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HUGH RILEY

## Estimation of physical properties of cultivated soils in southeast Norway from readily available soil information

Norwegian Crop Research Institute

Ås Science Park Ltd., Norway

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"Research Technician Svein Selnes taking undisturbed soil cores from a soil profile"

# Estimation of physical properties of cultivated soils in southeast Norway from readily available soil information

HUGH RILEY
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Measurements were made of important soil physical properties of cultivated topsoils and undisturbed subsoils, sampled throughout S.E. Norway over the period 1979-1993. In addition to soil texture (assessed by mechanical analysis), the measurements included organic matter content, dry bulk density, mean particle density, porosity, moisture retention and permeability properties. Interrelations between these parameters are explored in this paper, with the aim of facilitating the prediction of those properties which are difficult or time-consuming to measure. Organic matter is predicted for a wide range of mineral soils from ignition-loss with a correction for clay content, and, for peaty soils, from ignition-loss alone. Mean particle density of mineral soils is predicted from ignition-loss, again with a correction for clay content. Dry bulk density of mineral soils is predicted on the basis of their contents of organic matter, gravel, silt and clay as well as horizon depth, whilst that of peaty soils is predicted from ignition-loss. Total porosity, air-filled pore space and soil moisture retention at various matrix tensions are predicted from a combination of bulk density, organic matter and textural properties in the case of mineral soil. Organic matter alone was used in the case of peaty soils. Saturated hydraulic conductivity is predicted from air permeability, which is in turn predicted from air-filled pore space. Regression equations are given for various groupings of soil texture, and for topsoils and subsoils separately. In addition, calculated values are presented for different horizon depths of soil types most commonly found on cultivated land in S.E. Norway.

Key words: air permeability, dry bulk density, loss-on-ignition, mean particle density, moisture retention curves, particle-size distribution, pore-size distribution, prediction equations, saturated hydraulic conductivity, soil organic matter

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## Introduction

Increasing use is nowadays being made of simulation models, in order to gain insight into interactive soil processes and to make generalisations on questions related to soil water and nutrient management, soil productivity and the transport of pollutants and erosion material. Many such models require information on soil physical properties, such as their organic matter content, porosity, moisture retention and transport properties.

Unfortunately, many of these variables are time-consuming and/or expensive to measure. Moreover, they often exhibit a high degree of variability. The use of models may therefore be hindered by a lack of input data, or by uncertainty concerning the representivity of measurements made on small sample numbers. Thus, in many cases, it may be useful to estimate soil physical properties from known relationships with more readily available descriptors, such as soil textural classification, and/or simple estimates of organic matter content such as ignition loss.

This publication sets out to provide information on how to estimate some of the commonly required parameters for some cultivated soils of southeast Norway, mainly on the basis of information gathered from analyses performed at Planteforsk, Division Kise, during the period 1979-1994. The information is divided into five sections:

1. Soil organic matter
2. Mean particle density
3. Dry bulk density
4. Soil porosity and moisture retention
5. Air permeability and saturated hydraulic conductivity

The author wishes to acknowledge the invaluable contribution of Research Technician Svein Selnes for careful assistance both in the field and in the laboratory. Contributions of data from other colleagues in Planteforsk, mentioned as appropriate in the text, are also gratefully acknowledged. Thanks are also due to Professor Arnor Njøs for helpful comments on the manuscript.

# 1. Soil organic matter

## 1.1 Background

Soil organic matter (SOM) content has important influences on the soil's fertility, moisture retention, structural stability and thermal properties. SOM is most accurately assessed by measuring organic carbon (ORG-C), either by wet oxidation and titration, or by dry combustion and analysis based for example on the relative thermal conductivities of carbon dioxide and oxygen (Allen et al. 1974).

A crude estimate of SOM is often obtained by measuring the percentage weight loss on ignition (IGN-L). This is a simple and cheap method, but suffers from the disadvantage that it, besides burning off organic matter, may also cause losses of carbonates, volatile salts, ammonium and clay structural water. A means of correcting IGN-L for such losses is therefore required in order to give a more accurate estimate of SOM.

Corrections may differ between regions, due to variations in soil mineralogy and composition, and are specific to the laboratory procedures used, especially the temperature used for ignition (Ball 1964). The following corrections, quoted by Låg (1961) on the basis of earlier experience in Sweden, have often been used in Norway:

| Soil types | Clay content | Correction |
|---|---|---|
| Gravel, sand and silt | 0 - 15% | -1% |
| Light clays | 15 - 25% | -2% |
| Medium clays | 25 - 40% | -2.5% |
| Heavy clay | 40 - 60% | -3.5% |
| Very heavy clay | >60% | -4.5% |

In practice these corrections have been found to give rise to negative figures for SOM in some cases (Riley 1983), and equation (1.1) based on later Swedish investigations (Kälvesten 1975), has therefore sometimes been used.

(1.1) $$SOM = 0.89*IGN\text{-}L - 0.037*CLAY\% - 0.35 \quad (n=227, R^2=0.99)$$

This equation has, however, been found to overestimate SOM on morainic loams at Apelsvoll in S.E. Norway (Riley

& Eltun 1994). Approximately the same correction for clay nevertheless applied in this region, as shown in equation (1.2).

(1.2) $SOM = 0.81*IGN\text{-}L - 0.038*CLAY\% - 0.70$ ($n=120$, $R^2=0.97$)

Data from a wide variety of soil types in different regions of Norway is therefore used in the present study, in an attempt to find a suitable correction factor for the whole country. The contribution of data is gratefully aknowledged from colleagues at Holt, Kvithamar and Særheim Research Centres, in northern, central and southwestern Norway, respectively.

## 1.2 Materials and methods

Basic statistics of the samples used are summarized in Table 1.1.

The data set includes mostly loams from S.E. Norway with some clays and sands, mostly sandy soils from S.W. Norway and a variety of sands and clays from central and northern Norway, including many subsoil samples in the latter region. Very humus-rich soils (SOM 12-20%) and organic soils (SOM > 20%) were excluded, due to uncertainty about the accuracy of their clay content. A dataset of 27 such samples from several regions was treated separately.

IGN-L was measured by ignition at 550°C of oven-dry material for at least 2 hours (more in the case of samples with high SOM). ORG-C was measured using a Leco Carbon Analyser. A factor of 1.72 is assumed for the conversion of ORG-C to SOM in all later calculations. Clay content was measured by the pipette method of Elonen (1971).

## 1.3 Results

Linear regressions of SOM on IGN-L and clay content were performed. IGN-L was naturally of dominant importance, whilst clay content gave a minor but statistically significant contribution. The regression equation (1.3) for all samples from S.E. Norway was very similar to that previ-

Table 1.1. Basic statistics of the samples used for calculating the dependence of ignition-loss on the soil's contents of organic carbon and clay

| REGION | SOUTHEAST | SOUTHWEST | CENTRAL | NORTHERN |
|---|---|---|---|---|
| No. samples | 223 | 38 | 52 | 142 |
| IGNITION-LOSS (%) | | | | |
| Mean | 4.4 | 6.2 | 7.5 | 2.6 |
| Max. | 14.7 | 10.8 | 14.1 | 12.4 |
| Min. | 0.5 | 1.7 | 1.6 | 0.2 |
| Std.dev. | 2.9 | 1.7 | 3.6 | 2.5 |
| ORGANIC CARBON (%) | | | | |
| Mean | 1.4 | 2.3 | 2.5 | 0.8 |
| Max. | 6.7 | 5.0 | 5.5 | 6.0 |
| Min. | 0.1 | 0.7 | 0.3 | 0 |
| Std.dev. | 1.4 | 1.1 | 1.5 | 1.1 |
| CLAY CONTENT (%) | | | | |
| Mean | 17 | 7 | 15 | 7 |
| Max. | 64 | 23 | 39 | 52 |
| Min. | 1 | 0 | 1 | 0 |
| Std.dev. | 12 | 5 | 12 | 10 |

ously reported from Apelsvoll:

(1.3) SOM = 0.83*IGN-L - 0.036*CLAY% - 0.67 (n=223, $R^2$=0.95)

The coefficients varied somewhat in equations for the other regions, probably due to the smaller sample numbers. The combined equation (1.4) for the whole country had a larger correction for IGN-L and a smaller constant value, whilst the correction for clay was approximately the same as in previous equations:

(1.4) SOM = 0.74*IGN-L - 0.033*CLAY% - 0.35 (n=455, $R^2$=0.91, sey=0.736, $seb_1$=0.011, $seb_2$=0.003)

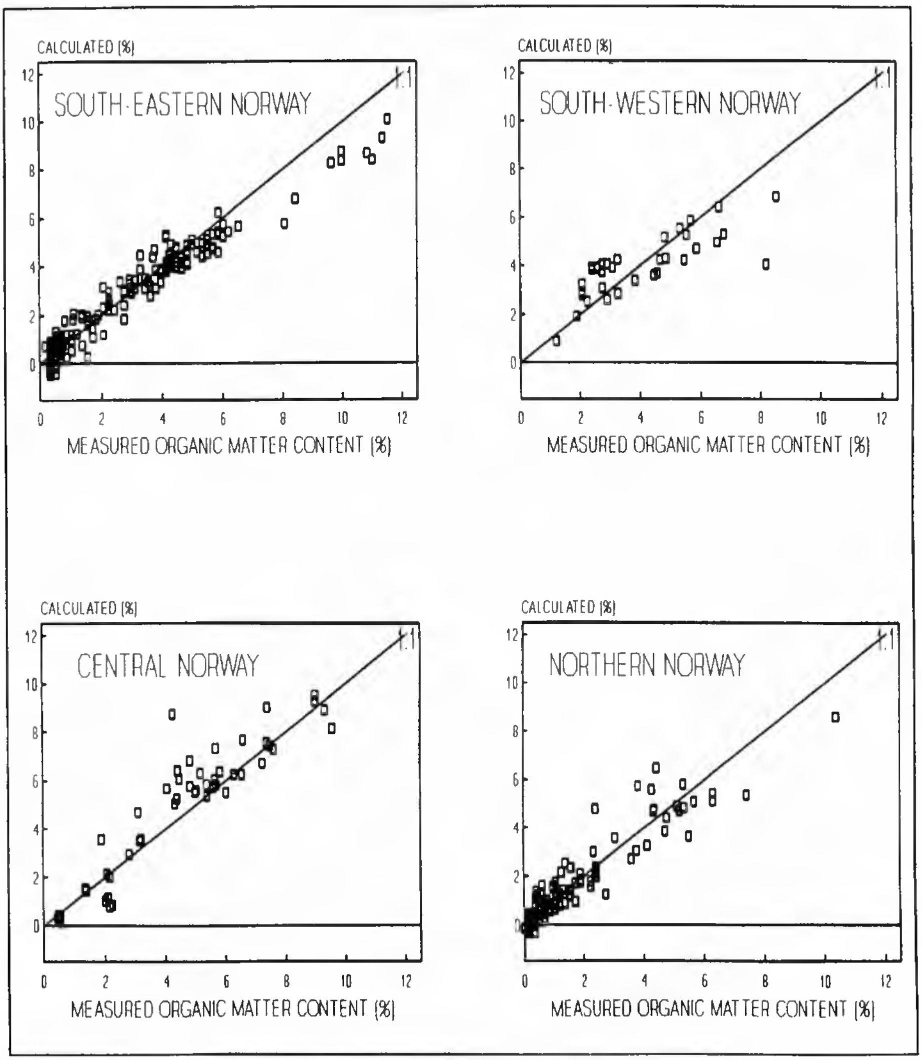


*Fig. 1.1. Comparison of measured contents of soil organic matter in different regions of Norway, with values calculated from loss-on-ignition and clay content using equation (1.4).*

Values calculated with equation (1.4) are plotted in Fig. 1.1 against values measured in each region. There was reasonable agreement in most cases, especially for SOM values below about 6%. At higher values the equation appears to underestimate SOM somewhat, especially in the S.E. region. A quadratic equation (1.5), aimed at rectifying the latter trend, gave no increase in the total amount of variance explained:

(1.5) SOM = 0.61*IGN-L + 0.011*(IGN-L)$^2$ - 0.031*CLAY% - 0.16 (n=455, $R^2$=0.91, sey=0.727, $seb_1$=0.037, $seb_2$=0.003,$seb_3$=0.003)

In a few cases the above equations predicted negative SOM values. Equation (1.6) was fitted for the combined data with no constant term, in an attempt to overcome such problems.

(1.6) SOM = 0.70*IGN-L - 0.041*CLAY% (n=455, sey=0.758, $seb_1$=0.009, $seb_2$=0.003)

A comparison of predictions of organic matter contents is given in Table 1.2, using equations (1.3) - (1.6) for a range of values typical of mineral soils in Norway. Equations (1.4) - (1.6) give slightly higher SOM values than equation (1.3) at low levels of IGN-L, whilst the reverse is true at higher levels. Little advantage appears to be offered by using equations (1.5) or (1.6), and equation (1.4) may therefore be recommended for most mineral soils with moderate organic matter content.

An independent test of equations (1.3) and (1.4) was made using data published by Rose (1991) from six field trials on widely varying soils in England (12-33% clay, 9-60% silt, 14-79% sand). Despite some variability, possibly due to differences in clay mineralogy or carbonate content, this test revealed no systematic over- or underestimation by the present equations (Fig. 1.2).

In the case of the humus-rich and organic soils, SOM was closely related with IGN-L, but not with clay content, equation (1.7):

(1.7) SOM = 0.90*IGN-L - 1.2 (n=27, $R^2$=0.98)

Table 1.2. Predicted values of soil organic matter (%) obtained using equations 1.3 - 1.6 for a range of ignition-loss and clay

| IGN-L | CLAY | Equ. 1.3 | Equ. 1.4 | Equ. 1.5 | Equ. 1.6 |
|---|---|---|---|---|---|
| 2 | 10 | 0.63 | 0.80 | 0.79 | 0.99 |
| 2 | 30 | -0.09 | 0.14 | 0.17 | 0.17 |
| 2 | 50 | -0.81 | -0.52 | -0.45 | -0.65 |
| 6 | 10 | 3.95 | 3.76 | 3.59 | 3.79 |
| 6 | 30 | 3.23 | 3.10 | 2.97 | 2.97 |
| 6 | 50 | 2.51 | 2.44 | 2.35 | 2.15 |
| 10 | 10 | 7.27 | 6.72 | 6.73 | 6.59 |
| 10 | 30 | 6.55 | 6.06 | 6.11 | 5.77 |
| 10 | 50 | 5.83 | 5.40 | 5.49 | 4.95 |

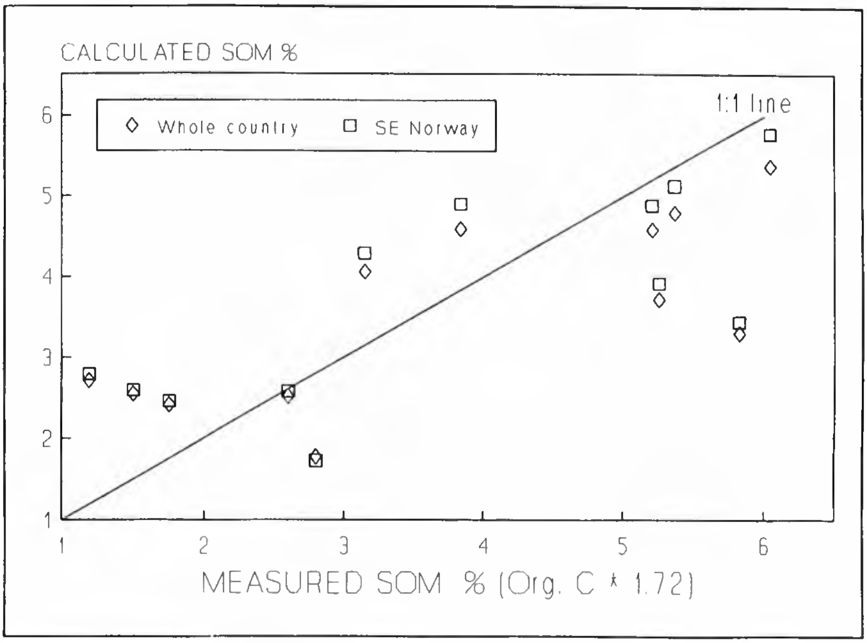


*Fig. 1.2. Calculated soil organic matter (SOM) for various English soils, obtained with equation 1.3 (S.E. Norway) and equation 1.4 (Whole country),using the data of Rose (1991).*

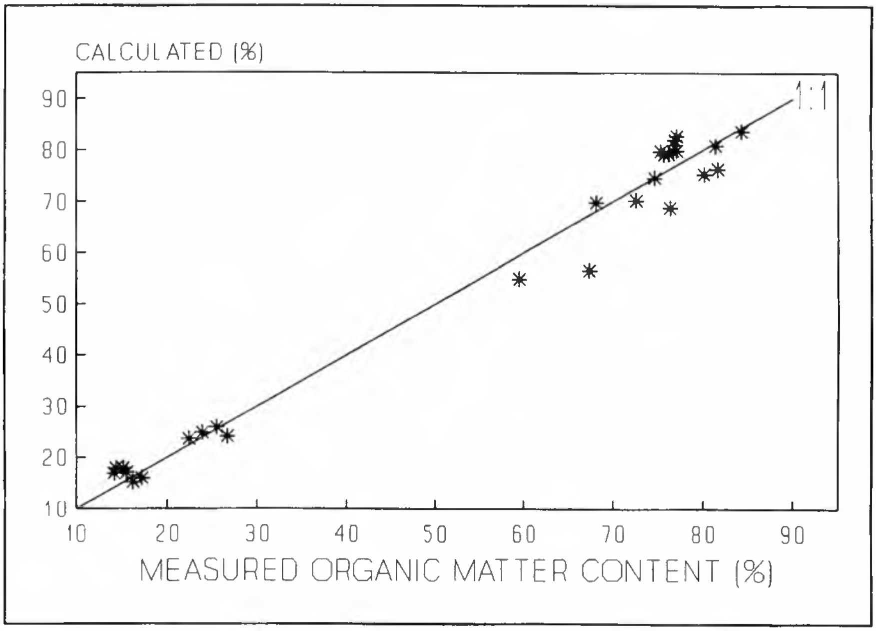


*Fig. 1.3. Soil organic matter calculated from ignition-loss versus measured values of some organic soils from various regions of Norway.*

The smaller correction for IGN-L in this equation, compared with those for mineral soils, is probably due to a lower loss of structurally-bound water from organic soils. The equation gives good estimation over a wide range of organic matter (Fig. 1.3).

