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Review

A review of the usefulness of relative bulk density values in studies of soil structure and compaction

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Abstract

The state of compactness is an important soil structure and quality attribute, and there is a need to find a parameter for its characterization that gives directly comparable values for all soils. The use of some relative bulk density value for this purpose, particularly the degree of compactness (Håkansson, 1990), is discussed in this review. The degree of compactness has been defined as the dry bulk density of a soil as a percent of a reference bulk density obtained by a standardized uniaxial compression test on large samples at a stress of 200 kPa. The bulk density should be determined at standardized moisture conditions, to prevent problems caused by water content variations in swelling/shrinking soils. The degree of compactness (D) makes results of soil compaction experiments more generally applicable. Whereas the bulk density or porosity optimal for crop growth vary greatly between soils, the optimal D-value is virtually independent of soil composition. Critical limits of penetration resistance (3 MPa) and air-filled porosity (10%, v/v) are similarly related to the D-value and matric water tension in most soils. As the D-value increases above the optimal, the tension range offering non-limiting conditions becomes increasingly limited. The D-value of the plough layer induced by a given number of passes by a certain vehicle is similar in all soils, provided the moisture conditions are comparable. The degree of compactness facilitates modelling of soil and crop responses to machinery traffic. Although this parameter was primarily introduced for use in annually disturbed soil layers, its use may be extended to undisturbed soil layers.

Keywords: Soil compaction; Soil structure; Relative bulk density; Degree of compactness; Aeration; Penetration resistance; Matric water tension; Crop growth; Machinery traffic

1. Introduction

To characterize the state of compactness of a soil layer, dry bulk density and total porosity are the most frequently used parameters. However, to characterize soil properties from a soil quality point of view, e.g., with respect to crop production, these parameters are unsatisfactory, since they lead to crop response curves and optimum values with respect to crop yield that are different for different soils. To overcome this problem, efforts have been made to find a parameter that eliminates, as much as possible, the differences between soils in crop response curves and optimum

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values. This has mainly been made by relating the bulk density to some reference bulk density obtained by a standardized compaction test. In this way, a parameter often simply named the relative bulk density has been used rather than the bulk density itself to characterize the state of soil compactness. As a reference test, a standard Proctor test was used by Pidgeon and Soane (1977), Carter (1990) and da Silva et al. (1994) and a uniaxial compression test by van Wijk and Beuving (1984).

In Swedish soil compaction research, Håkansson (1973) and Eriksson et al. (1974) introduced a uniaxial compression test as such a reference test and named the resulting relative-bulk-density parameter the ''degree of compactness''. This parameter was originally intended for characterization of the conditions in soil layers disturbed annually by tillage. So far, it has mainly been used in experimental work on soil and crop responses to agricultural machinery traffic. The degree of compactness, *D*, was defined as the dry bulk density of a soil layer in percent of a reference dry bulk density of the same soil obtained by a standardized, long-term uniaxial compression test at a stress of 200 kPa. Håkansson (1990) provided a detailed description of the procedures. For its determination, very large soil samples have generally been used. Field sampling (normally at field capacity water content, Section VII) has mostly been made using a 0.5 m^2 frame, and in the uniaxial test, the sample volume has been 12 l. This parameter has also been used in Norway (Riley, 1983, 1988) and in Poland (Lipiec et al., 1991). A nearly identical parameter was used by da Silva et al. (1997), but they just named it the relative bulk density or the relative compaction. The only difference of possible importance was that they used smaller samples.

The main objective of introducing the degree of compactness to characterize the state of soil compactness was to simplify various compaction studies. The initial hypothesis was that the use of the degree of compactness rather than bulk density or porosity would lead to less site-specific, and consequently, to more generally applicable experimental results. This parameter was thought to be a ''high-level integrating parameter for soil physical quality'' (Topp et al., 1997). It was expected to be a useful link between studies of soil responses to machinery traffic and studies of crop responses to the resulting soil conditions. It was also thought to facilitate modelling of soil and crop responses to field traffic and to enhance understanding and practical utilization of experimental results among farmers.

The objective of this paper is to review the information available today on the merits of using some relative bulk density value such as the degree of compactness to characterize the state of compactness of a tilled soil layer in studies of soil and crop responses to machinery traffic. The possibilities of extending the use of such a parameter to soil layers not annually disturbed by tillage are also discussed, as well as problems caused by water content variations in swelling/shrinking soils. Although not explicitly discussed, from the review it can be deduced that some relative bulk density value may be a useful indicator of soil quality even with respect to other soil functions than crop production.

2. Crop response to the degree of compactness of the plough layer

When using dry bulk density or porosity to characterize the state of compactness of soils with respect to crop growth, it is well known that the crop response curves may be very different for soils with different texture and organic matter content, and the same is true for the optimal values, i.e., the values of these parameters resulting in maximum crop yields (e.g., Håkansson, 1966; Edling and Fergedal, 1972; Petelkau, 1984; Boone, 1986; Lipiec and Simota, 1994). In contrast, Håkansson (1990) used the degree of compactness in a series of about 100 field experiments in a wide range of soils with spring barley (*Hordeum vulgare* L.) as a common test crop. In the experiments, tractor traffic had been used to create a series of *D*-values in the 4–25 cm layer. A good and uniform, 4 cm deep seedbed had been created in all treatments to make sure that a good and uniform crop establishment was obtained irrespective of the compactness of the 4–25 cm layer. To verify that *D* is independent of soil texture, a regression analysis was carried out to study the influences of soil texture and organic matter content on the optimal *D*-value with respect to grain yield (D_{opt}) in the layer between sowing and ploughing depths (about 4–25 cm). The results are illustrated in Fig. 1. The ''best'' regression

