areas of 1 × 1 m². Shallow ponding (a few mm) was maintained during the infiltration. Afterwards, samples were taken from the soil 2 cm below the surface by cylinders with a length of 20 cm and a diameter of 21.5 cm (three replicates in treatments with D-values of 81 and 91 and one replicate in treatments with D-values of 86 and 93). The samples were brought to the laboratory and sectioned horizontally at 2 cm depth intervals. At each depth, the number of stained pores was counted. Furthermore, the percent of the area stained by the blue dye (mainly continuous bio-pores and fissures) was determined with an area meter and averaged for the whole column.

2.4. Stomatal resistance

Abaxial stomatal resistance was measured using an automatic porometer Mk3 (Eijkelkamp, The Netherlands). We have observed that stomata are sensitive to temporary changes in solar radiation, and because of this, the measurements reported here were made with the radiation not affected by clouds.

3. Results

Fig. 1 shows examples of primary results of the penetrometer measurements. They indicate that penetration resistance was approximately linearly related...
to the degree of compactness. The mean values were derived from diagrams showing the penetration resistance as a function of the degree of compactness and the soil water content. In the loamy sand, coefficient of variation (CV) varied from 27 to 34% at a matric water tension of 30 kPa and from 26 to 58% at 1000 kPa. In the silty loam the corresponding values were 20 and 37% at 30 kPa and 21 and 35% at 1000 kPa. Generally CV decreased with increasing degree of compactness.

Fig. 2 shows examples of primary results concerning the air-filled porosity as a function of the degree of compactness. The presentation is limited to the wet water content range in which the risk of oxygen deficiency is great. As expected, air-filled porosity decreased approximately linearly when degree of compactness increased irrespective of soil water tension in both soils. The increase of air-filled porosity between the water tensions of 3 and 30 kPa was greater in the loamy sand than in the silty loam because of greater water release in the former. Depending on the matric tension and the degree of compactness CV varied from 3 to 22% for the loamy sand and from 3 to 28% for the silty loam. The CV values decreased with increasing matric water tension.

Fig. 3 shows a series of values of air-filled porosity (from 7 to 16%) and penetration resistance (from 1 to 4 MPa) as functions of the degree of compactness and matric water tension in the investigated soils. For simplicity, all functions are shown in a linear form, though their actual form varied slightly between soils.

The positions of the critical limits of penetration resistance and air-filled porosity specified above, viz., 3 MPa and 10% (v/v), respectively, were transferred from the diagrams for individual soils in Fig. 3 to a common diagram (Fig. 4). This diagram is similar to those presented by Boone (1988) and da Silva et al. (1994), but degree of compactness is used here instead of porosity or bulk density, and matric tension is used to characterize the moisture situation. In this way the critical values of penetration resistance at matric tensions in dry range and air-filled porosity in wetter range are very similar between the soils, in spite of considerable differences in texture, porosity and water holding properties. The lines for the matric tensions of 1500 and 10 kPa were crossed by the critical limits for penetration resistance and air-filled porosity, respectively, at very similar $D$-values.

In the experiment with infiltration of methylene blue solution, increasing degree of compactness reduced both total volume of macropores and the volume of stained pores (=macropores that actively contributed to the water flow) (Table 2). The latter was relatively more affected by soil compaction than the former, which resulted in decreased ratio of the volume of stained pores to total volume of macropores.
Fig. 5 shows the area of dye-stained pores in the soil cross-section and the number of stained pores which took active part in preferential water movement. At most depths, both area and number of stained pores were largest in the loosest soil and decreased with increasing compaction. The distribution of both area and number of stained pores with depth was rather variable.

Fig. 6 shows the course of abaxial stomatal resistance of spring wheat grown on the silty loam. Generally the values of stomatal resistance were greatest for the most compacted soil with a $D$-value of 97. The differences between the compaction treatments were more pronounced in periods with relatively scarce rainfalls, mostly due to increase of stomatal resistance in the most compacted soil. This increase in stomatal resistance was highest in the most compacted soil.

### Table 2

<table>
<thead>
<tr>
<th>Number of passes</th>
<th>Degree of compactness ($D$)</th>
<th>Volume of macropores ($M$) (%)</th>
<th>Stained pores ($S$) (%)</th>
<th>$S:M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>81</td>
<td>13.4</td>
<td>0.83</td>
<td>0.062</td>
</tr>
<tr>
<td>1</td>
<td>86</td>
<td>11.9</td>
<td>0.58</td>
<td>0.049</td>
</tr>
<tr>
<td>3</td>
<td>91</td>
<td>8.5</td>
<td>0.37</td>
<td>0.043</td>
</tr>
<tr>
<td>8</td>
<td>93</td>
<td>5.6</td>
<td>0.11</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Fig. 3. Various values of penetration resistance (1–4 MPa) and air-filled porosity (7–16%, v/v) as functions of the degree of compactness and matric water tension in the plough layer (5–25 cm) in soils 1–4.