## 2. Mean particle density

### 2.1 Background

Mean particle density is of little direct interest, but it is a necessary parameter, together with dry bulk density, for the calculation of the soil's total porosity. Mean particle density (MPD) varies primarily with organic matter content, since the particle density of SOM is 1.3 g/cm$^3$ as opposed to that of soil minerals, which is about twice this figure. Quartz and many minerals have particle densities around 2.65 g/cm$^3$, but micas and iron oxides have values around 3 and 4 g/cm$^3$, respectively.

MPD is commonly measured by means of water pycnometer, in which the density of soil particles is estimated by fluid displacement. It is known that this may give rise to overestimation of MPD in finely divided, active powders such as clay (Gradwell, 1955), due to the dipolar nature of water. For this reason, it was of interest to study the influence of clay content on measured values.

### 2.2 Material and methods

The dependence of MPD on IGN-L and clay content was studied in 538 soil samples collected in three districts of S.E. Norway (Ringsaker, Romerike and Solør), which are dominated by morainic loams, silty clays and silt soils respectively (Table 2.1).

MPD was measured according to the procedure described by Blake (1965), using 50 ml glass pycnometers. Seived (<2 mm) samples of oven-dry soil (approx. 10 g) were used, and air was removed from the pycnometer bottles by boiling in distilled water.

Table 2.1. Basic statistics of the samples used for calculating the dependence of mean particle density on the soil's ignition loss and clay content

| SOIL TYPE | MORAINIC LOAM | SILTY CLAY | SILT SOIL |
|---|---|---|---|
| No. samples | 176 | 192 | 170 |
| PARTICLE DENSITY (g cm$^{-3}$) | | | |
| Mean | 2.57 | 2.72 | 2.61 |
| Max. | 2.69 | 2.81 | 2.67 |
| Min. | 2.40 | 2.59 | 2.42 |
| Std.dev. | 0.58 | 0.49 | 0.50 |
| IGNITION LOSS (%) | | | |
| Mean | 11.1 | 4.2 | 5.0 |
| Max. | 20.6 | 8.0 | 9.4 |
| Min. | 5.7 | 1.2 | 2.4 |
| Std.dev. | 3.6 | 1.7 | 1.6 |
| CLAY CONTENT (%) | | | |
| Mean | 14 | 29 | 7 |
| Max. | 21 | 42 | 13 |
| Min. | 5 | 18 | 2 |
| Std.dev. | 3 | 6 | 3 |

## 2.3 Results

Simple regressions against IGN-L accounted for about 75-80% of the variation in MPD within individual soil types (Fig. 2.1). The relationships for clay and loam soil lay approximately in line with each other, whilst that for silt soils suggested lower MPD values at the same level of IGN-L. Regression of MPD against both IGN-L and clay content, for all three soil types together, resulted in equation (2.1), in which the inclusion of clay increased the amount of variance explained from 65% to 88%. Use of SOM, calculated according to equation (1.4), yielded equation (2.2), with the same $R^2$-value as for IGN-L.

(2.1) MPD = 2.66 - 0.014*IGN-L + 0.0041*CLAY (n=538, $R^2$=0.88, sey=0.013)

(2.2) MPD = 2.65 - 0.019*SOM + 0.0035*CLAY

A similar influence of clay content on measured MPD may be detected in data published for Finnish and Swedish soils (Heinonen 1954; Andersson & Wiklert 1972). In both cases values increased from around 2.67 on soils with low clay content to around 2.80 on heavy clay. Assuming that the influence of clay on measured results is caused by using water pycnometers, it is therefore logical to

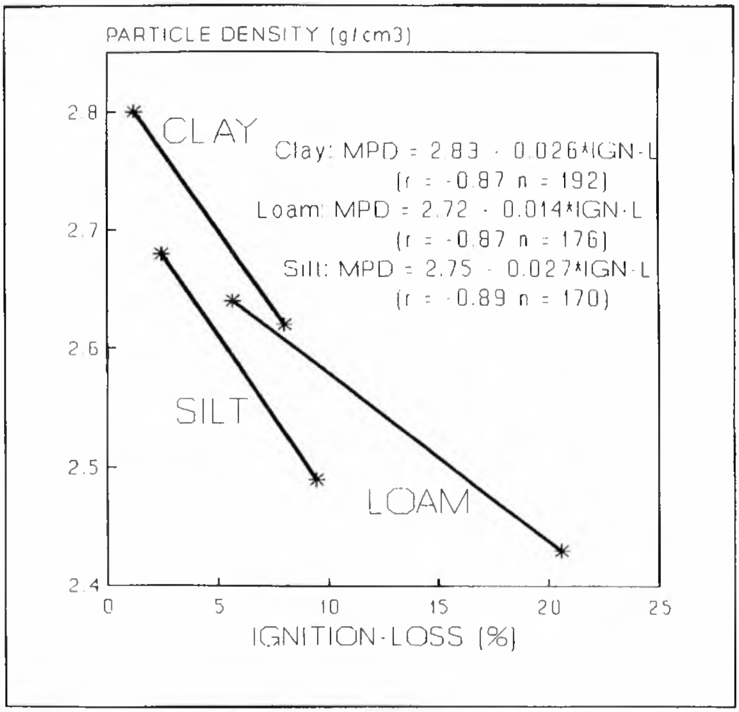


*Fig. 2.1. The relationship of mean particle density (MPD) to ignition-loss (IGN-L) for three soil types, calculated in each case for the range covered by regression equations.*

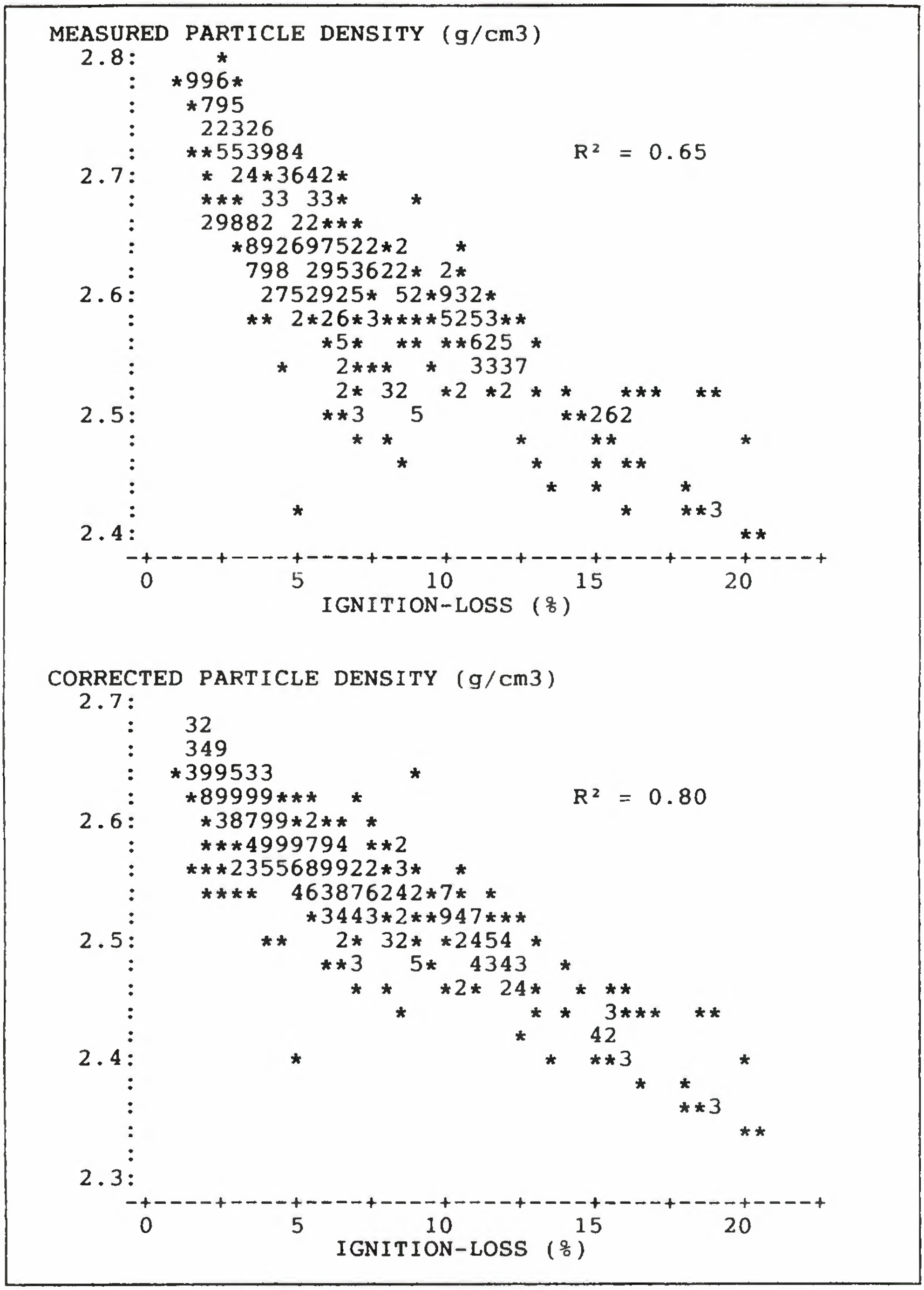


*Fig. 2.2. The relationship with ignition-loss of measured particle density (upper half) and particle density corrected for clay content as described in text (lower half).*

correct measured values by subtracting the clay term in equation (2.1).

The effect of such a correction on the relationship with IGN-L is illustrated in Fig. 2.2. (Note: numbers in this and other subsequent figures indicate the number of converging data points). Corrected data show considerably less scatter, and the MPD value for soil with low IGN-L is close to the reported value for most soil minerals (2.65).

# 3. Dry bulk density

## 3.1 Background

As mentioned under particle density, this parameter is required for the calculation of total porosity. It is also required for the expression of soil nutrient content in absolute terms, as in the calculation of mineral nitrogen levels in the soil profile, and in some cases for the estimation of soil moisture-holding capacity, as discussed in section 4, below. Moreover, it may be useful as a substitute for other, less readily available soil structure analyses, since it gives a rough indication of the soil's compaction status.

Besides compaction status, which is likely to be affected both by soil type and soil depth, dry bulk density (BD) is affected by the soil's content of both SOM and gravel.

## 3.2 Materials and methods

The relationship of BD with soil factors was examined in the material presented in section 4, which is derived from profile studies on a wide range of cultivated mineral soils throughout S.E. Norway, and for a smaller subset of cultivated humose and peaty soils. The data spread for topsoil (0-30 cm), upper subsoil (30-60 cm) and lower subsoil (60-90 cm) of the mineral soils is shown in Table 3.1. A dataset of 39 samples, taken from different depths, was used in the case of the organic soils.

## 3.3 Results

Linear regessions of BD against IGN-L within individual depth groupings of mineral soil gave only low $R^2$-values (0.12-0.45). The overall equation for all depths accounted for 49% using IGN-L and to 54% using SOM (either measured directly or calculated as described in section 4.1). Inclusion of gravel in the equation explained a further 10% of the variation in both cases. Smaller, but statistically highly significant, increases were found for the inclusion of sample depth, silt and clay content in equations (3.1) and (3.2). Sand content appeared to have little effect.

(3.1) BD = 1.534 - 0.046*IGN-L + 0.0067*GRAVEL + 0.0028*DEPTH(cm) - 0.0016*SILT + 0.0042*CLAY (n=961, $R^2$=0.69)

(3.2) BD = 1.522 - 0.065*SOM + 0.0064*GRAVEL + 0.0026*DEPTH(cm) - 0.0015*SILT + 0.0022*CLAY (n=961, $R^2$=0.70)

The positive effects of gravel and increasing depth were to be expected, whilst the negative effect of silt content reflects the higher water-holding capacity of such soils. The positive effect of clay content is less easy to explain, but may reflect the low air capacity often found in such soils. Similar effects of these variables have previously been found (Riley 1988) on the standard degree of compactness of topsoils (SDC), see equation (3.3). SDC is the dry bulk density of wet soil which has been subjected to a long-term, uniaxial, static load of 200 kPa, and is a parameter used as a reference for characterizing the state of compactness in soil compaction studies (Håkansson 1990).

(3.3) $SDC = 1.751 - 0.032*IGN\text{-}L - 0.0032*SILT + 0.0065*GRAVEL + 0.0029*CLAY$ ($n=29, R^2=0.79$)

Bulk density values calculated using equation (3.1) are given in Table 3.2 for several soil depths, using pertinent combinations of gravel, silt and clay content for some typical Norwegian soils. Corresponding data are also shown for the relative degree of compactness (RDC), calculated by dividing BD with values of SDC calculated from equation (3.3). RDC values were 81-89% of SDC for topsoil with high humus content, which is considered the optimal range for plant growth (Lipiec et al. 1991; Riley 1988) and 86-95% for topsoil with low humus content. Subsoil RDC values were consistently higher (93-102% at 45 cm and 98-108%

Table 3.1. Mean values and standard deviations of dry bulk density measured at different depths in four groupings[1] of soil. The number of samples in each grouping is shown in brackets

| Soil depth: | 0 - 30 cm mean | sd | 30 - 60 cm mean | sd | 60 - 90 cm mean | sd |
|---|---|---|---|---|---|---|
| SOIL GROUPING | | | | | | |
| COARSE SANDS/GRAVELS | 1.364 | 0.130 (72) | 1.657 | 0.151 (67) | 1.791 | 0.155 (27) |
| FINE SAND/SILTY SOIL | 1.272 | 0.162 (153) | 1.642 | 0.215 (131) | 1.702 | 0.216 (38) |
| LOAMS (15-25% CLAY) | 1.371 | 0.148 (190) | 1.641 | 0.204 (90) | 1.748 | 0.150 (33) |
| CLAYS ( >25% CLAY) | 1.415 | 0.136 (70) | 1.603 | 0.165 (64) | 1.634 | 0.197 (26) |

[1] See section 4.2 for description of grouping criteria.