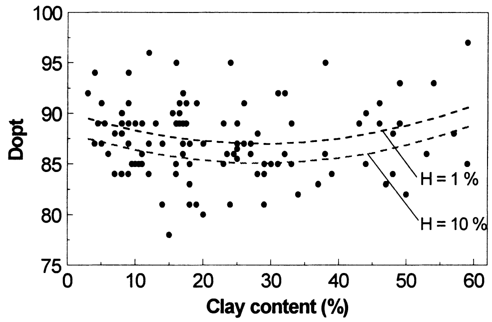

Fig. 1. Estimated optimal degree of compactness with respect to grain yield (D_{opt}) in the 4–25 cm layer (the plough layer excluding the seedbed) in 102 individual field experiments with spring sown barley carried out in Sweden in 1969–1981 in soils with clay contents between 2 and 60% and organic matter contents between 1 and 11%. Regression curves according to Eq. (1) are drawn for soil organic matter contents (*H*) of 1 and 10%. (Data from the investigation by Håkansson, 1990.)

equation found was

$$D_{opt} = 90.3 - 0.216C + 0.0038C^2 - 0.214H$$
$$(2 < C < 60;\ 1 < H < 11;\ n = 102;\ r^2 = 0.07) \quad (1)$$

where *C* is the clay content and *H* is the organic matter content (%). When only *C* was included in the model the regression equation was

$$D_{opt} = 87.3 + 0.0007C$$
$$(2 < C < 60;\ n = 102;\ r^2 = 0.00) \quad (2)$$

This means that in Swedish mineral soils with clay contents ranging between 2 and 60% and organic matter contents between 1 and 11%, the mean optimal *D*-value was virtually the same (about 87) independent of soil texture. Since the group of soils constitutes a representative sample of arable mineral soils in Sweden, the very low r^2-values imply that, for these soils, the main objective of introducing the degree of compactness was nearly achieved. However, Eq. (1) indicates a slight curvilinear relationship between D_{opt} and clay content ($p < 0.05$). D_{opt} also decreased slightly with the organic matter content, but this decrease was not statistically significant. These results indicate that most of the variation in D_{opt} in Fig. 1 was caused by other factors than soil composition, particularly the variations in weather between sites and years (Section 3.4). Very similar D_{opt} as in Sweden was obtained in experiments with spring sown small grain cereals, in most cases barley, in Norway (Riley, 1983, 1988) and in Poland (Lipiec et al., 1991). Furthermore, ongoing work (Braunack, M., 1998, pers. commun.) indicates that D_{opt} for sugar-cane in Queensland, Australia, is very similar to that for barley in Scandinavia.

Thus, it can be stated that the use of the degree of compactness to characterize the state of soil compactness eliminates most of the differences in crop response between soils. Organic soils seem to be an exception. In such a soil, Håkansson (1990) obtained an optimal *D*-value some units lower than that in mineral soils, which is in agreement with Eq. (1). At least part of the reason was thought to be that the reference test, being developed and tested only in mineral soils, was not sufficiently adapted to organic soils. When used in organic soils, the test may have to be modified by reducing the loading time (which may require shallower samples and/or porous plates at both ends of the samples during loading) and extending the time for rebound of the soil after unloading.

While the degree of compactness eliminates most of the differences between soils in optimal *D*-value, variations caused by other factors still remain. The weather seems to be the most important of these factors (Section 3.4). Various crops also have somewhat different *D*-optima. Håkansson (1986) summarized results of a series of compaction experiments in Sweden (part of the series in Fig. 1) where different crops or varieties had been grown side by side with barley used as a common reference crop. A grouping of the crops studied with respect to the optimal *D*-value in the 4–25 cm layer is presented in Table 1. The range between groups 1 and 4 in this table was estimated to be about 5 *D*-units. Since the mean D_{opt} for barley in the whole series of 102 experiments was about 87, mean D_{opt} for groups 1–4 in Table 1 can be estimated to about 87, 85, 84 and 82, respectively. The placement of the crops in these groups, however, may to some extent depend on the varieties. In the experiments, there was some evidence for varietal differences, and such differences are also reported from other investigations (Lipiec and Simota, 1994).

The order between the crops may also depend on which of the growth factors that is the most limiting. The latter may be illustrated by investigations in peas and barley by Grath (1996). When these crops were grown side by side in a well-drained soil where compaction did not cause oxygen deficiency and

Table 1
Grouping of some crops grown in Sweden with respect to the mean optimal degree of compactness (D_{opt}) of the plough layer[a] (After Håkansson, 1986)

Group	Crop	N[b]	Sign.[c]
1 (Highest D_{opt})[d]	Barley (*Hordeum vulgare* L.)	–	–
	Wheat (*Triticum aestivum* L.)	14	n.s.
	Sugar beet (*Beta vulgaris* L.)	6	n.s.
2	Peas (*Pisum sativum* L.)	6	n.s.
	Oats (*Avena sativa* L.)	13	*
3	Rape (*Brassica* species)	12	*
	Field beans (*Vicia faba* L.)	6	**
4 (Lowest D_{opt})[d]	Potato (*Solanum tuberosum* L.)	8	*

[a] Applies to the 4–25 cm layer. In the experiments, a 4 cm deep, high-quality seedbed was created in all treatments to assure a good crop establishment irrespective of the state of compactness of the 4–25 cm layer.
[b] Number of sites where the crop in question was compared with barley.
[c] Significance level for the mean difference in D_{opt} between the crop in question and barley: n.s. — not significant; * — $p<0.05$; ** — $p<0.01$.
[d] The difference in mean D_{opt} between groups 1 and 4 was about 5 D-units.

where no root rot infestation occurred, both crops responded similarly to soil compaction. In contrast, peas grown in the same year in an adjacent field, where compaction caused oxygen deficiency in the soil and where heavy infestation by *Aphanomyces* root rot occurred, responded much more negatively to compaction.

In the series of field experiments summarized by Håkansson (1986) it was also observed that on soils where the crop suffered from manganese deficiency the optimal D-value was higher than normal, but when spraying the crop with manganese sulphate to eliminate this deficiency, D_{opt} was moved to the normal position. Furthermore, a slight increase of the optimal D-value with increased nitrogen fertilization was observed (Fig. 2), but this increase was not statistically significant. This implies that negative effects of excessive soil compaction on crop yield can only be marginally reduced by increased nitrogen fertilization.