Fig. 4. Positions of the critical limits of penetration resistance (3 MPa) and air-filled porosity (10%, v/v) as functions of the degree of compactness and matric water tension in the plough layer (5–25 cm) in soils 1–4.
resistance can be associated with shallow root system and reduced water uptake. Consequently, grain yield in this experiment on the most compacted treatment was reduced by 22% relative to the loosest soil. Furthermore, at most occasions, there was a week tendency towards lower resistance at a $D$-value of 91 than 83, indicating the existence of an optimum at an intermediate $D$-value.

Fig. 5. Percent of stained areal porosity relative to total area and number of stained pores in horizontal sections (0.036 m$^2$) in the silty loam at various degree of compactness ($D$).

Fig. 6. Stomatal resistance of spring wheat grown on silty loam in 1994. The bars represent LSD$_{0.05}$. SH = shooting; H = heading; MR = milk ripeness. The sums of rainfalls for periods between the measurements are also shown.
4. Discussion

Fig. 4 indicates that in loamy sand compared with soil of finer texture the critical limit of penetration resistance over some range of $D$-values is reached at lower matric water tensions. This is due to the fact that this soil releases much water at low tensions. Furthermore, sandy soils with low surface area may require only a small amount of clay to cement and harden when drying (Ibanga et al., 1980; Heinonen, 1985).

The range of soil water tensions at which mechanical impedance or aeration are not restrictive for plant growth becomes narrower as the degree of compactness increases (Figs. 3 and 4). Consequently, this increases the probability that adverse soil mechanical impedance or aeration will occur during the growing season, but the actual occurrence depends on the precipitation and resulting soil wetness. Adverse soil conditions in the root zone strongly influence several plant growth determinants affecting crop yield (Wild, 1988). Stomatal closure is one of the earliest shoot responses to stress conditions (Sojka, 1992). Our studies indicate that increase of stomatal resistance of plants grown in soil with a $D$-value of 97 occur mostly in droughty periods (Fig. 6). Lipiec et al. (1996) reported that a substantial increase in stomatal resistance also occurred when wetness of soils with similar $D$-values increased and associated air-filled porosities decreased. This indicates that a high degree of compactness may influence stomatal behavior similarly, whether the main problem is mechanical impedance or oxygen deficiency, since both may impair root growth and functions. However, the relative influence of high mechanical impedance and of poor aeration will depend on intensity and distribution of rainfall during the growing season. The stomatal closure together with decreased leaf area in compacted soil (Lipiec et al., 1991) may largely account for the substantial crop yield reduction when the $D$-value in the plough layer exceeds 87 (Håkansson, 1990). Significant effects of stomatal behavior on crop yield have previously been reported (Box, 1986; Sojka, 1992).

The results in Table 2 indicate that increasing $D$-values reduced the volume of water-conducting pores relatively more than the total macropore volume. Taking into consideration that the reduction was mostly due to collapsing of the largest pores and Poiseuil’s law indicating that the water conductivity in a bundle of circular pores with the same total volume is proportional to the square of the pore radius, the changes in the pore space geometry will significantly reduce internal drainage and gaseous diffusion. As a consequence this will enhance anaerobic soil conditions in wet seasons (Stepniewski et al., 1994).

In recent studies, Lipiec et al. (1998) showed that the changes in pore structure patterns caused by soil compaction were well reflected in the values of the two-dimensional fractal dimension which decreased with increasing degree of compactness. The trends of fractal dimension values with depth were similar for water conducting pores and roots, which indicates a relationship between distribution patterns of pores and roots. This can be associated with preferential growth of roots into pre-existing macropores, allowing roots to bypass zones of high mechanical impedance. The same macropores may alleviate oxygen stress under wet conditions, since they remain air-filled at lower water tension than smaller pores. Positive relationship between fractal dimensions of roots and macropores in various soils has been reported by Hatano and Sakuma (1990). Further studies on the quantitative relationships between the macropore functions and plant growth factors are required.

5. Conclusions

Critical limits of penetration resistance and air-filled porosity were related to the degree of compactness and matric water tension in a very similar way in soils of different textures. This explains why the degree of compactness optimal for crop growth is very similar in various soils, whereas the optimal bulk density or porosity varies considerably. Therefore, the degree of compactness appears to be a more useful parameter than bulk density or porosity in studies of biological effects of soil compaction. Stomatal behavior is a significant plant growth determinant of crop yield in compacted soil.

References