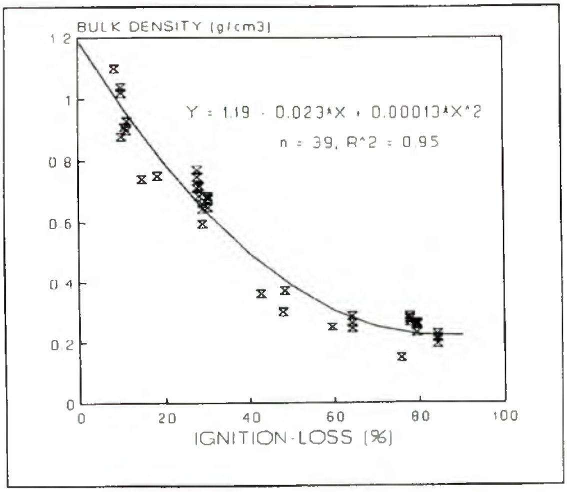


*Fig. 3.1. The decline of bulk density with increasing ignition-loss in some cultivated organic soils of southeast Norway.*

Table 3.2. Calculated values of dry bulk density for typical soil types of SE Norway, from the relationship with SOM, depth, gravel content[1] and textural composition, and corresponding data for the relative degree of compactness (in brackets).

| SOIL TYPE | TEXTURE Sand | Silt | Clay | DEPTH: 15 cm SOM: 5.5% | 15 cm 2.5% | 45 cm 1.1% | 75 cm 0.8% |
|---|---|---|---|---|---|---|---|
| SAND | 92 | 5 | 3 | 1.20 (81) | 1.40 (86) | 1.56 (93) | 1.66 (98) |
| GRAVELLY SAND | 92 | 5 | 3 | 1.36 (82) | 1.56 (87) | 1.73 (94) | 1.82 (98) |
| SILTY SAND | 67 | 30 | 3 | 1.17 (83) | 1.36 (89) | 1.53 (96) | 1.63 (101) |
| SANDY SILT | 30 | 65 | 5 | 1.12 (86) | 1.31 (92) | 1.48 (100) | 1.58 (105) |
| SILT | 5 | 90 | 5 | 1.08 (89) | 1.27 (95) | 1.44 (103) | 1.54 (108) |
| LOAM | 45 | 37 | 18 | 1.18 (84) | 1.38 (90) | 1.55 (97) | 1.65 (102) |
| GRAVELLY LOAM | 45 | 37 | 18 | 1.35 (86) | 1.54 (91) | 1.71 (97) | 1.81 (102) |
| SILTY LOAM | 15 | 67 | 18 | 1.14 (87) | 1.34 (93) | 1.51 (100) | 1.60 (106) |
| CLAY LOAM | 30 | 37 | 33 | 1.22 (85) | 1.41 (91) | 1.58 (98) | 1.68 (103) |
| SILTY CLAY LOAM | 10 | 57 | 33 | 1.19 (87) | 1.38 (93) | 1.55 (100) | 1.65 (105) |
| HEAVY CLAY | 5 | 45 | 50 | 1.24 (87) | 1.44 (92) | 1.61 (99) | 1.71 (104) |

[1] 25% gravel assumed in gravelly sand and gravelly loam.

at 75 cm). In the case of the organic soils, BD showed an almost linear decline with increasing IGN-L up to around 50%, but smaller decreases thereafter. A quadratic function accounted for 95% of the variation in the dataset (Fig. 3.1). The curvilinear effect probably reflects differences in the degree of humification. The relationship found here agrees closely with values quoted for Danish conditions by Østergaard & Mamsen (1990).

# 4. Soil porosity and moisture retention

## 4.1 Background

Soil porosity and moisture retention properties are fundamental to the productivity of agricultural ecosystems, and at a larger scale to the hydrology of whole catchments. Basic data on these properties are required for many purposes, such as irrigation planning and scheduling, run-off calculation and prediction, flood warning, pollutant transport etc. Soil porosity is closely linked with bulk density (section 3), and is dominantly affected by the soil's compaction status. Moisture retention is affected both by soil texture and by the way soil particles are aggregated.

A previous study (Riley 1979) presented regression equations for the dependence of porosity and moisture retention on the soil's bulk density, organic matter content and soil texture, derived from some 60 soil profiles, dominantly from the counties of Hedmark and Oppland. Whilst these equations gave relatively good prediction, particularly for loam soils, it was concluded that more data was required for sandy, silty and clayey soils.

The present study uses data collected in connection with soil profile investigations over the period 1979-1993. It includes data for 961 soil horizons from about 250 whole profile studies, representing most of the common soil types found in southeast Norway. Permission to include the data of Haraldsen et al. (1994) and Sveistrup et al. (1994), comprising 100 soil horizons, is gratefully acknowledged. The data previously used by Riley (1979) is not included in the present dataset, but is used for verification purposes. Results for organic soils are presented separately, based on the dataset of 39 samples mentioned in section 3.

Different approaches have been adopted in previous studies to derive information on pore size distribution from basic soil properties. The use of multiple regression, as mentioned above, has been common (e.g. Gupta & Larson 1979, Rawls & Brakensiek 1982, Riley 1979). Such methods are useful aids to the understanding of relationships, but may have limitations for use in practice (see Jonasson 1991). They are probably of most use for the prediction of specific pore size intervals (e.g. available water capacity or air capacity). Other methods have been proposed for the estimation of the whole moisture retention curve from single equations (e.g. Brooks & Corey 1964, van Genuchten 1980), which are useful in connection with calculations of unsaturated hydraulic conductivity. A method for deriving parameters for the van Genuchten equation was proposed by Jonasson (1991). Standard stepwise multiple regression is used in the present study, but it is planned to make use of the latter methods in a future publication.

## 4.2 Materials and methods

An outline of the origin and nature of the soil samples, grouped according to municipality or region, is given in Table 4.1, and the spread of data within the Norwegian soil textural triangle (Sveistrup & Njøs 1984), is shown in Fig. 4.1. The most frequent soil types are light clays of morainic origin, but most of the other soil types are represented about equally for both topsoil and subsoil. The low number of sandy clays and heavier clays reflects the smaller distribution of such soils in Norway (Njøs & Sveistrup 1977). This may be attributed to the juvenility of soils in this region.

Table 4.1. Geographical origin and nature of parent material of the soil samples used to determine moisture retention properties

| Municipality or region | Number of profiles | Dominant soil types | Parent material |
|---|---|---|---|
| Nes på Hedmark | 82 | Light clay, sand | Morainic till |
| Stange | 5 | " " " | " " |
| Østre Toten | 24 | " " " | " " |
| Solør | 27 | Silt, silty sand | Alluvial deposits |
| Romerike | 17 | Silty medium clay | Marine deposits |
| Ås | 36 | " " " | " " |
| Vestfold | 4 | Sand, silty sand | End moraine |
| Aust-Agder | 36 | Sand, light clay | Alluvium, moraine |
| Gudbrandsdal | 15 | Silt, light clay | " " |

Undisturbed soil samples were taken by excavating 100 $cm^3$ steel cylinders pressed into the profile wall. Three cores were normally taken per sample, but the number varied from two to four in some cases. Horizons were sampled at 10-15 cm depth intervals, down to the limit of rooting depth (min. 50 cm and max. 90 cm).

In the laboratory samples were saturated from below for 2-4 days, weighed and placed on ceramic plates in standard equipment supplied by Soil Moisture Inc. Water retention was measured by weighing after equilibration (2 to 4 weeks) at various pressures up to 300 kPa. Pressures of 10 and 100 kPa (equivalent to pF 2 and pF 3) were used in all cases, whilst pressures of 2 and 300 kPa (equivalent to pF 1.3 and pF 3.5) were included in 33% and 11% of all cases, respectively. The pF scale is used hereafter, in addition to expressing suction in kPa, in conformity with common practice in Norway.

Core samples were dried at 105° C, weighed for bulk density determination and thereafter sieved (<2 mm). Gravel contents were weighed and the cores from each horizon were bulked for determination of permanent wilting point (1500 kPa, pF 4.2), using subsamples of about 10 g soil in pressure membrane apparatus. A correction for gravel content was made as described by Riley (1979), assuming zero water retention in gravel at this tension.

Mechanical analysis was performed by means of the pipette method of Elonen (1971), using the Atterberg limits for particle size distribution. This method was found, in a comparison of samples with widely varying texture, to give slightly higher clay and lower silt contents than the hydrometer method previously used at Kise (Riley, unpublished). It is deemed more accurate since it does not entail the matching of two summation curves.

Ignition-loss was measured by combustion of sieved material at 550 °C for two hours, and converted to organic matter contents (except where this had been measured directly) by means of equation (1.4). This gave negative values in 30 cases, for which equation 1.5 was applied. Eleven remaining negative values were set to zero organic matter. Equation (1.3), derived for soils from SE Norway alone, was not used, as it gave many more negative values than equation (1.4). The overall mean values were however similar for all soil types with either method of calculation.

Soil porosity was both estimated as

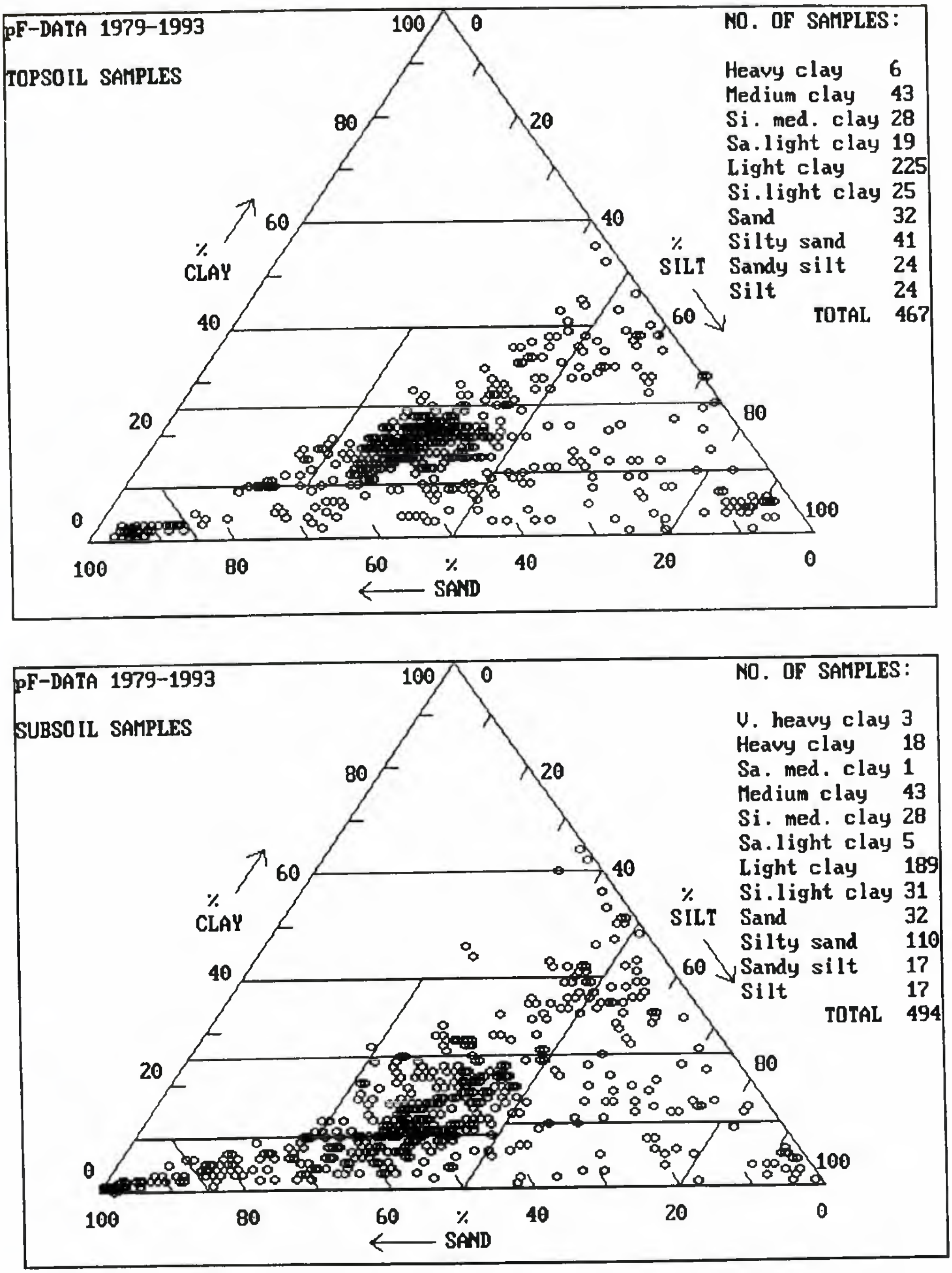


*Fig. 4.1. Distribution within the Norwegian textural triangle of the soil samples used in moisture retention analyses.*

water content at saturation (saturation capacity) and calculated using measured bulk density and mean particle density estimated as described in section 2.3, with the inclusion of a correction for gravel content. For those samples on which measurements at pF 1.3 and pF 3.5 were not made, water contents were calculated from relationships found for the samples with measurements. These included a representantive selection of most soil types:

(4.1) VOL% pF1.3 = 20.4 + 0.83* VOL% pF2 - 7.6 BD ($n = 317$, $R^2 = 0.96$)

(4.2) VOL% pF3.5 = 0.78* VOL% pF3 - 0.032*%SILT + 0.19* %CLAY - 0.63 ($n = 103$, $R^2 = 0.92$)

In both cases the nearest measured point on the retention curve was used, as well as those variables considered most likely to affect results. All the variables included gave significant increases in the variance accounted for. Equation (4.1) reflects the reduction in large pores which is found on soil compaction whilst equation (4.2) reflects the effect of texture on the shape of the pF curve. The ability of these equations to predict actual values is demonstrated in Fig. 4.2.

Air capacities at pF 1.3 and 2 were calculated by subtraction of the respective water contents from saturation capacity (calculated porosities were not used as they were found to give negative values in some cases). Physically available water capacity (AWC) was calculated as that held between pF 2 and 4.2. The former value has been found to give a good representation of field capacity in the region (Riley 1989). A further distinction was made at pF 3, between readily available and more weakly available water. This corresponds roughly with the lower limit of water extraction by roots in deeper subsoil layers (Andersen 1986, Madsen & Platou 1983, Riley 1989).

For the purposes of data presentation and subsequent statistical analyses, a grouping of data was adopted. This was based on considerations of obtaining a manageable number of relatively similar soil types with an adequate number of samples in each grouping for meaningful conclusions to be drawn. A higher value of clay (15%) clay was chosen as the division between loamy soils and sandy/silty soils than the value (10%) used in the Norwegian textural triangle. This gave a better distribution of samples within groups, and corresponds with the classifications used previously in Norway and elsewhere in Scandinavia (Heinonen 1975, Landbruksministeriet 1976, Låg 1975).

**COARSE SANDY SOILS:**
(abbreviated to «SAND»)
Clay content less than 15% of fine earth (<2 mm)
Gravel + coarse sand + medium sand > fine sand + silt

**SILTY/FINE SANDY SOILS:**
(abbreviated to «SILT»)
Clay content less than 15% of fine earth (<2 mm)
Fine sand + silt > gravel + coarse sand + medium sand

**LOAMY SOILS:**
(abbreviated to «LOAM»)
Clay content 15-25% of fine earth (<2 mm)

**CLAYS/SILTY CLAY SOILS:**
(abbreviated to «CLAY»)
Clay content greater than 25% of fine earth (<2 mm)

Mean grain size distributions of fine

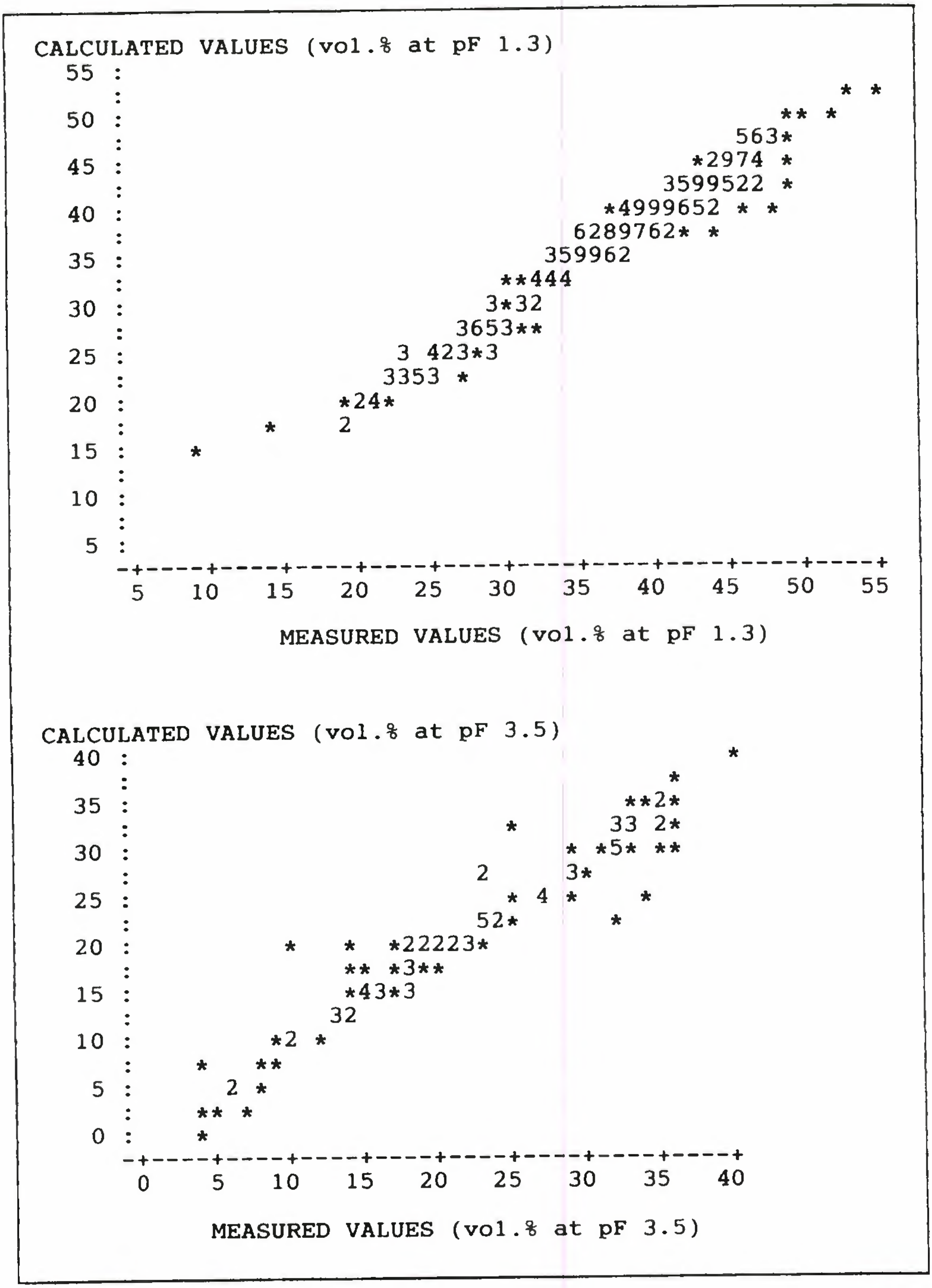


*Fig. 4.2. Calculated versus measured values for soil water content (vol. %) at pF values of 1.3 and 3.5.*