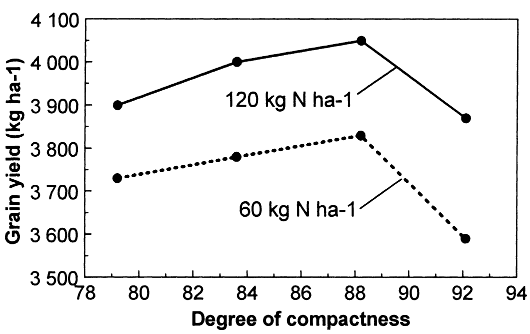

Fig. 2. Mean grain yield of barley as a function of the degree of compactness of the 4–25 cm layer (the plough layer excluding the seedbed) in a series of 11 field experiments (part of the series in Fig. 1) on various soils in Sweden with a fertilization rate of 60 and 120 kg N ha^{-1}. (After Håkansson, 1983).

3. Effects of degree of compactness and matric water tension on various growth factors in annually disturbed soil

3.1. Effects of excessive compaction

Since the degree of compactness influences crop growth similarly in most soils, it can be assumed that it also influences the most significant compaction-dependent growth factors similarly. The factors usually identified as the most critical in excessively compacted soils are aeration and penetration resistance (Allmaras et al., 1988; Håkansson et al., 1988; Boone and Veen, 1994; Lipiec and Simota, 1994), and therefore, they are of special interest here. As discussed by Håkansson (1992) this led to a supposition that critical limits for aeration and penetration resistance are similarly related to the D-value and to the soil moisture situation in most soils.

Several reports in literature indicate that an air-filled porosity of 10% (v/v) and a penetration resistance of 3 MPa often represent critical limits of soil

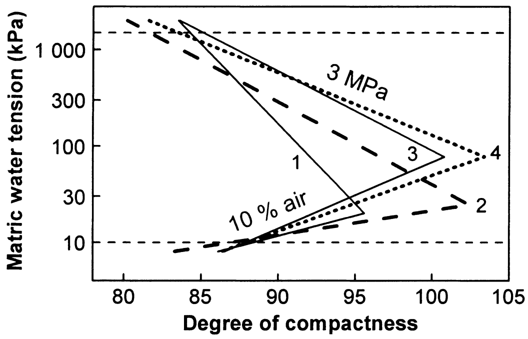

Fig. 3. Positions of the critical limits of penetration resistance (3 MPa, upper line) and air-filled porosity (10%, v/v, lower line) as functions of the degree of compactness and matric water tension in the 5–25 cm layer (the plough layer excluding the seedbed) in a loamy sand (1), a light loam (2), a silty loam (3) and a clay loam (4). (From Lipiec and Håkansson, 2000).

aeration and rootability, respectively (Gliński and Stępniewski, 1985; Boone et al., 1986; Allmaras et al., 1988; Boone, 1988; Bengough and Mullins, 1990). Lipiec and Håkansson (2000) investigated whether these limits were similarly related to the *D*-value and the matric water tension in four Polish soils. The positions of these limits as functions of the *D*-value and the matric water tension in the soils are shown in Fig. 3.

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 conditions. This presentation led to greater similarities between the four soils studied. Thus, the maximal difference in *D*-values for the points where the lines for 10% air-filled porosity crossed the line for a matric tension of 10 kPa was 2%, and where the lines for 3 MPa penetration resistance crossed the line for a matric tension of 1500 kPa was 4%. When using dry bulk density instead of degree of compactness, the corresponding maximal differences were 10 and 9%, respectively, and when using porosity the maximal differences were 13 and 10%, respectively.

Thus, the degree of compactness resulted in greater similarities between the soils in the positions of the critical limits, which is in agreement with the initial hypothesis mentioned in the introduction. However, for this group of soils the similarities could not be dramatically improved, since the ranges of textures and organic matter contents were relatively limited and the reference bulk density varied by only 9% (clay content 6–20%; organic matter content 1.2–2.2%; reference bulk density 1.62–1.79 Mg m^{-3}). As a comparison, within the group of 102 mineral soils investigated by Håkansson (1990) the reference bulk density varied by 33% (1.20–1.79 Mg m^{-3}) because of wider ranges of textures (2–60% clay) and organic matter contents (1–11%).

Unfortunately, the influences of degree of compactness and matric water tension on air-filled porosity and penetration resistance were not systematically studied by Håkansson (1990). However, it was possible to calculate the air-filled porosity in individual treatments at the time when the *D*-values were determined. The matric water tension was not measured, but determinations were usually made when soil water content was slightly below field capacity and matric tension could be estimated to 10–25 kPa. Fig. 4 shows air-filled porosity as a function of the degree of compactness for soils of various textures. For the soils in groups A, B and C, the air-filled porosity was 10% when the *D*-value was between 89 and 94, provided the water content was slightly below field capacity. When soil water content was considerably below field capacity, 10% air-filled porosity was obtained at *D*-values higher than 94, and when the water content was above field capacity 10% air-filled porosity was obtained at *D*-values lower than 89. In sandy soils with clay contents between 8 and 12% and a water content slightly below field capacity, 10% air-filled porosity was obtained at *D*-values near 100, and in a coarse sandy soil with a clay content of only 3%, the air-filled porosity was >20% at a *D*-value of 100.