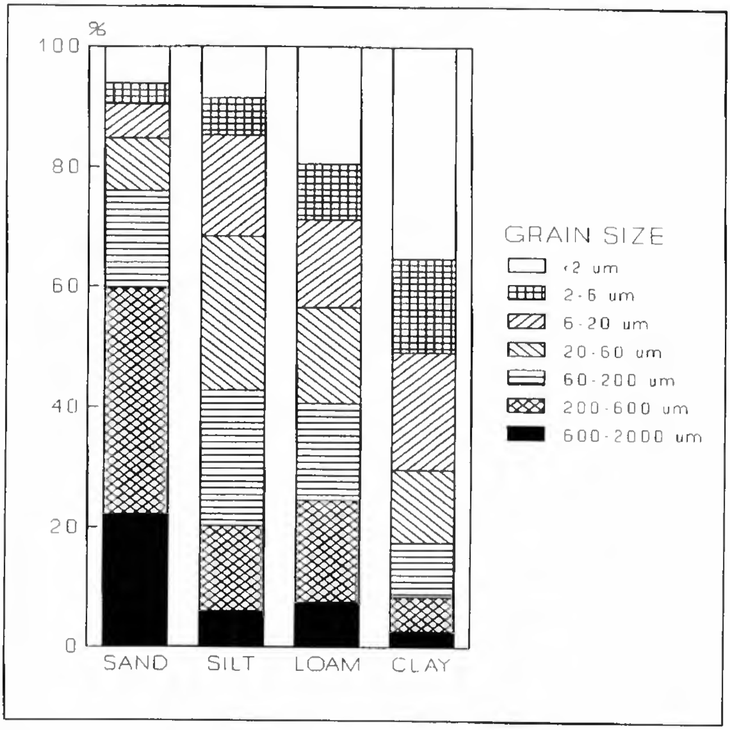


*Fig. 4.3. Mean grain size distribution of fine earth in the four soil groupings used in the statistical analysis.*

Table 4.2. Number of samples, soil organic matter and textural composition of soil groupings used in the statistical analysis

| SOIL GROUP | DEPTH cm | SAMPLE NUMBER | S.O.M. mean | S.O.M. sd | GRAVEL mean | GRAVEL sd | SAND mean | SAND sd | SILT mean | SILT sd | CLAY mean | CLAY sd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SAND | 0-30 | 72 | 3.7 | 1.7 | 14 | 9 | 75 | 16 | 18 | 11 | 7 | 5 |
| | 30-60 | 67 | 1.2 | 0.7 | 26 | 13 | 77 | 13 | 17 | 10 | 6 | 4 |
| | 60-90 | 27 | 0.8 | 0.7 | 22 | 11 | 74 | 15 | 21 | 12 | 5 | 4 |
| SILT | 0-30 | 135 | 4.0 | 2.3 | 7 | 8 | 37 | 20 | 54 | 21 | 9 | 4 |
| | 30-60 | 144 | 0.9 | 1.1 | 10 | 8 | 46 | 20 | 46 | 20 | 8 | 4 |
| | 60-90 | 43 | 0.6 | 0.7 | 10 | 8 | 49 | 23 | 43 | 22 | 8 | 4 |
| LOAM | 0-30 | 190 | 4.5 | 1.8 | 12 | 8 | 43 | 10 | 38 | 9 | 19 | 2 |
| | 30-60 | 90 | 1.2 | 1.0 | 10 | 8 | 38 | 12 | 43 | 12 | 19 | 3 |
| | 60-90 | 33 | 0.9 | 1.1 | 11 | 7 | 37 | 10 | 43 | 10 | 19 | 3 |
| CLAY | 0-30 | 70 | 2.9 | 1.8 | 3 | 4 | 17 | 11 | 49 | 8 | 34 | 6 |
| | 30-60 | 64 | 0.7 | 0.5 | 5 | 6 | 17 | 12 | 47 | 9 | 36 | 7 |
| | 60-90 | 26 | 0.7 | 1.0 | 5 | 5 | 19 | 14 | 44 | 8 | 38 | 11 |

earth for each soil group are shown in Fig. 4.3. The data were further grouped into three depth intervals (0-30 cm, 30-60 cm and 60-90 cm). The number of samples in each subgroup are shown in Table 4.2, together with means and standard deviations for textural composition. Loamy and silty soils were represented with over 300 samples each, whilst sandy and clayey soils had about 160 samples each. There were approximately equal numbers of topsoil and subsoil samples in all four soil groups.

## 4.3 Results for mineral soils

### *4.3.1 Data description and variability*

The mean pore size distribution for each soil group is shown in Fig. 4.4. There was in all cases a marked difference in total porosity between topsoil and subsoil, and smaller differences between the two subsoil depth groups. Data for the latter two groups were therefore combined in later calculations.

Sandy soils had the lowest total porosity. Silty soils had highest porosity in the topsoil, whilst in the subsoil this was true of clay soils. Air capacity (0-10 kPa, or pore size >30μm) was highest in sandy soils and lowest in clay soils, as expected. Available water capacity (10-1500 kPa, or pore size 0.2-30 μm) was highest in silty soils, somewhat lower in loams and lowest in both clays and sands. The amount of non-available water (1500 kPa, or pore size <0.2 μm) was highest for clays, followed by loams. It increased with depth in both these soil groups, whereas it decreased with depth on sandy and silty soils. This may be explained by a differential effect of organic matter between soils on aggregate formation, as suggested by Riley (1986).

Average pF-curves for the four soil groups are shown in Fig. 4.5.

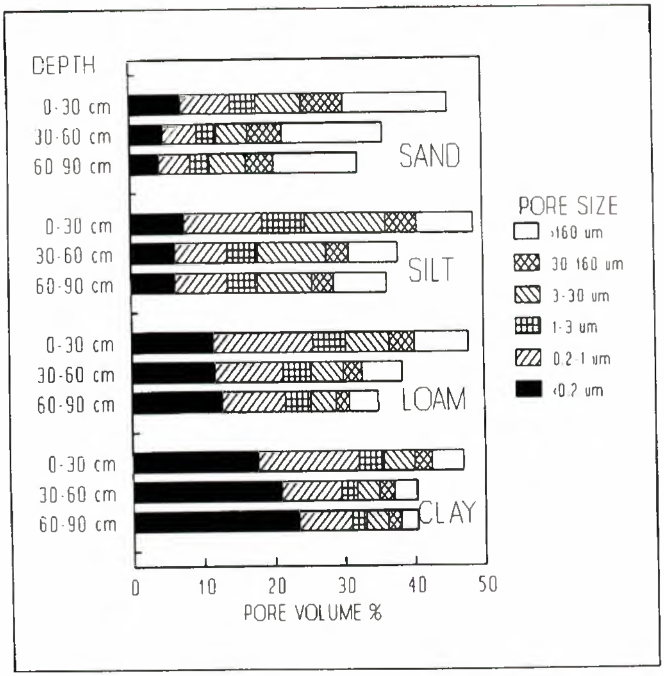


*Fig. 4.4. Mean pore size distribution of the soil groups used in the statistical analysis.*

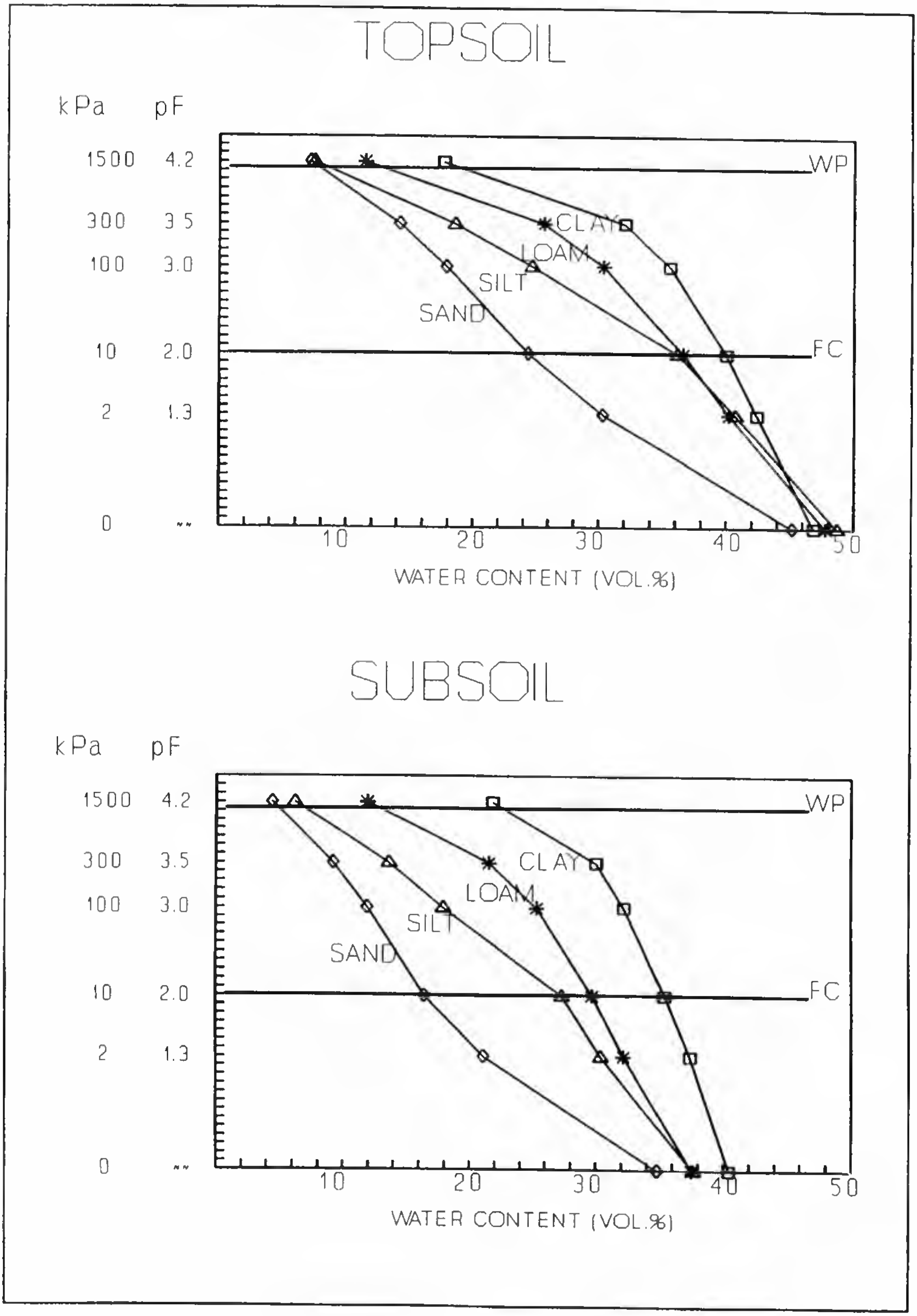


*Fig 4.5. Moisture retention curves based on mean data for topsoil (0-30 cm) and subsoil (30-90 cm) of four soil groups.*

The variability within soil groups of the moisture content at different tensions, and of the various pore size groupings, is expressed by their coefficients of variation (Table 4.3). Approximately the same degree of variability was found in all soil groups, and it was in all cases higher in subsoils than in topsoils. Lowest variability was found for total porosity and moisture content at low tensions. Highest variability was found for air capacity (0-2 and 0-10 kPa) and readily available water capacity (10-100 kPa), which are the pore size groupings with a dominant influence on transport properties. The coefficients of variation for pooled horizons (not shown) were similar to, or slightly higher than, the figures for subsoils alone.

An important consideration in the use of soil physical data is that of the degree of spatial variation which may be encountered. This affects both the number of samples which are required in order to determine a particular parametre, and also the size of area for which results are likely to be valid. A pioneering study of such variability under Norwegian conditions was made by Høstmark (1994), which included data from the same region as this study. Little consideration is given to this topic in the present work. It is planned, however, to address this matter in a later paper.

Principal component analysis of the datasets for topsoil and subsoil, including both pore size distribution and textural composition of all soil groups, explained about 90% of the total variance in terms of four factors. There was a marked similarity in these factors at both soil depths. The variables with the highest loadings are summarized in Table 4.4. The first factor includes the influence of sand content on moisture holding capacity, whilst the second contains a combined effect of clay content and increasing bulk density. The third factor reflects opposite influences of silt content and SOM/clay, and the fourth, which shows a smaller, additional effect of SOM and of gravel content, is probably related to the morainic loamy soils.

Table 4.3. Coefficients of variation (%) for soil moisture content and pore size groupings in topsoil and subsoil of four soil groups

| | SAND | | SILT | | LOAM | | CLAY | |
|---|---|---|---|---|---|---|---|---|
| | Top. | Sub. | Top. | Sub. | Top. | Sub. | Top. | Sub. |
| Porosity | 10 | 17 | 11 | 22 | 12 | 20 | 11 | 17 |
| Vol% satn. | 9 | 14 | 10 | 21 | 9 | 17 | 10 | 15 |
| " 2 kPa | 20 | 22 | 14 | 24 | 12 | 17 | 8 | 15 |
| " 10 kPa | 25 | 34 | 17 | 28 | 13 | 19 | 8 | 16 |
| " 100 kPa | 32 | 40 | 25 | 32 | 12 | 15 | 7 | 17 |
| " 300 kPa | 35 | 45 | 30 | 38 | 13 | 15 | 9 | 18 |
| " 1500 kPa | 31 | 50 | 36 | 48 | 23 | 24 | 22 | 23 |
| 0-2 kPa | 34 | 47 | 61 | 61 | 49 | 57 | 67 | 67 |
| 0-10 kPa | 28 | 43 | 47 | 55 | 42 | 49 | 57 | 52 |
| 10-100 kPa | 31 | 44 | 50 | 89 | 31 | 57 | 34 | 59 |
| 100-1500 kPa | 39 | 41 | 31 | 35 | 20 | 32 | 24 | 46 |
| 10-1500 kPa | 28 | 34 | 23 | 41 | 19 | 35 | 25 | 39 |

Table 4.4. Variables with the highest loadings on factors found by principal component analysis of topsoil and subsoil data, including all four soil groups

| Factor no. | 1 | 2 | 3 | 4 | Sum |
|---|---|---|---|---|---|
| % variance | | | | | |
| Topsoil | 44 | 25 | 15 | 6 | 90 |
| Subsoil | 46 | 26 | 12 | 7 | 91 |
| Positively loaded variables | Sand<br>Air cap.<br>Gravel | Clay<br>BD<br>pF 4.2 | Silt<br>pF 2-3<br>pF 2-4.2 | pF 4.2 | |
| Negatively loaded variables | pF 1.3<br>pF 2.0<br>pF 3.0<br>pF 3.5<br>Total AWC | Porosity<br>Air cap.<br>pF 2-3<br>SOM | SOM<br>Clay<br>Vol% satn.<br>Air cap.<br>pF 3.5<br>pF 4.2 | SOM<br>Gravel<br>pF 3-4.2<br>Sand | |
| Main trend | Sand/ moisture | Clay+BD/ porosity | Silt/ SOM+clay | SOM+gravel | |

### *4.3.2 Regression equations*

Several considerations are important when selecting a multiple regression equation for prediction purposes. Firstly, the equation should give a good explanation of the data variability. This is often expressed by the coefficient of determination ($R^2$).

However, if the variance in the dataset is large, a high $R^2$ value does not necessarily imply good prediction. The standard error of prediction should therefore also be examined. Secondly, for ease of use, the equation should preferably contain as few variables as possible. Sometimes additional variables, even if statistically significant, give very little extra precision. At worst, they may give illogical effects, due to intercorrelations with other variables. Finally, one must remember that the automatic selection of a variable by a stepwise procedure need not imply a causal relationship. For example, the effect of bulk density may sometimes be confounded with that of SOM. In practice the inclusion of bulk density may be undesirable, since data for this parameter is seldom readily available.

The efficiency of equations selected by stepwise multiple regression is shown in Table 4.5 for various groupings of soil. There was wide variation in the amount of variance accounted for (40-90%) and in standard errors of prediction (5-60% of mean). Equations for total porosity and water contents at tensions below 300 kPa have the lowest relative errors of prediction, whereas those for readily available water (10-100 kPa) have the highest. Better prediction was often found in equations for individual soil groups than for all soils taken together, despite somewhat higher $R^2$ values in the latter case. Grouping all topsoils and all subsoils separately gave somewhat better prediction than use of pooled data, and was approximately equally as efficient as using the different soil groups. Separate equations for different depths within soil groups were derived for total AWC, but, as similar equations were found at both depths in most cases, the remaining calculations were performed using pooled data for each soil group and for groupings of all topsoils and all subsoils.

Table 4.6 shows the amount of variance explained by the variables included in the equations for total porosity and water content at different tensions, together with an indication of their direction of influence (positive or negative). The full equations are given in Appendix I. A similar presentation for air capacity and plant-available water fractions and total capacity is given in Table 4.7 and Appendix II. Variable selection was on the whole

Table 4.5. The efficiency of multiple regression equations relating soil moisture content and pore size groupings to texture, bulk density and organic matter content

| | Sand soil | Silt soil | Loam soil | Clay soil | Top-soils | Sub-soils | All soils |
|---|---|---|---|---|---|---|---|
| | COEFFICIENTS OF DETERMINATION ($R^2 \cdot 100$) | | | | | | |
| Porosity | 64 | 74 | 71 | 65 | 59 | 36 | 63 |
| Vol% satn. | 70 | 70 | 72 | 70 | 59 | 43 | 66 |
| " 2 kPa | 84 | 87 | 82 | 86 | 76 | 87 | 86 |
| " 10 kPa | 82 | 83 | 72 | 80 | 76 | 86 | 83 |
| " 100 kPa | 86 | 69 | 66 | 70 | 80 | 84 | 84 |
| " 300 kPa | 88 | 72 | 65 | 74 | 85 | 90 | 88 |
| " 1500 kPa | 78 | 66 | 36 | 70 | 78 | 91 | 83 |
| 0-2 kPa | 71 | 60 | 47 | 57 | 65 | 78 | 70 |
| 0-10 kPa | 78 | 69 | 58 | 64 | 72 | 83 | 76 |
| 10-100 kPa | 49 | 76 | 60 | 54 | 64 | 65 | 63 |
| 100-1500 kPa | 73 | 56 | 51 | 67 | 44 | 38 | 82 |
| 10-1500 kPa | 69 | 86 | 63 | 78 | 61 | 76 | 72 |
| | STANDARD ERRORS OF PREDICTION (% of mean) | | | | | | |
| Porosity | 12 | 12 | 10 | 10 | 8 | 16 | 12 |
| Vol% satn. | 10 | 11 | 9 | 8 | 6 | 14 | 11 |
| " 2 kPa | 11 | 9 | 7 | 5 | 8 | 9 | 9 |
| " 10 kPa | 15 | 11 | 9 | 6 | 10 | 12 | 12 |
| " 100 kPa | 16 | 19 | 9 | 8 | 12 | 16 | 14 |
| " 300 kPa | 16 | 20 | 10 | 7 | 12 | 15 | 14 |
| " 1500 kPa | 22 | 26 | 19 | 14 | 20 | 21 | 23 |
| 0-2 kPa | 23 | 39 | 40 | 46 | 37 | 36 | 38 |
| 0-10 kPa | 18 | 29 | 31 | 35 | 28 | 28 | 29 |
| 10-100 kPa | 30 | 36 | 27 | 34 | 35 | 58 | 48 |
| 100-1500 kPa | 23 | 26 | 20 | 25 | 23 | 33 | 28 |
| 10-1500 kPa | 20 | 14 | 18 | 19 | 17 | 22 | 21 |

Table 4.6. The amount of variance (%) explained by variables selected by stepwise multiple regression, and their influence (+ = positive, - = negative) on porosity and moisture content

| Dependent variable | Soil group | GRA-VEL | SAND | SILT | CLAY | SOM | BD |
|---|---|---|---|---|---|---|---|
| Total porosity | SAND | 13 - | 3 - | 5 - | | 43 + | |
| | SILT | 19 - | | 2 + | | 50 + | |
| | LOAM | 1 - | | 9 + | | 61 + | |
| | CLAY | | 22 - | | | 43 + | |
| | TOP. | 4 - | | 11 + | 7 - | 37 + | |
| | SUB. | 20 - | | | | | |
| Vol% at satn. | SAND | 12 - | 3 - | 2 - | | 53 + | |
| | SILT | 22 - | | 3 + | 3 - | 42 + | |
| | LOAM | 2 - | 6 - | | | 64 + | |
| | CLAY | 3 - | 19 - | | | 51 + | |
| | TOP. | 4 - | | 9 + | | 46 + | |
| | SUB. | 23 - | 2 - | | | 18 + | |
| Vol% at | SAND | 11 - | | 14 + | 1 + | 57 + | 1 - |
| 2 kPa | SILT | <1 - | 20 - | | | <1 + | 66 - |
| | LOAM | 9 - | | | <1 + | 4 + | 68 - |
| (pF 1.3) | CLAY | 3 - | | | 8 + | 2 + | 73 - |
| | TOP. | 8 - | 45 - | | | 23 + | • |
| | SUB. | 1 - | 69 - | | | 1 + | 16 - |
| Vol% at | SAND | 7 - | | 26 + | 1 + | 48 + | |
| 10 kPa | SILT | 1 - | | 61 + | | 2 + | 19 - |
| | LOAM | 15 - | | | 1 + | 6 + | 50 - |
| (pF 2.0) | CLAY | 5 - | | 12 + | | 3 + | 60 - |
| | TOP. | 7 - | 53 - | | | 13 + | 3 + |
| | SUB. | 1 - | 77 - | | | 2 + | 6 - |
| Vol% at | SAND | 6 - | | 2 + | 61 + | 16 + | 1 + |
| 100 kPa | SILT | 2 - | 2 - | | 49 + | 18 + | 1 + |
| | LOAM | 29 - | | | 5 + | 32 + | |
| (pF 3.0) | CLAY | 9 - | | | 21 + | 3 + | 37 - |
| | TOP. | 3 - | | 6 + | 58 + | 9 + | 4 + |
| | SUB. | 1 - | 6 - | | 74 + | 2 + | 1 + |
| Vol% at | SAND | 3 - | | 1 + | 68 + | 14 + | 2 + |
| 300 kPa | SILT | 2 - | 2 - | | 49 + | 18 + | 1 + |
| | LOAM | 22 - | <1 - | | 11 + | 31 + | |
| (pF 3.5) | CLAY | 5 - | | 1 + | 48 + | 2 + | 18 - |
| | TOP. | 2 - | | 1 + | 74 + | 6 + | 2 + |
| | SUB. | 1 - | 1 - | | 86 + | 1 + | 1 + |
| Vol% at | SAND | 7 - | | | 17 + | 49 + | 5 + |
| 1500 kPa | SILT | | | | 52 + | 7 + | 7 + |
| | LOAM | 3 - | | | 22 + | 7 + | 4 + |
| (pF 4.2) | CLAY | 3 - | | | 56 + | | 12 + |
| | TOP. | 1 - | | | 74 + | 1 + | 2 + |
| | SUB. | <1 - | | | 90 + | | 1 + |

similar for all soil groups and in both topsoil and subsoil. The relative importance of variables for moisture content varied between tension levels. Soil organic matter (SOM) showed a positive effect at all levels, whilst gravel had a negative effect at all levels. Silt and sand, which have opposite effects, were most important for moisture content around field capacity, whereas the influence of clay increased sharply with tension. Increasing bulk density (BD) was found to have a negative effect on water content at low tensions and a positive effect at higher tensions.

Air capacities were positively related to sand and gravel contents, and negatively related to BD, as expected. They were also negatively related to SOM on all but clay soils. This somewhat unexpected effect of SOM may be explained by its having a greater effect on moisture content than on total porosity. A similar finding in another data set was reported by Riley et al. (1990). Silt and clay appeared also to have negative effects on air capacity in some cases. Available water capacity (AWC) was dominantly

Table 4.7. The amount of variance (%) explained by variables selected by stepwise multiple regression, and their influence (+ = positive, - = negative) on air capacity and available water

| Dependent variable | Soil group | GRAVEL | SAND | SILT | CLAY | SOM | BD |
|---|---|---|---|---|---|---|---|
| Air capacity at 2 kPa | SAND | 5 + | | 50 - | | 5 - | 11 - |
| | SILT | 2 + | 25 + | | | 5 - | 28 - |
| | LOAM | 21 + | | | | 5 - | 21 - |
| | CLAY | 25 + | | | 6 - | | 26 - |
| (pF 1.3) | TOP. | 10 + | 41 + | 1 - | | 4 - | 8 - |
| | SUB. | 2 + | 51 + | | | 1 - | 14 - |
| Air capacity at 10 kPa | SAND | 4 + | | 50 - | | 6 - | 18 - |
| | SILT | 2 + | 23 + | | | 3 - | 41 - |
| | LOAM | 20 + | | | | 5 - | 33 - |
| | CLAY | 25 + | | | 5 - | | 34 - |
| (pF 2.0) | TOP. | 9 + | 42 + | 1 - | | 5 - | 15 - |
| | SUB. | 1 + | 51 + | | | 1 - | 29 - |
| Readily available water | SAND | 3 - | | 10 + | 21 - | 2 + | 13 - |
| | SILT | | 28 + | 40 + | | 4 - | 4 - |
| | LOAM | 4 - | | | 3 - | | 54 - |
| | CLAY | | 9 + | | | | 45 - |
| (pF 2-3) | TOP. | 1 - | | 33 + | 28 - | | 2 - |
| | SUB. | | | 23 + | 26 - | 2 - | 14 - |
| Weakly available water | SAND | 2 - | | 4 + | 57 + | 10 + | |
| | SILT | 3 - | 18 - | 6 - | | 29 + | |
| | LOAM | 10 - | | | | 2 + | 39 - |
| | CLAY | | | 2 + | 8 - | 2 + | 54 - |
| (pF 3-4.2) | TOP. | 3 - | 24 - | | | 14 + | 3 + |
| | SUB. | 1 - | | 26 + | | 11 + | |
| Total available water | SAND | 6 - | | 40 + | | 23 + | |
| | SILT | 1 - | | 65 + | 3 - | | 17 - |
| | LOAM | 10 - | | | <1 - | <1 + | 52 - |
| | CLAY | 2 - | | | 19 - | 2 + | 65 - |
| (pF 2-4.2) | TOP. | 4 - | | 43 + | 3 - | 11 + | |
| | SUB. | 1 - | | 46 + | 14 - | <1 + | 15 - |

effected by silt and SOM, both in a positive direction, whilst gravel and BD both showed negative effects. Sand content showed a positive effect on the readily available fraction in silt and clay soils, whilst clay content showed a negative effect on this fraction in sand and loam soils.

The exclusion of BD from equations, on the grounds that data for this variable are hard to come by, considerably increased the apparent effect of SOM, but at the same time reduced the prediction efficiency of the equations somewhat. The effect of BD per se is probably important for air capacity, whilst for moisture capacity it may be reasonable to assume that it is to a large extent intercorrelated with an opposite effect of SOM. Additional equations for total AWC, without the use of BD, are therefore included in Appendix II.

*4.3.3 Independent equation validation*

The independent dataset used by Riley (1979), comprising observations from 124 soil horizons, was used as a reference for validating some of the regression equations presented above. This dataset includes a wide range of data for sandy, silty and loamy soils, but very little data for clay soils (Fig. 4.6).

Calculations were made for water content at four tension levels (0, 10, 100 and 1500 kPa), as well as for air capacity (0-10 kPa) and total available water capacity (10-1500 kPa). The use of separate equations for each soil grouping, irrespective of soil horizon, was compared with the use of separate equations for topsoil and subsoil, irrespective of soil grouping. Both procedures gave reasonably good results, as judged by the amount of variance accounted for (Table 4.8). On this criterion, the data fit was in most cases almost as good as that obtained with the

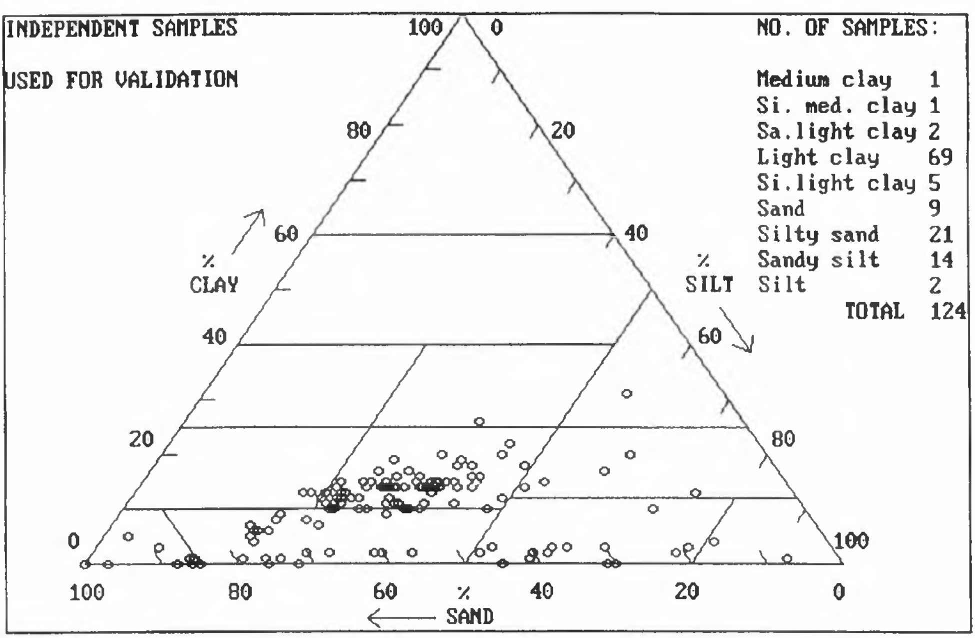


*Fig. 4.6. Plotting within textural triangle of samples used for independent validation of equations derived in the present study. The independent data are from Riley (1979).*

original data from which the equations were derived. The equations for water content at saturation appeared to underestimate this parameter somewhat, but otherwise the estimations showed little consistent bias. This is illustrated in Fig 4.7, using the equations for individual soil groupings. The reason for the poorer agreement for water content at saturation is not clear, but it may reflect differences in sampling technique. This can affect the degree of sample disturbance, and hence the total porosity. The technique used in the present study was thought to give minimal disturbance, and the total porosity data presented here may therefore be assumed to be correct.

### *4.3.4 Predictions for common soil types*

Predicted values of air capacity, total AWC and wilting point are given in Tables 4.9-4.11 for eleven common soil types, at varying levels of SOM and BD (in the same manner as in Table 3.2, and assuming the BD-values given in that table). The predictions by the two different sets of equations were in most cases fairly similar. Exceptions were found in the case of loam and clay loam soils, for which separate soil group equations gave lower air capacity and higher AWC values than separate horizon equations.