These results strongly support the initial hypothesis mentioned in the introduction except for the sandy soils. The conditions in these soils are discussed in Section 3.2. The hypothesis is also supported by investigations in two Canadian soils by da Silva et al. (1994), if it is assumed that their reference test (Proctor test with an impact energy of 597 kJ m^{-3}) results in a soil dry bulk density a few percent higher than that obtained by the uniaxial reference test at a stress of 200 kPa. Furthermore, it is supported by Riley (1983, 1988) who found that in several Norwegian soils the air-filled porosity at a matric water tension of 10 kPa decreased to a value <10% when the *D*-value exceeded 85–90. However, to be able to

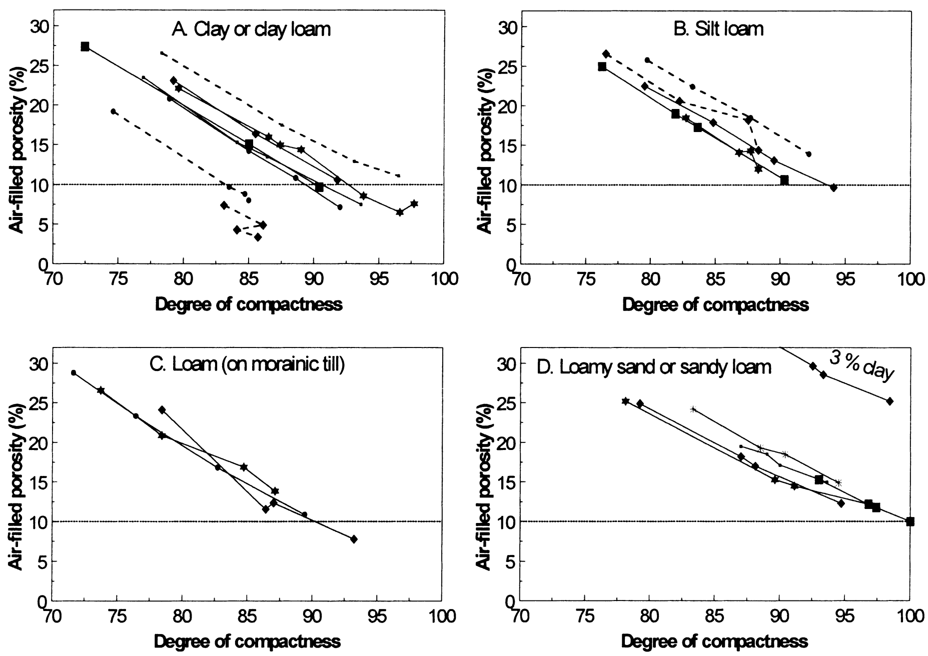

Fig. 4. Air-filled porosity as a function of the degree of compactness of the 4–25 cm layer (the plough layer excluding the seedbed) in soils with various textures. In most cases (solid lines), the determinations were made at a soil water content slightly below field capacity (estimated matric tension 10–25 kPa). In some cases (broken lines), the matric tension was estimated to be either lower than 10 kPa or higher than 25 kPa. Ranges of clay and organic matter contents are: in group A 28–59% and 2.8–4.9%, respectively, in group B 10–27% and 2.9–4.9%, respectively, and in group C 15–16% and 3.1–8.3%, respectively. In group D the ranges are 8–12% and 1.4–4.0% respectively, except for one soil with only 3% clay and 1.0% organic matter. (Unpublished results from the investigation by Håkansson, 1990).

show more definitely to which extent the hypothesis holds true, it would be necessary, and also very valuable, to study the variations in the positions of the critical limits in a sufficiently wide range of soils by new investigations specifically designed for this purpose. The investigations carried out so far have had other primary purposes. New investigations might even result in methods by which the D-value can be estimated from combined measurements of matric water tension and penetration resistance (provided it is possible to handle the complications caused by hysteresis effects and by age-hardening after soil disturbance).

3.2. A schematic diagram

Fig. 5 shows in a schematic form the approximate positions of the critical limits of penetration resistance and air-filled porosity as functions of the degree of compactness and matric water tension in annually disturbed soils. This figure is derived from the results presented in Figs. 3 and 4, and it seems to be applicable to most soils with only minor variations.

Thus, at a matric water tension of 10 kPa (field capacity in humid regions), most soils can be expected to have an air-filled porosity <10% when D is higher than about 87, and >10% when D is lower than that. The higher the D-value the higher is the tension (the lower the water content) at which aeration becomes critical. At a matric tension of 1500 kPa (wilting point) the penetration resistance of most soils can be expected to exceed 3 MPa when D exceeds 85. The higher the D-value the lower is the tension (the higher the water content) at which penetration resistance becomes critical.

When D is lower than about 85, neither soil aeration nor penetration resistance become critical within the 10–1500 kPa tension range. However, the higher the D-value the more limited is the tension range offering adequate conditions (the unshaded area in the diagram), and before D reaches 100 this range usually vanishes.

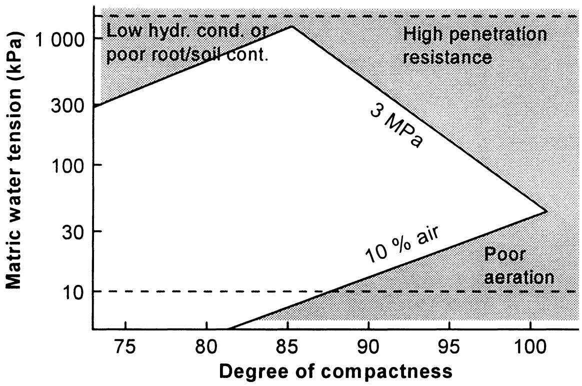

Fig. 5. Schematic diagram showing how a soil air content of 10% (v/v) and a penetration resistance of 3 MPa, usually regarded as critical limits with respect to plant growth, are related to the degree of compactness and matric water tension of the plough layer (excluding the seedbed). As demonstrated in field experiments, problems for crop growth occur even in the upper left corner of the diagram, and it is supposed that these are mainly caused by low unsaturated hydraulic conductivity and/or poor root-to-soil contact.

In a situation represented by the shaded area in the upper right corner of Fig. 5, root growth rate is severely reduced by mechanical impedance. This may lead to a limited root system and seriously reduced uptake of water and nutrients. However, the water tension often increases slowly from an originally low value and remains within the unshaded area until many roots have penetrated the compacted layer. Then it may be less serious if the critical limit is subsequently exceeded. Under Scandinavian conditions, the likelihood of a rapid increase in water tension in the deeper parts of the plough layer is greatest in soils with an intermediate clay content (Heinonen, 1985; Stenberg et al., 1995), and this may be the reason for the curvilinear relationship between D_{opt} and clay content (Eq. (1); Fig. 1).

In the shaded area in the lower right corner of Fig. 5, oxygen deficiency occurs in the soil. This causes problems whenever it restrains normal development of the root system or when the situation in a substantial part of an existing root zone turns critical for more than a short period. The maximum tolerable length of a period with oxygen deficiency depends on several factors such as growth stage, temperature, biological activity and buffering capacity of the soil. Most studies of aeration effects on plants have been performed at early growth stages in pot or lysimeter experiments (Gliński and Stępniewski, 1985). At these stages, the tolerable periods of oxygen stress may vary from a few hours to several days depending on plant species. After establishment, the period can be longer (Cannell and Jackson, 1981). A characteristic plant response to oxygen stress in the root zone is stomatal closure (Drew, 1990) which does not completely recover when aeration is improved (Sojka, 1992; Lipiec et al., 1996).

It is too simplistic, of course, to suggest that an abrupt change occurs from a completely non-restrictive to a completely restrictive situation as soon as one of the critical limits is exceeded. In reality, as illustrated by Lipiec and Håkansson (2000), there is a gradual change, which must be taken into consideration in any detailed studies.

Furthermore, the critical limits may vary between soils. In soils with a relatively high clay content and a continuous and reasonably stable macropore system, aeration can be adequate for crop growth at a lower air-filled porosity than 10% (v/v), even though some intra-aggregate sites may be anaerobic. Thus, Håkansson (1965) reported that good root development and crop growth was obtained in a clay loam soil at an air-filled porosity of 5% (v/v) and McAfee et al. (1989) reported adequate aeration of a clay soil at an air-filled porosity of 8% (v/v). On the other hand, in sandy soils with low content of fine material, the critical air-filled porosity is generally higher than 10% due to lack of stable and continuous macropores. Thus, Bakker et al. (1987, cit. by Boone and Veen, 1994) found that the diffusion coefficient approached zero at a considerably higher air-filled porosity in sand than in clay, and Lindström (1990) reported that the air-filled porosity had to be as high as 30% in a sandy loam for the air permeability to become adequate, while about 10% was sufficient in some clay soils. Stępniewski (1981) observed that the oxygen diffusion coefficient approached zero at a higher air-filled porosity in a soil with 8% clay than in three soils with 19–30% clay.

These results indicate that the critical limit of air-filled porosity will be higher than 10% in many sandy soils. On the other hand, in these soils the line for 10% air-filled porosity will often be found in a lower position than that indicated in Fig. 5. This is the case for the sandy soils shown in Fig. 4, particularly in the soil with the lowest clay content. Similar results were reported by da Silva et al. (1994). Therefore, the critical limit of air-filled porosity may still fall in a position similar to that in Fig. 5, except for very coarse sandy soils.

Even the critical limit for penetration resistance in disturbed soil layers may vary slightly between soils, but these relations still seem to be poorly known (Bengough and Mullins, 1990). Probably the critical limit is usually lower in sandy soils than in clay soils, because of the differences in soil structure. The studies of stained pores by Lipiec and Håkansson (2000) indicate that compaction may reduce not only the volume of macropores but also their continuity. This may influence the critical limits of both penetration resistance and air-filled porosity and render them less general. In addition, as the matric water tension increases, the critical limit for penetration resistance decreases and may approach zero (the roots wilt) at a tension of 1500 kPa (Dexter, 1987; da Silva et al., 1994).

As indicated above, crop responses to excessive soil compaction can largely be explained by the relations illustrated in Fig. 5. However, the degree of compactness influences many growth factors besides those illustrated in this figure, and this may presumably affect the crop response curves, at least in specific situations.

3.3. Reason for problems in too loose soils

Numerous field experiments show that crop growth is reduced not only in excessively compacted soils but also in very loose soils, particularly when the growing season, or at least the first part of it, is dry. Therefore, there are some problems for the crops even in the shaded, upper left corner of the diagram (Fig. 5). Less information is available on the nature of these problems, but experience from field experiments indicates that even these problems are similar in most soils. One of the problems seems to be low unsaturated hydraulic conductivity (Kemper et al., 1971). Thus, Lipiec and Tarkiewicz (1988) reported that the hydraulic conductivity of a loamy sand at high matric water tension was low in loose soil, which limited the water supply to plants in soils with a low root density. Another problem is poor root-to-soil contact (Kooistra et al., 1992; Lipiec et al., 1993). Both low unsaturated hydraulic conductivity and poor root-to-soil contact may negatively influence uptake of water and nutrients (Veen et al., 1992). The problems for the plants in this corner of the diagram (Fig. 5) would deserve comprehensive investigations, but are probably very complicated.

3.4. Influences of various weather conditions

From Fig. 5 it can be concluded that the crop response to the state of compactness of a soil can only be understood if the dynamics of the moisture conditions throughout the growing season is also considered. This may explain the experimental results showing that the *D*-value optimal with respect to crop growth has varied considerably between years (Fig. 1). From several investigations it seems as if the optimal state of soil compactness usually is higher in years with a continuously dry than in years with a continuously wet growing season (Håkansson, 1966; Edling and Fergedal, 1972; Voorhees et al., 1985; Voorhees, 1987). However, Lipiec and Simota (1994) quoted several examples with opposite results. Furthermore, in the extensive Swedish series of field experiments (Fig. 1) no simple and consistent rules for the influence of the mean weather conditions during the whole growing season on the optimal *D*-value were found, probably because of variations in conditions during the seasons. In many cases, the conditions during some short critical period may have been the most decisive.

4. Relations between external loading and degree of compactness

A *D*-value of 100 indicates the densest state that can be attained in the laboratory when a uniaxial stress of 200 kPa is applied to a soil that is previously loosened in a way similar to that of soil tillage. The type of loading by a wheel in the field resembles to same degree that of the uniaxial loading. Therefore, in all soils, it can be assumed that a *D*-value slightly higher than 100 is the highest that can be induced in the plough layer by wheel traffic that causes a maximal vertical, normal stress in the soil of 200 kPa. If the stress is lower/higher, the highest possible *D*-value is also lower/higher. However, the *D*-value will also be affected by several other factors such as soil water content, wheel slip, vibration and number and duration of loading events. Nevertheless, the resulting *D*-value after a certain number of passes by a certain machine with a given axle load and ground contact stress will be rather similar in all soils, provided the moisture conditions are comparable. A certain alteration of the moisture conditions at the time of traffic also alters the compaction effects similarly in most soils, provided the moisture conditions are suitably characterized.