Table 4.8. Coeffients of determination (%) of some regression equations in tests against independently measured data, using two altrnative methods of calculation[1]. Figures in brackets are the average CD-values found for these equations using the original datasets from which they were derived (see Table 4.5)

| | CALC. METHOD I | CALC. METHOD II |
|---|---|---|
| Vol% at satn. | 47 (51) | 54 (71) |
| Vol% at 10 kPa | 76 (81) | 69 (79) |
| Vol% at 100 kPa | 84 (82) | 80 (73) |
| Vol% at 1500 kPa | 78 (85) | 79 (63) |
| Air cap. at 10 kPa | 77 (78) | 68 (67) |
| Avail. water cap. (10 - 1500 kPa) | 71 (65) | 75 (60) |

[1]
I = equations for topsoil and subsoil, pooled soil groups
II = equations for soil groupings, pooled horizon depths

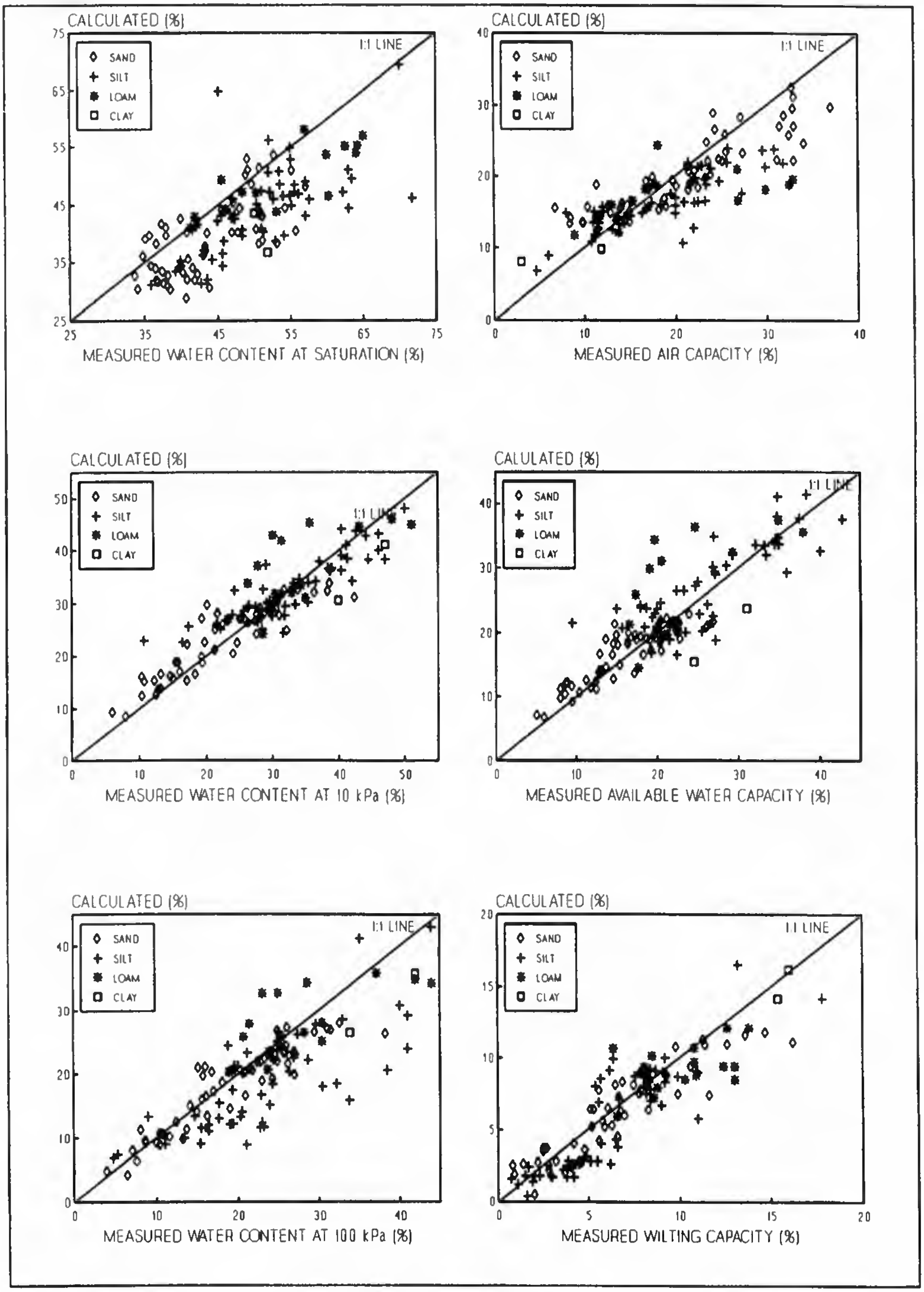


*Fig. 4.7. Plots of some independently measured soil properties (data from Riley 1979) against values calculated using equations for separate soil groupings obtained in the present study.*

Table 4.9. Calculated values of air filled pore-space at field capacity (pF 2) for typical soil types of SE Norway, from the relationships with SOM, texture, gravel content[1] and dry bulk density[2]. Values shown for two methods of calculation[3].

| SOIL TYPE | TEXTURE Sand | Silt | Clay | DEPTH: SOM: | 15 cm 5.5% | 15 cm 2.5% | 45 cm 1.1% | 75 cm 0.8% |
|---|---|---|---|---|---|---|---|---|
| SAND | 92 | 5 | 3 | I | 22.0 | 20.3 | 21.8 | 19.9 |
| | | | | II | 25.4 | 25.2 | 23.2 | 21.0 |
| GRAVELLY SAND | 92 | 5 | 3 | I | 23.2 | 21.5 | 20.3 | 18.6 |
| | | | | II | 24.2 | 23.9 | 21.7 | 19.8 |
| SILTY SAND | 67 | 30 | 3 | I | 17.6 | 16.3 | 16.9 | 14.9 |
| | | | | II | 19.3 | 17.9 | 15.4 | 13.5 |
| SANDY SILT | 30 | 65 | 5 | I | 11.5 | 10.2 | 9.7 | 7.7 |
| | | | | II | 12.8 | 11.4 | 9.0 | 7.0 |
| SILT | 5 | 90 | 5 | I | 7.5 | 6.2 | 5.0 | 3.0 |
| | | | | II | 8.6 | 7.2 | 4.8 | 2.8 |
| LOAM | 45 | 37 | 18 | I | 13.8 | 12.1 | 11.5 | 9.5 |
| | | | | II | 10.4 | 9.0 | 6.8 | 5.0 |
| GRAVELLY LOAM | 45 | 37 | 18 | I | 14.6 | 13.3 | 10.2 | 8.2 |
| | | | | II | 15.1 | 13.9 | 11.7 | 9.9 |
| SILTY LOAM | 15 | 67 | 18 | I | 8.7 | 7.0 | 5.6 | 3.9 |
| | | | | II | 9.3 | 7.7 | 5.2 | 3.5 |
| CLAY LOAM | 30 | 37 | 33 | I | 10.4 | 9.1 | 7.4 | 5.4 |
| | | | | II | 8.6 | 6.3 | 4.1 | 2.9 |
| SILTY CLAY LOAM | 10 | 57 | 33 | I | 7.1 | 5.8 | 3.5 | 1.6 |
| | | | | II | 9.0 | 6.6 | 4.5 | 3.2 |
| HEAVY CLAY | 5 | 45 | 50 | I | 5.7 | 4.1 | 1.0 | -1.0 |
| | | | | II | 6.6 | 4.1 | 2.0 | 0.7 |

[1] 25% gravel assumed in gravelly sand and gravelly loam.

[2] Values of dry bulk density from Table 3.2 assumed.

[3] I = equations for topsoil and subsoil, pooled soil groups
II = equations for soil groupings, pooled horizon depths

Table 4.10. Calculated values of available water capacity (pF 2 - pF 4.2) for typical soil types of SE Norway, from the relationships with SOM, texture, gravel content[1] and dry bulk density[2]. Values shown for two methods of calculation[3].

| SOIL TYPE | TEXTURE Sand | Silt | Clay | DEPTH: SOM: | 15 cm 5.5% | 15 cm 2.5% | 45 cm 1.1% | 75 cm 0.8% |
|---|---|---|---|---|---|---|---|---|
| SAND | 92 | 5 | 3 | I | 21.7 | 18.0 | 11.5 | 10.6 |
| | | | | II | 16.9 | 13.1 | 11.3 | 11.0 |
| GRAVELLY SAND | 92 | 5 | 3 | I | 17.2 | 13.5 | 9.4 | 8.6 |
| | | | | II | 14.1 | 10.4 | 8.6 | 8.2 |
| SILTY SAND | 67 | 30 | 3 | I | 27.3 | 23.6 | 18.7 | 17.8 |
| | | | | II | 26.9 | 24.5 | 22.4 | 21.2 |
| SANDY SILT | 30 | 65 | 5 | I | 34.9 | 31.2 | 28.4 | 27.5 |
| | | | | II | 34.9 | 32.6 | 30.4 | 29.2 |
| SILT | 5 | 90 | 5 | I | 40.5 | 36.8 | 35.7 | 34.8 |
| | | | | II | 41.2 | 38.8 | 36.7 | 35.5 |
| LOAM | 45 | 37 | 18 | I | 26.9 | 23.2 | 16.3 | 15.3 |
| | | | | II | 31.8 | 27.1 | 23.6 | 21.8 |
| GRAVELLY LOAM | 45 | 37 | 18 | I | 22.4 | 18.7 | 14.3 | 13.4 |
| | | | | II | 21.8 | 17.2 | 13.7 | 12.0 |
| SILTY LOAM | 15 | 67 | 18 | I | 33.7 | 30.0 | 25.0 | 24.2 |
| | | | | II | 31.1 | 28.6 | 26.5 | 25.4 |
| CLAY LOAM | 30 | 37 | 33 | I | 25.0 | 21.3 | 11.8 | 10.8 |
| | | | | II | 29.5 | 21.9 | 16.8 | 13.9 |
| SILTY CLAY LOAM | 10 | 57 | 33 | I | 29.5 | 25.8 | 17.6 | 16.7 |
| | | | | II | 30.1 | 22.5 | 17.2 | 14.6 |
| HEAVY CLAY | 5 | 45 | 50 | I | 24.6 | 20.9 | 8.9 | 8.0 |
| | | | | II | 24.9 | 17.1 | 11.8 | 9.2 |

[1] 25% gravel assumed in gravelly sand and gravelly loam.

[2] Values of dry bulk density from Table 3.2 assumed.

[3] I = equations for topsoil and subsoil, pooled soil groups
II = equations for soil groupings, pooled horizon depths

Table 4.11. Calculated values of wilting capacity (pF 4.2) for typical soil types of SE Norway, from the relationships with SOM, texture, gravel content[1] and dry bulk density[2]. Values shown for two methods of calculation[3].

| SOIL TYPE | TEXTURE Sand | Silt | Clay | DEPTH: SOM: | 15 cm 5.5% | 15 cm 2.5% | 45 cm 1.1% | 75 cm 0.8% |
|---|---|---|---|---|---|---|---|---|
| SAND | 92 | 5 | 3 | I | 6.2 | 5.7 | 3.4 | 3.9 |
| | | | | II | 8.1 | 5.9 | 5.2 | 5.3 |
| GRAVELLY SAND | 92 | 5 | 3 | I | 5.6 | 5.1 | 2.9 | 3.4 |
| | | | | II | 6.7 | 4.5 | 3.8 | 3.9 |
| SILTY SAND | 67 | 30 | 3 | I | 6.0 | 5.5 | 3.2 | 3.7 |
| | | | | II | 5.8 | 4.3 | 4.0 | 4.2 |
| SANDY SILT | 30 | 65 | 5 | I | 6.4 | 5.8 | 4.1 | 4.6 |
| | | | | II | 6.3 | 4.8 | 4.5 | 4.7 |
| SILT | 5 | 90 | 5 | I | 6.1 | 5.5 | 3.9 | 4.4 |
| | | | | II | 6.2 | 4.6 | 4.3 | 4.5 |
| LOAM | 45 | 37 | 18 | I | 11.6 | 11.1 | 11.4 | 11.9 |
| | | | | II | 10.9 | 10.4 | 10.9 | 11.5 |
| GRAVELLY LOAM | 45 | 37 | 18 | I | 11.1 | 10.5 | 10.9 | 11.4 |
| | | | | II | 10.6 | 10.0 | 10.5 | 11.1 |
| SILTY LOAM | 15 | 67 | 18 | I | 11.3 | 10.8 | 11.2 | 11.7 |
| | | | | II | 11.2 | 9.7 | 9.4 | 9.6 |
| CLAY LOAM | 30 | 37 | 33 | I | 17.4 | 16.9 | 19.7 | 20.2 |
| | | | | II | 16.4 | 18.4 | 20.1 | 21.1 |
| SILTY CLAY LOAM | 10 | 57 | 33 | I | 17.2 | 16.6 | 19.5 | 20.0 |
| | | | | II | 16.1 | 18.1 | 19.8 | 20.8 |
| HEAVY CLAY | 5 | 45 | 50 | I | 23.8 | 23.3 | 29.0 | 29.5 |
| | | | | II | 24.6 | 26.6 | 28.4 | 29.4 |

[1] 25% gravel assumed in gravelly sand and gravelly loam.

[2] Values of dry bulk density from Table 3.2 assumed.

[3] I = equations for topsoil and subsoil, pooled soil groups
II = equations for soil groupings, pooled horizon depths

## 4.4 Results for organic soils

### *4.4.1 Data description*

The 39 samples used were fairly evenly distributed within the soil groupings classified in Norway as humus-rich mineral soil (6-20% SOM), humose soil (20-40% SOM) and humified peat (40-75% SOM). SOM was calculated from ignition-loss, using equation (1.7). Some humus-rich mineral soils were included in order to cover the transition from mineral to organic soils. All samples were from drained and cultivated soil profiles, and a moderate to high degree of humification is assumed, although no detailed assessment of this was made. Basic statistics for the physical properties of each soil grouping are shown in Table 4.12.

Calculated values of total porosity were somewhat higher than the measured water contents at saturation in these samples. The former are deemed to be more accurate in this case, due to the difficulty of maintaining saturation during weighing of such soil. They also showed closer correlation with SOM.

### *4.4.2 Regression equations*

Total porosity and moisture-holding capacity at all tensions increased with increasing SOM in a curvilinear way, suggesting that maximum values occurred around 60% SOM, with little increase thereafter (Fig. 4.8). The relationship was well described by means of quadratic regression equations in most cases (Table 4.13), but in the case of moisture content at wilting point (1500 kPa), a third degree

Table 4.12. Basic statistics of the soil samples used to study the properties of some cultivated organic soils of SE Norway

| SOIL CLASS: | HUMUS-RICH[1] | | HUMOSE[2] | | PEATY[3] | |
|---|---|---|---|---|---|---|
| No. of samples | 9 | | 14 | | 16 | |
| | Mean | SD | Mean | SD | Mean | SD |
| Soil org. matter % | 9.2 | 2.8 | 25.4 | 3.5 | 63.3 | 10.9 |
| Ignition-loss % | 11.5 | 3.1 | 29.6 | 3.9 | 71.7 | 12.1 |
| Total porosity | 62.3 | 6.1 | 71.6 | 3.9 | 86.4 | 2.2 |
| Vol% saturation | 62.0 | 5.6 | 67.9 | 5.9 | 81.4 | 3.4 |
| " 2 kPa | 45.2 | 8.2 | 59.2 | 7.4 | 72.3 | 6.6 |
| " 10 kPa | 38.4 | 6.9 | 53.7 | 6.5 | 64.6 | 8.2 |
| " 100 kPa | 30.8 | 7.2 | 42.0 | 6.5 | 50.3 | 7.4 |
| " 300 kPa4[4] | nd | nd | 32.3 | 5.9 | 43.1 | 3.7 |
| " 1500 kPa | 9.9 | 4.6 | 16.2 | 3.1 | 13.4 | 4.3 |
| 0-2 kPa | 17.1 | 6.0 | 12.4 | 4.1 | 14.0 | 6.4 |
| 0-10 kPa | 23.9 | 6.4 | 17.9 | 3.6 | 21.7 | 8.2 |
| 10-100 kPa | 7.6 | 2.2 | 11.7 | 1.9 | 14.3 | 6.1 |
| 100-1500 kPa | 21.0 | 7.2 | 25.7 | 6.9 | 36.9 | 8.6 |
| 10-1500 kPa | 28.5 | 7.9 | 37.4 | 7.2 | 51.2 | 8.4 |

[1] 6-20% SOM [2] 20-40% SOM [3] 40-75% SOM

[4] Data at 300 kPa only available for 21 of the 39 samples.

polynomial gave the best data-fit. The reason for the latter relation is unclear, and may simply be a random effect. There was little effect of SOM on air-filled pore-space at tensions of 2 and 10 kPa, and all three soil classes had relatively high values for aeration properties. The total avail-able water-holding capacity was somewhat variable, but it never-theless showed a marked increase up to around 60% SOM (Fig. 4.9).