The statements in the previous paragraph are based on results obtained by Ljungars (1977), Lipiec et al. (1991), Etana (1995) and Arvidsson (1997). In all these studies the same number of passes by machines of the same type at comparable moisture conditions in the spring resulted in very similar *D*-values in the plough layer of soils with very different textures. Arvidsson (1997) even showed that a compression index calculated on the basis of tractor traffic in the field did not increase with the clay content, while a traditional uniaxial laboratory test on the same soils, in agreement with many other laboratory investigations, resulted in a compression index that increased substantially with the clay content. Arvidsson (1997) suggested several possible reasons for the discrepancy between the laboratory and field results, but probably the main reason was a difference in loading time.

In field investigations in several Swedish autumn ploughed soils, Ljungars (1977) studied the effects of tractor traffic in spring on the degree of compactness of the layer between sowing depth and ploughing depth (about 4–24 cm). Examples of his results are given in Fig. 6, which shows the *D*-value after 1, 3 and 9 passes by a 4.03 Mg tractor in a clay soil and in a fine sandy loam at four moisture situations. These situations represent the range encountered in practice during seedbed preparation in spring at the actual sites and were subjectively classified as wet, moist, normal and dry. At the intermediate water contents the *D*-values were similar in both soils, but alteration of the water content influenced the *D*-values in the clay soil much more than in the fine sandy loam. This was probably because the same alteration of the water content, within the actual moisture range, influenced the matric water tension much more in the former soil than in the latter. Unfortunately, however, the matric tension was not measured.

da Silva et al. (1997) investigated the effects of tillage, wheel traffic, soil texture and organic matter content on dry bulk density and relative bulk density (determined in nearly the same way as the degree of compactness) as characteristics of the state of soil compactness. While dry bulk density was strongly influenced by all these factors, the use of the relative bulk density virtually eliminated the effects of soil texture and organic matter content and enhanced the effects of soil tillage and machinery traffic.

It can be concluded that various factors related to the field traffic affect the *D*-value in the plough layer very similarly in all soils with only moderate and probably rather consistent differences between various textural groups. It would be of great interest to systematically study these differences.

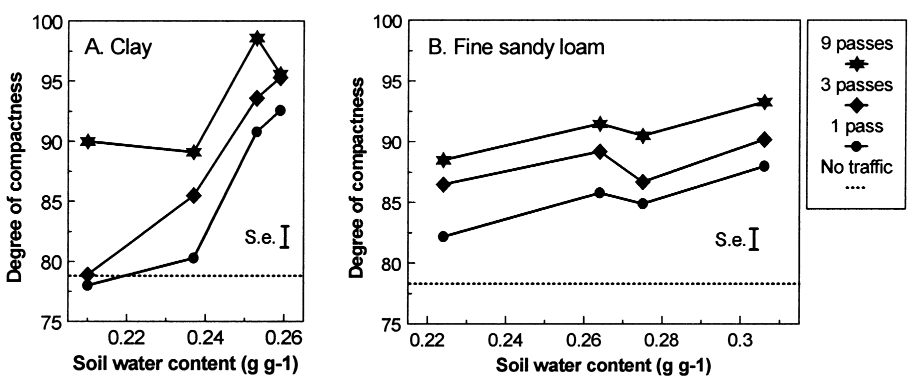

Fig. 6. Degree of compactness of the plough layer (excluding the seedbed) as a function of soil water content in two Swedish autumn ploughed fields after 1, 3 and 9 passes in spring by a 4.03 Mg tractor (rear axle 3.03 Mg, tyres 12.4 × 36"; front axle 1.00 Mg, tyres 7.50 × 16"). The *D*-values are means for two inflation pressures in the rear tyres (150 and 70 kPa). In both cases, inflation pressure in the front tyres was 110 kPa. In each field, traffic was applied at four moisture situations, subjectively classified as (from right to left) wet, moist, normal and dry. Bars show mean standard error for individual data points. (After Ljungars, 1977).

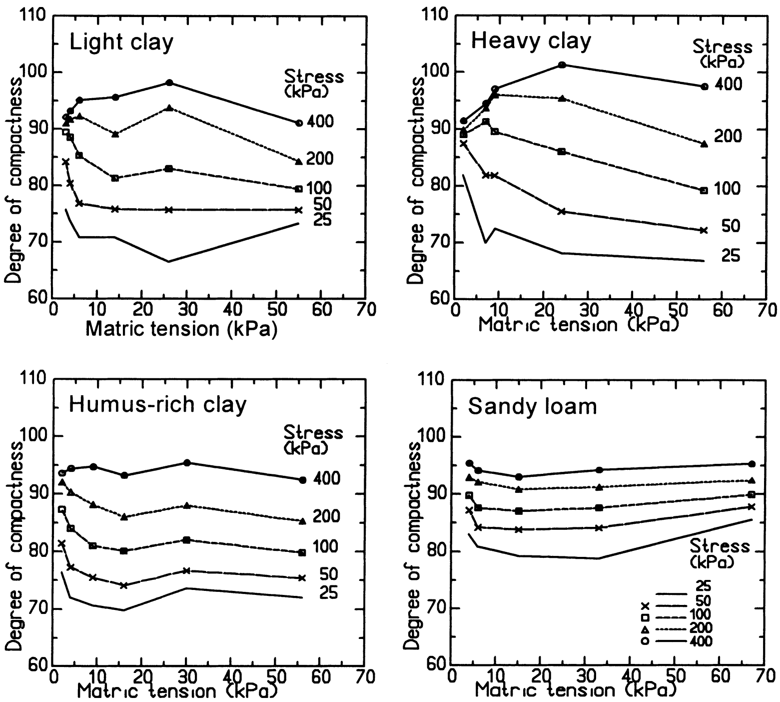

Fig. 7. Degree of compactness obtained after short-term loading of large samples from the plough layer of light clay, heavy clay, humus-rich clay and sandy loam with different matric water tensions by a series of uniaxial stresses (25–400 kPa, loading time 20 s, followed by unloading). Data from Fig. 3 in Etana et al. (1997) are redrawn here using matric tension rather than water content to characterize the soil moisture situation.

From the studies by Etana et al. (1997) it can be derived that the use of matric water tension to characterize the soil moisture situation probably results in more general relations than the use of soil water content. In Fig. 7 the data from Fig. 3 in Etana et al. (1997) were redrawn with the use of matric tension rather than water content to characterize the moisture situation. The D-values presented in this figure were obtained by short-term loading, whereas the reference test was made by long-term loading. Therefore, the maximum D-values after the same stress as in the reference test (200 kPa) was less than 100.

When presented as in Fig. 7, the groups of curves for different soils show considerably greater similarities than the original groups of curves (Fig. 3 in Etana et al., 1997). However, it cannot be excluded that some more sophisticated method to characterize the moisture conditions may result in still greater similarities. The results in Fig. 7 indicate that the two soils in Fig. 6 might also have shown more similar results if matric tension instead of water content had been used to characterize the moisture situation.

It appears possible to go one step further and combine the groups of curves for the individual soils in Fig. 7 into a common diagram, provided this diagram covers a sufficiently wide range of stresses and D-values. An effort of that kind is made in Fig. 8. From one curve to the next in this diagram the stress is doubled. However, the scales on the axes must be adjusted to fit the individual soils. One of the curves (a) with the stress σ_a reaches the D-axis at a right angle at $D = D_a$. Consequently, σ_a and D_a would be two important characteristics of the curve system. For instance, both of them are much higher for the sandy loam than for the heavy clay. The area in the diagram can be divided into four sections. In Section I, D is linearly related to the log of stress and to the matric tension. The distance, ΔD, between the parallel curves (larger for clay than for sandy loam) and their slopes would be two other important characteristics. The same is true for the positions and slopes of the lines

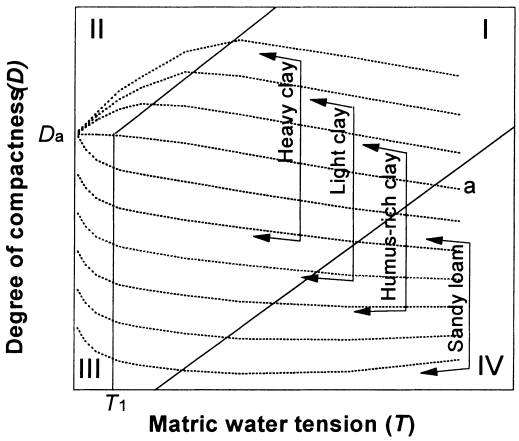

Fig. 8. A conceptual diagram showing how the groups of curves for the soils in Fig. 7 can be combined into one diagram provided this covers a sufficiently wide range of matric tensions, soil densities and stresses.

delimiting Section I. In Section II, the linearity is broken and the compaction is limited because of a high water saturation (>90%). In Sections III and IV the relations are non-linear for other reasons. It will probably be possible to find rather simple and consistent relations between soil texture and organic matter content on one hand and the individual parameters that characterize the curve system in this diagram on the other. This, however, requires an extensive study. Furthermore, as indicated by Arvidsson (1997) the parameters may differ between traditional compaction tests in the laboratory and wheel induced compaction in the field.

For simplicity, the curves in Fig. 7 were drawn without considering the changes in matric tension that occurred as a result of compaction (Etana et al., 1997). Instead, the tension measured after application of the lowest uniaxial stress (25 kPa) was used throughout the diagrams. In reality, in situations falling in Section I of Fig. 8, the tension usually increased when stresses increased, whereas in Section II it decreased. Furthermore, no compensation was made for the effects of swelling/shrinking of the soils with changing water content (compare Section VII). The *D*-values in the diagrams were calculated using bulk density at the existing water content. To make the *D*-values of swelling/shrinking soils fully comparable, ideally they should have been adjusted for changes in bulk density that would have occurred if all soil samples after compaction had been brought to the same matric water tension, e.g., to field capacity. Then, swelling would have reduced the bulk density and *D*-values in the drier soils and shrinking would have increased these values in the wetter soils. If the two factors mentioned in this paragraph had been considered, some of the diagrams would have been considerably distorted.

Results and discussions above indicate that it is easier to model machinery-induced compaction of the plough layer in terms of degree of compactness than in terms of bulk density. The results will also be less site-specific, and therefore, more generally applicable. They can also be more directly used to estimate crop responses. This approach was used in the model by Arvidsson and Håkansson (1991), which is probably the only model available today that goes all the way from machinery traffic to crop response.

5. Alternative methods to determine reference bulk density values

We have argued that the degree of compactness is a useful parameter in studies of soil and crop responses to machinery traffic and facilitates generalization of the results. However, as discussed by Håkansson (1990), relative bulk density values based on some other reference test may offer similar advantages. It would be of great interest to compare the positions of critical limits for aeration and penetration resistance when using alternative reference tests. The bulk density values obtained by a standard Proctor test is higher than the values obtained by the uniaxial reference test at a stress of 200 kPa. In the study by Håkansson (1990) with six soils of various textures, the values obtained by a Proctor test with an impact energy of 2.6 MJ m^{-3} was between 7 and 17% higher than those obtained by the uniaxial reference test at a stress of 200 kPa. Unfortunately, the differences between the soils in this respect were too large to be disregarded. Therefore, it is of importance to decide which of these two tests or other possible reference tests should be used.

The reference test that results in the greatest similarities between soils in the positions of the critical limits of air-filled porosity and penetration resistance in a diagram similar to that in Fig. 3 seems to be the most useful one in agricultural applications, but the final choice should be supported by an extensive field experimentation under various soil and moisture conditions. However, as compared with the uniaxial test with a stress of 200 kPa no great improvement seems to be possible.