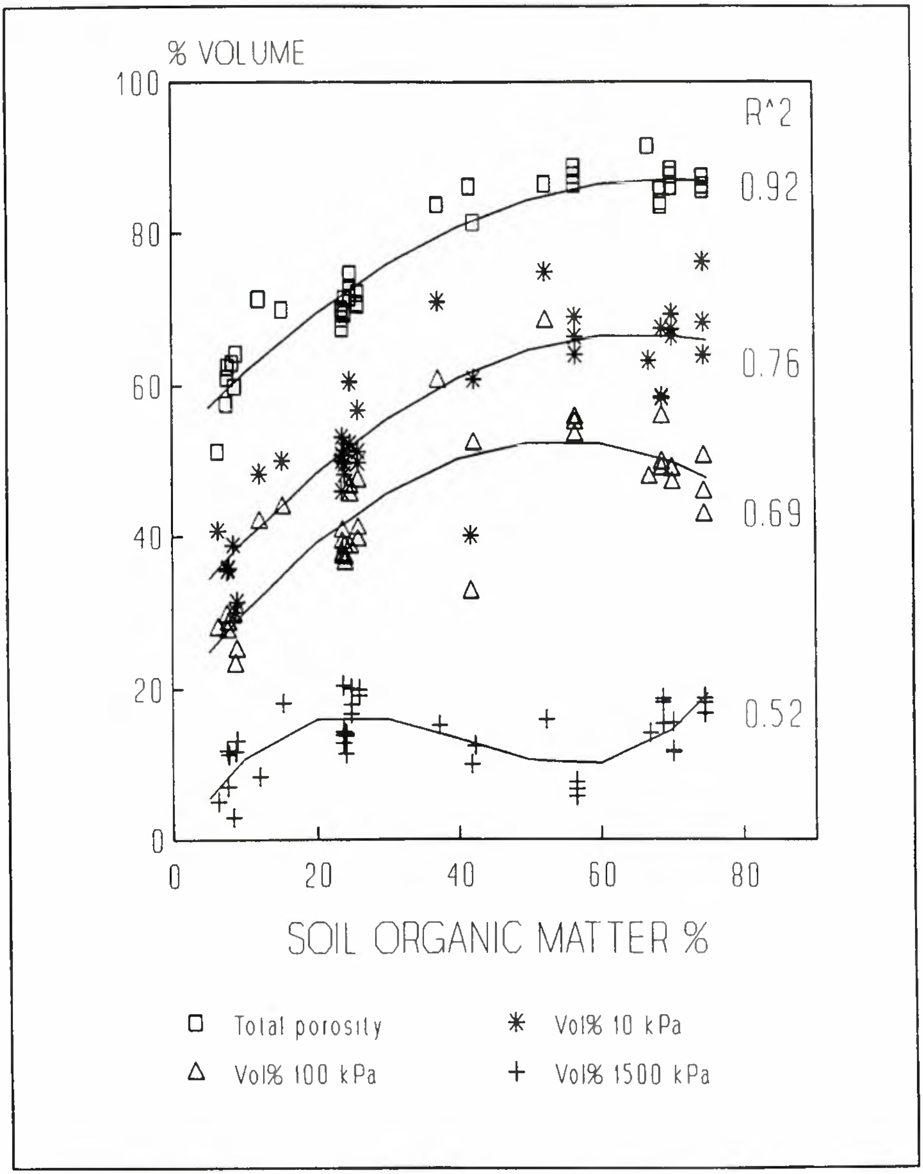


*Fig. 4.8. The relationship of total porosity and moisture retention at various tensions with soil organic matter on some cultivated organic soils of southeast Norway.*

Table 4.13. Regression equations for the relationship of soil organic matter with porosity, moisture content at various tensions and the total available water-holding capacity of some cultivated organic soils in SE Norway

| Variable | | Regression equation | R² |
|---|---|---|---|
| Porosity | = | 52.5 + 0.99*SOM - 0.0071*SOM**2 | 0.92 |
| Vol% satn. | = | 54.4 + 0.69*SOM - 0.0041*SOM**2 | 0.81 |
| Vol% 2 kPa | = | 34.1 + 1.22*SOM - 0.0095*SOM**2 | 0.78 |
| Vol% 10 kPa | = | 28.6 + 1.17*SOM - 0.0089*SOM**2 | 0.76 |
| Vol% 100 kPa | = | 18.8 + 1.25*SOM - 0.0114*SOM**2 | 0.69 |
| Vol% 1500 kPa | = | -20.3 + 1.74*SOM - 0.0506*SOM**2 + 4.2E-9*SOM**3 | 0.52 |
| Avail. water | = | 19.3 + 0.93*SOM - 0.0065*SOM**2 | 0.65 |

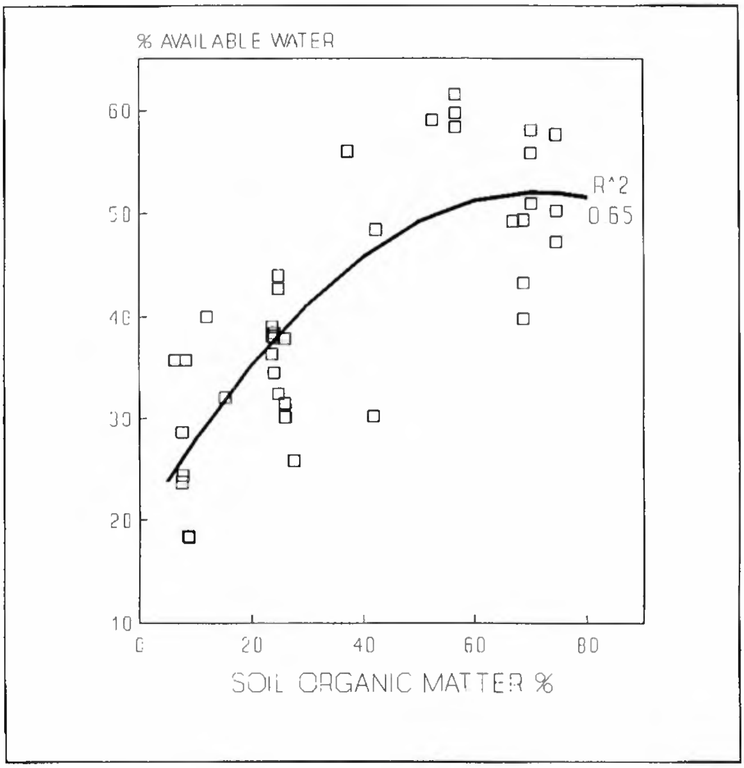


*Fig. 4.9. The relationship between total available water-holding capacity (pF 2 - 4.2) and soil organic matter on some cultivated organic soils of southeast Norway.*

# 5. Air permeability and saturated hydraulic conductivity

## 5.1 Background

The importance of soil transport properties for aeration, water supply and drainage is fundamental. Unfortunately, however, such properties typically show a much higher degree of variability than many other soil physical properties (Warrick & Nielsen, 1980), and they are often difficult or expensive to measure directly. This is particularly true of gas diffusion and unsaturated hydraulic conductivity, which are probably the major transport processes within the rooting zone of agricultural soils. Because of their high variability, it is often difficult to relate transport properties directly to soil texture.

A simple measure of soil aeration is that of intrinsic air permeabilty (AIRPERM), which may quickly and readily be measured on cylinder core samples in conjunction with pore-size analysis. Whilst this is a measure of mass air flow, which may only account for a small part of the total gaseous exchange in soils (Hillel, 1980), it is likely that both air permeability and gas diffusion are governed to a large extent by the amount of air-filled pore-space (AIRCAP) in the soil, as illustrated in Fig. 5.1, using data from Schønning (1988). The latter parameter, either measured directly or predicted as

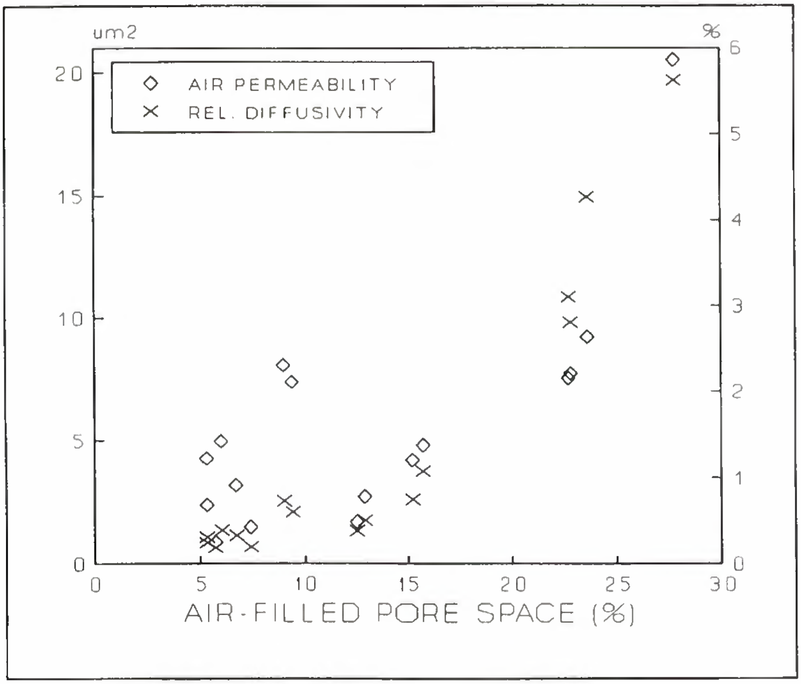


*Fig. 5.1. Illustration of the relationships of air permeability (μ m²) and relative oxygen diffusion rate (%) with air-filled pore space, using data for Danish soil from Schønning (1988).*

suggested in section 4.3, may therefore be a good starting point for deriving information on aeration.

Saturated hydraulic conductivity (KSAT) describes the soil's ability to transport water at depths beneath the water table, and at shallower depths under prolonged or high-intensity rainfall conditions. It is also used as a scaling factor, together with the moisture retention curve, in many of the methods proposed for estimating water flow under unsaturated conditions. Unlike that of AIRPERM, the measurement of KSAT is difficult to combine with routine analysis of water retention, since the soil structure of saturated core samples is easily disrupted during handling. However, as both transport processes are governed largely by the volume of soil macropores, a reasonably close relationship is usually found between these two parameters, thus enabling KSAT to be estimated directly from AIRPERM, or indirectly from AIRCAP.

Air permeability data for the majority of the soil samples presented in section 4 is used in this section in order to examine its dependence on air-filled pore space. A previously found relationship for Norwegian soils between AIRPERM and KSAT (Riley & Ekeberg 1989) is also used for an assessment of the variation in KSAT between soils.

### 5.2 Materials and methods

Air permeability data included measurements from 745 mineral soil horizons,

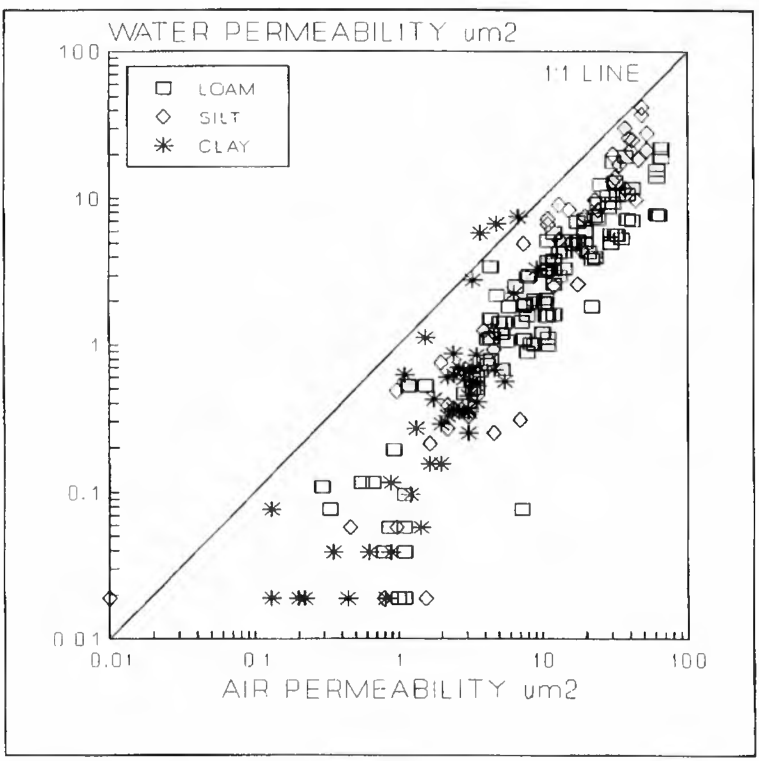


*Fig. 5.2. Relationship between intrinsic air and water permeability constants measured in some Norwegian soils. Data from Riley & Ekeberg (1989).*

expressed as means of 2-4 soil core samples in each case, as in section 4. Their distribution between the four soil groupings was 17%:34%:39%:10% for sandy, silty, loamy and clayey soils, respectively, fairly equally divided between topsoil and subsoil. AIRPERM was measured at 10 kPa tension (assumed field capacity), as described by Green & Fordham (1975), by measuring air flow through core samples at a pressure of 1-3 kPa (normally 2).

The intrinsic permeability constant of a stable soil is theoretically identical for both air and water (Hillel, 1980). In practice, however, that of water is usually lower than that of air, due to airlocking or changes in pore geometry which take place on saturation. The water permeability constants in this study were estimated from those of air, using equation (5.1), after Riley & Ekeberg (1989). This equation was derived from parallel measurements of both parametres on 229 samples from tillage trials on loam, silt and clay soil (Fig. 5.2) from Hedemarken, Solør and Østfold, respectively.

(5.1) Water perm. ($\mu m^2$) = 0.106*AIR PERM$^{1.31}$ (n=229, $R^2$=0.86)

This relationship, which was similar for all three soil types, is almost identical to that found for Danish soils by Schønning (1986), and indicates that the permeability constant for water is about 20-50% that of air in very permeable soils, and declines to only 2-10% in soils with low permeability. The latter soils presumably exhibit most airlocking or disruption of internal structure upon saturation.

Water permeability is converted to hydraulic conductivity by means of a factor representing fluidity, which of course is temperature dependent. Values of this factor at temperatures of 0, 5, 10, 15 and 20 °C are 1.98, 2.25, 2.70, 3.10 and 3.52, respectively, with KSAT expressed in units of cm/hour.

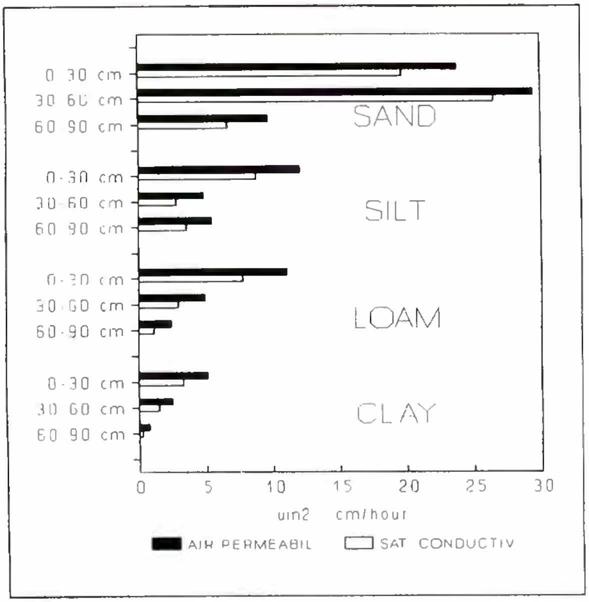


*Fig. 5.3. Mean values for intrinsic air permeability ($\mu m^2$) and saturated hydraulic conductivity at 10° C (cm/hour) in four soil and three depth groupings.*

## 5.3 Results

Mean values of AIRPERM and KSAT at different depths in the four groups of soil are shown in Fig. 5.3. The differences between soils were as expected, with sandy soils having markedly higher values than the other groups, and with clay soils being least permeable. There was in most cases a marked decline in permeability with increasing depth. The variability in transport properties was extremely high, also as expected, and there was evidence of positive skewness (Table 5.1), suggesting that the data were log-normally distributed.

The relationship between AIRPERM and air-filled pore space is shown in Fig. 5.4, plotted for each soil grouping. The relationship was close in sandy and loamy soils, but there was greater scatter in the case of silty soils. There was also a fairly close relationship for clayey soils, although there were limited data in this case and very few observations with high permeability.

Exponential regression equations were fitted, using the natural logarithms of AIRPERM and KSAT at 10° C as dependent variables, both for individual soil groups and for the pooled data (Table 5.2). Such equations only explained more variance than linear equations in the case of clay soils, but they are nevertheless considered more appropriate than the latter since they avoid the prediction of negative permeability at low values of AIRCAP.