6. Use of the degree-of-compactness concept in undisturbed soil layers

So far, the degree-of-compactness concept has generally been used only for layers annually loosened by tillage. However, it may be useful for untilled layers, such as the subsoil or the surface layer under no-till, as well. In such case, however, some alterations of the pretreatment of the soil samples for the reference test and of the procedure for this test may be required. To get accurate and reproducible values it seems necessary to make sure that a non-negligible part of the soil after pretreatment does not have an aggregate density that is greater than the bulk density that can be obtained by the stress applied in the test. Furthermore, it must be noted that the critical limits of air-filled porosity and penetration resistance, and consequently, the relations between *D* and crop growth, probably differ between undisturbed and annually disturbed soils. The main reason would be a better continuity and stability of the macropores in undisturbed soils.

The great significance of continuous and stable macropores such as biopores, interpedal voids or dessication cracks for the root growth as well as for gas, water and solute transport has been shown by many authors (e.g., Allmaras et al., 1988; Hatano and Sakuma, 1990; Edwards et al., 1992; Whalley and Dexter, 1994) and may be advantageous in many respects, e.g., from the point of view of N conservation (Lipiec and Stępniewski, 1995). Among the macropores, biopores may be the most resistant to vertical compression. The improved macropore continuity and stability in undisturbed soils lead to a reduction of the critical limit of air-filled porosity in undisturbed as compared to disturbed soil (Boone et al., 1986; Lindström and McAfee, 1989), even though part of the soil may be water-filled and anoxic (Zausig et al., 1993).

Continuous and stable macropores through a hard layer may also enable root growth, while the strength of the soil matrix is too high for root penetration. This will move the critical limit of penetration resistance to a higher value (e.g., Ehlers et al., 1983). On the other hand, when a soil layer is no longer disturbed, age-hardening may gradually increase soil strength as measured with a penetrometer (Dexter et al., 1988). This would, for instance, move the position of the 3 MPa line in Fig. 5 downwards, but is probably less important than the increase in the critical value.

Therefore, it may be supposed that the critical limits for both air-filled porosity and penetration resistance will generally move in such a way that the requirements of the plants are met at higher *D*-values in untilled than in tilled soils. This means that the unshaded area in Fig. 5 is widened, and probably more so in clay soils than in sandy soils because of the differences in structure between these groups of soils. It also means that the curve showing the crop yield as a function of *D* is flatter in untilled than in tilled soil.

These suppositions are supported by many reports in the literature that demonstrate that reduced tillage often results in good crop growth, even when soil bulk density is considerably higher than in a system with annual ploughing. This seems to particularly apply to soils with intermediate to high clay content and less to coarse-textured soils (Rydberg, 1992). Thus, both Rydberg (1987), Comia et al. (1994) and Etana et al. (1999) showed that good crop growth was obtained in fine-textured soils even when the *D*-value in the deeper parts of a previous plough layer after reduction of the tillage depth was as high as 95–106. It may be hypothesized that the optimal degree of compactness in an undisturbed soil is similar to that in a disturbed soil, but that a higher degree of compactness is less negative, particularly in fine-textured soils, because of the better macropore continuity. If the positions of the critical limits in various soils under tilled and untilled conditions were systematically compared and possible problems with the reference test solved, the applicability of the degree-of-compactness concept could probably be extended to untilled soil layers such as the topsoil under permanent grass or direct drilling, or even the subsoil. This, however, would require further studies.

7. Problems of soil swelling/shrinking when determining the degree of compactness

In swelling/shrinking soils, the water content influences the bulk density. Bulk density changes caused by changes in water content are largely reversible, and ideally, the *D*-value should not be influenced by the reversible part of the bulk density changes. There are two possibilities to achieve this. The method used with reasonable success by Håkansson (1990) was to determine the bulk density in the field at a standardized moisture condition which was as close to field capacity as possible. In the field, however, the situation cannot be completely standardized because of the spatial and temporal variations in moisture conditions, the hysteresis effects involved, and the fact that swelling takes time. Another possibility might be to determine the bulk density at an arbitrary moisture state but correct the value with respect to the deviation from the standardized condition. However, such methods have not been developed, yet this problem is very important.

The swelling/shrinking problem is not limited to the case when the state of soil compactness is characterized by the degree of compactness. It is just as large when bulk density or porosity are directly used. In many investigations reported in the literature, however, it is disregarded, and this has probably often led to misinterpretations of the results, e.g., when temporal changes in bulk density in long-term field experiments are reported.

To some extent, the magnitude of the problem depends on the method of bulk density determination. For instance, when carrying out core sampling, wide desiccation cracks are probably usually avoided. This means that the bulk density values obtained are influenced by the swelling/shrinking not only in the vertical direction but also in the horizontal. When using large samples such as in the frame sampling technique (Håkansson, 1990), desiccation cracks are included in the samples, and only the vertical swelling/shrinking influences the results. However, even this may have great importance.

8. Conclusions

Whereas the bulk density and porosity optimal for crop growth vary considerably between soils, the optimal degree of compactness of annually disturbed soils is virtually independent of soil texture and organic matter content. The main reason is that critical limits of penetration resistance and air-filled porosity are related to the degree of compactness and matric water tension in a very similar way in most soils. Therefore, the degree of compactness is a more useful parameter than bulk density or porosity in studies of biological effects of soil compaction. It is also more useful in studies of the effects of field traffic on soil conditions. Whereas bulk density and porosity of the plough layer induced by a certain number of passes by a particular machine vary considerably between soils, the degree of compactness is very similar, provided the moisture situation is comparable. Therefore, this parameter can form a useful link between studies within various parts of the casual chain: machinery traffic–soil compactness–soil properties–crop growth. It can also facilitate the modelling of soil and crop responses to field traffic. It seems possible to extend the use of the degree-of-compactness concept to soil layers not annually disturbed by tillage, but this would require further methodological studies. When using bulk density or any parameter derived from this, such as the degree of compactness, to characterize the state of soil compactness in swelling/shrinking soils, attention must be payed to the soil moisture content.

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