The AIRPERM equation for loamy soils was almost identical to that found previously for such soil in another dataset (Riley & Ekeberg, 1989). The differences between soil groups found here were somewhat similar to those reported by Schønning (1986). A relevant consideration is whether to use permeability equations for individual soils or those for the pooled data. The data-spread is such that individual equations are unlikely to be statistically different from one another. Nevertheless, they do differentiate between soil groups in a logical manner, especially at low levels of AIRCAP (ran-

Table 5.1. Basic statistics of intrinsic air permeability and saturated hydraulic conductivity at 10° C in four soil groups used to relate permeability with air-filled pore space

| SOIL GROUP | SAND | SILT | LOAM | CLAY |
|---|---|---|---|---|
| No. of samples | 127 | 256 | 289 | 73 |
| AIR PERMEABILITY ($\mu m^2$) | | | | |
| Mean | 24.0 | 7.4 | 8.5 | 3.1 |
| Max. | 66.0 | 52.1 | 57.2 | 42.9 |
| Min. | 0.4 | 0.1 | 0.0 | 0.1 |
| Std. dev. | 18.9 | 9.7 | 9.7 | 6.4 |
| Skewness | 0.7 | 2.6 | 2.0 | 4.2 |
| SATURATED CONDUCTIVITY (cm/hour) | | | | |
| Mean | 20.7 | 4.9 | 5.7 | 1.9 |
| Max. | 69.1 | 50.7 | 57.3 | 39.3 |
| Min. | 0.1 | 0.2 | 0.0 | 0.0 |
| Std. dev. | 19.8 | 8.7 | 8.5 | 5.3 |
| Skewness | 1.0 | 3.4 | 2.8 | 5.4 |

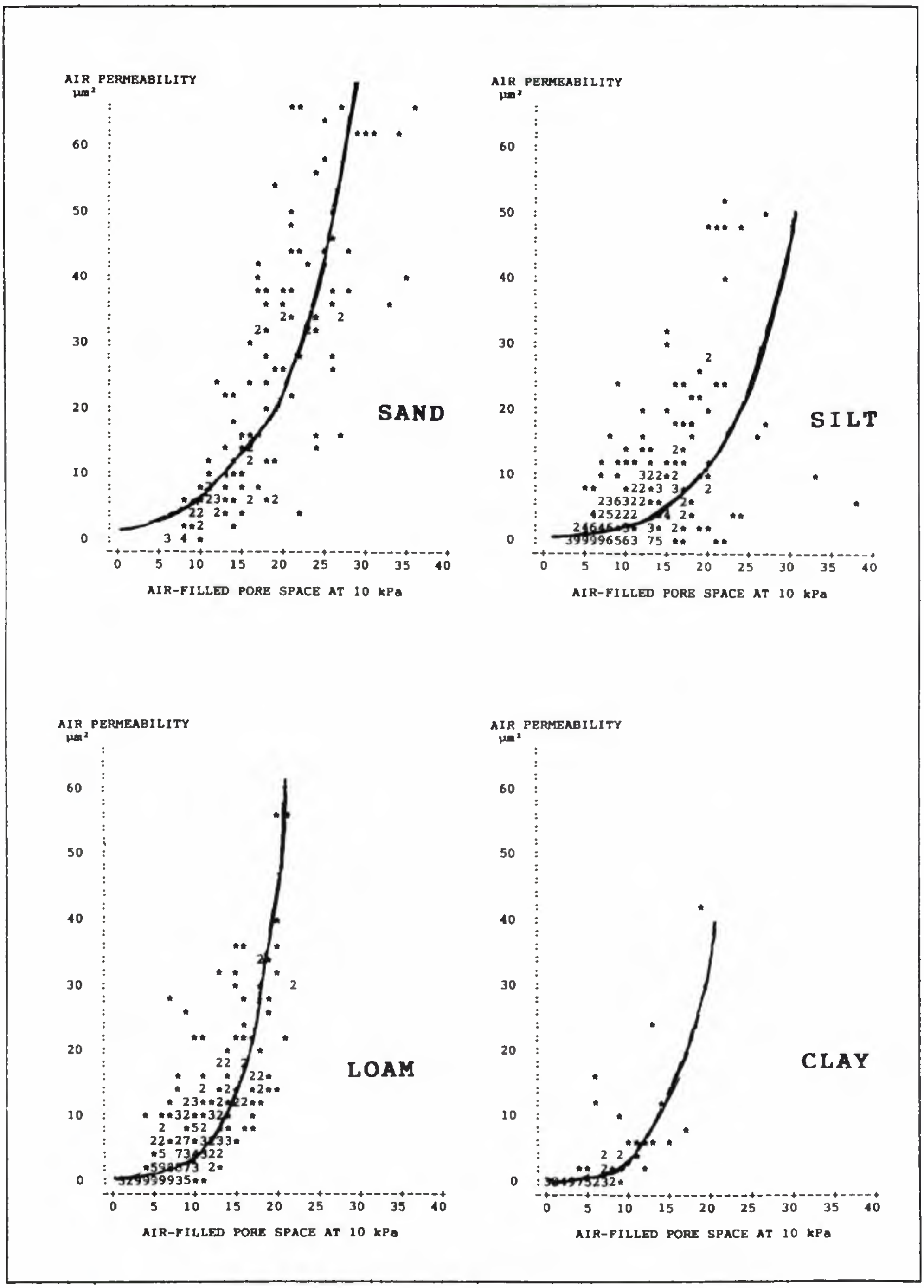


*Fig. 5.4. The relationship between intrinsic air permeability and air-filled pore space at 10 kPa tentsion in four soil groups. Curves drawn from equations given in Table 5.2.*

Table 5.2. Exponential regression equations[1] relating intrinsic air permeability ($\mu m^2$) and saturated hydraulic conductivity at 10° C to air-filled pore space (%) in different soil groups

| | Const. (a) | Coeff. (b) | s.e.b | $R^2$ |
|---|---|---|---|---|
| SANDY SOIL | | | | |
| Air permeability | 1.444 | 0.13 | 0.009 | 0.62 |
| Sat. conductivity | 0.462 | 0.17 | 0.012 | |
| SILTY SOIL | | | | |
| Air permeability | 0.542 | 0.15 | 0.013 | 0.34 |
| Sat. conductivity | 0.128 | 0.20 | 0.017 | |
| LOAMY SOIL | | | | |
| Air permeability | 0.313 | 0.25 | 0.012 | 0.62 |
| Sat. conductivity | 0.064 | 0.33 | 0.015 | |
| CLAY SOIL | | | | |
| Air permeability | 0.118 | 0.32 | 0.028 | 0.65 |
| Sat. conductivity | 0.017 | 0.42 | 0.037 | |
| ALL SOILS | | | | |
| Air permeability | 0.425 | 0.19 | 0.006 | 0.56 |
| Sat. conductivity | 0.094 | 0.25 | 0.008 | |

[1] $y = a * e^{b*x}$, where e = base of natural logarithms

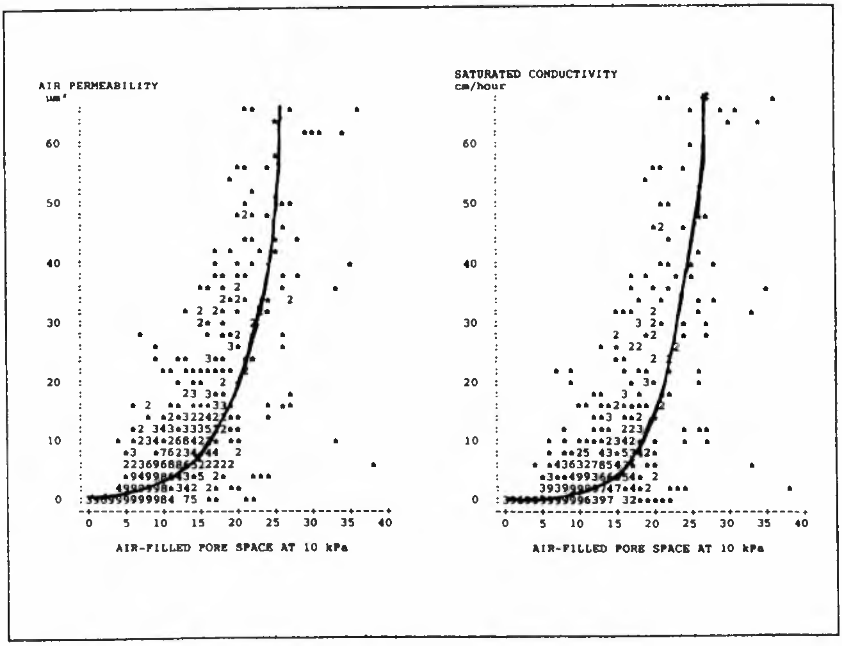


*Fig. 5.5. The relationships of intrinsic air permeability and saturated hydraulic conductivity at 10° C with air-filled pore space at 10 kPa tension in pooled soils. Curves drawn from equations given in Table 5.2.*

king: sand>silt>loam>clays).

Care must be taken, however, when using equations for individual soils, not to extrapolate beyond the range of the data from which they were derived. In the present context, this means that the equations for clay and loam soils should not be used at AIRCAP values greater than about 15% and 20%, repectively, since this would lead to overestimation of permeability. In such cases the relationships for the pooled data should be used (Fig. 5.5).

Table 5.3 contains values of AIRPERM and KSAT at 10° C, calculated for some typical Norwegian soil types, using the AIRCAP values given in the previous section (Table 4.9, calculation method II). The equations for individual soil groupings were used here, as the AIRCAP values were in all cases well within the measured ranges of individual soils.

It is difficult to assess the represen-

Table 5.3. Values of (I) intrinsic air permeability ($\mu m^2$) and (II) saturated conductivity at 10° C (cm/hour) for typical soil types of SE Norway, calculated from their relationships with air capacity, assuming the values of the latter given in Table 4.9

| SOIL TYPE | TEXTURE Sand | Silt | Clay | DEPTH: SOM: | 15 cm 5.5% | 15 cm 2.5% | 45 cm 1.1% | 75 cm 0.8% |
|---|---|---|---|---|---|---|---|---|
| SAND | 92 | 5 | 3 | I | 39.2 | 38.2 | 29.5 | 22.1 |
| | | | | II | 34.7 | 33.5 | 23.8 | 16.4 |
| GRAVELLY SAND | 92 | 5 | 3 | I | 33.6 | 32.3 | 24.3 | 18.9 |
| | | | | II | 28.3 | 26.9 | 18.5 | 13.4 |
| SILTY SAND | 67 | 30 | 3 | I | 9.8 | 7.9 | 5.5 | 4.1 |
| | | | | II | 6.1 | 4.6 | 2.8 | 1.9 |
| SANDY SILT | 30 | 65 | 5 | I | 3.7 | 3.0 | 2.1 | 1.5 |
| | | | | II | 1.7 | 1.3 | 0.8 | 0.5 |
| SILT | 5 | 90 | 5 | I | 2.0 | 1.6 | 1.1 | 0.8 |
| | | | | II | 0.7 | 0.5 | 0.3 | 0.2 |
| LOAM | 45 | 37 | 18 | I | 4.2 | 3.0 | 1.7 | 1.1 |
| | | | | II | 2.0 | 1.2 | 0.6 | 0.3 |
| GRAVELLY LOAM | 45 | 37 | 18 | I | 13.6 | 10.1 | 5.8 | 3.7 |
| | | | | II | 9.3 | 6.3 | 3.0 | 1.7 |
| SILTY LOAM | 15 | 67 | 18 | I | 2.2 | 1.7 | 1.2 | 0.9 |
| | | | | II | 0.8 | 0.6 | 0.4 | 0.3 |
| CLAY LOAM | 30 | 37 | 33 | I | 1.9 | 0.9 | 0.4 | 0.3 |
| | | | | II | 0.6 | 0.2 | 0.1 | 0.06 |
| SILTY CLAY LOAM | 10 | 57 | 33 | I | 2.1 | 1.0 | 0.5 | 0.3 |
| | | | | II | 0.7 | 0.3 | 0.1 | 0.06 |
| HEAVY CLAY | 5 | 45 | 50 | I | 1.0 | 0.4 | 0.2 | 0.1 |
| | | | | II | 0.2 | 0.1 | 0.04 | 0.02 |

tivity of these calculated values, owing to the scarcity of published data on such transport parameters for Norwegian soils. Nevertheless the values for both AIRPERM and KSAT fall well within the ranges normally reported in other countries (see, for example, Glinski & Stepniewski, 1985, for AIRPERM and Thomasson, 1975, for KSAT). Compaction studies in Norway (Riley, 1988) have suggested that crop growth may be limited at air permeability values below about 3 $\mu m^2$, but this figure should only be used as a rough guide.

Many different classifications of hydraulic conductivity have been proposed, but according to that used in England by Thomasson (1975), the present soils may be grouped as follows:

| | **Topsoils** | **Subsoils** |
|---|---|---|
| Sandy soils | Rapid/very rapid | Moderately rapid/rapid |
| Silty soils | Moderately slow | Slow/moderately slow |
| Loamy soils | Moderately rapid/rapid | Mod. slow/mod. rapid |
| Clayey soils | Moderately slow/slow | Slow/very slow |

# Summary and conclusion

The purpose of this paper is to present and summarize a considerable amount of information on the physical properties of a wide range of cultivated topsoils and undisturbed subsoils from some important agricultural regions of Norway. Emphasis has been placed on establishing relationships between properties, in order to provide a framework for the estimation of the most commonly required parameters, on the basis of available soil descriptors. These are usually limited to, at best, grain size distribution and ignition-loss, or, not infrequently, simply to textural class and estimated organic matter content.

*Section 1:* Equations for the calculation of soil organic matter (SOM) from ignition-loss and clay content were derived on the basis of 455 mineral soil samples from a wide range of locations throughout Norway, and for a smaller dataset of 27 organic soils. An equation including both parameters gave good prediction in all regions up to about 8% SOM. At higher levels of SOM, the simple relationship SOM = 0.9* ignition-loss - 1.2 gave good agreement.

*Section 2:* Mean particle density, which is used to calculate total porosity, was measured by means of water pycnometers in 538 soil samples, with varying organic matter content up to 20%, equ-ally divided between three groups of soil (clay, loam and silt). Significant correlations were found with both ignition-loss (negative) and clay content (positive). It was considered that the latter correlation was due to the interaction of clay particles with dipolar water molecules, which is known to cause an apparent increase in particle density. This relationship was therefore used as a means of correcting particle density values measured in this way. This resulted in considerably reduced scatter in the simple regression between particle density and ignition-loss. It also gave values more in accordance with those expected for the dominant soil minerals in soil with low SOM content (i.e. values around 2.65 g/cm$^3$ rather than around 2.8).

*Section 3:* Dry bulk density was measured in undisturbed core samples taken at 10-15 cm depth intervals down to 90 cm from 246 soil profiles in localities throughout S.E. Norway. The dataset included 467 topsoil horizons and 494 subsoil horizons. Of these, 166 were classified as coarse sand/gravel, 322 as fine sand/silt, 313 as loam and 160 as clay soil. The best-fit multiple regression equation for bulk density in these samples ($R^2$=0.70) included negative terms for SOM and silt contents, and positive terms for gravel content, clay content and for increasing depth. The first four of these variables are the same as those previously found to explain variation in the soil's «standard degree of compactness», in an independent study. Calculated values of expected dry bulk density are presented for 11 common Norwegian soil types, at three different depths (15, 45 and 75 cm) and with two levels of SOM in the topsoil (2.5 and 5.5%). Corresponding values are also presented for relative compactness in relation to the above-mentioned standard. These values indicate that the present compaction status of Norwegian soils is lowest in sandy soils, intermediate in loam and clay soils and highest in silt soil. The bulk density of organic soils, studied in a smaller dataset of 39 horizons, showed a negative curvilinear relationship with ignition-loss ($R^2$=0.95), declining from around 0.8 $g/cm^3$ at 20% to 0.4 at 50%, and further to just over 0.2 at 80% ignition-loss.

*Section 4:* Soil porosity and moisture retention properties were measured for all horizons in the same datasets as those mentioned in section 3. Measurements included moisture retention at 10, 100 and 1500 kPa for all samples. Measurements at 2 and 300 kPa were made on representative subsets, and calculated for the remainder on the basis of relationships established in the subsets. Air capacities at 2 and 10 kPa were calculated, as were capacities for readily-available water (10-100 kPa), more strongly-held water (100-1500 kPa) and total available water (10-1500 kPa).

Regression equations are presented for porosity, moisture retention at different tensions and for the above-mentioned capacities, both for individual soil groups and for topsoil and subsoil samples separately. Both groupings gave broadly similar standard errors of prediction. The influence of SOM, texture and bulk density in the equations is discussed, and the equations were validated using an independent dataset from a previous study. This confirmed that the present equations are suitable for prediction purposes in most cases. Calculated values of air capacity, available water capacity and permanent wilting point are given for the same 11 soil types as in the above section.

In the case of organic soils, porosity and moisture retention were found to be curvilinearly related to SOM. Available water capacity increased almost linearly from around 25% at 10% SOM to around 50% at 60% SOM, and thereafter remained unchanged.

*Section 5:* Air permeability was measured at assumed field capacity (10 kPa) in 745 of the horizons mentioned in section 4. Saturated hydraulic conductivity was not measured directly, but was calculated from a previously-established relationship with air permeability. Due to the high variability of these properties, no attempt was made to relate them directly to soil texture. Instead they were related to measured air capacity, by means of exponential regression equations. The results were found to conform well with previous experience in Norway and Denmark. These equations may be used in conjunction with values for air capacity obtained as described in section 4. Estimated values for both air permeability and saturated hydraulic conductivity are presented for the same 11 soil types as above.

*Overall conclusion:* Important soil physical properties may be predicted for soil types typically encountered in S.E. Norway, on the basis of their texture and organic matter content. The uncertainty associated with such predictions is in many cases probably no greater than that which accompanies direct measurements, due to spatial variability in the field. Calculated values of soil physical properties may be recommended for a variety of purposes, both in connection with the mapping of soil suitability and for use in simulation models of, for example, water balance, crop productivity and solute transport and/or leaching.

# Sammendrag og konklusjon

Hensikten med denne artikkelen er å presentere og sammenfatte en stor mengde informasjon om jordfysiske egenskaper hos et bredt spekter av dyrkete matjordssjikt og uforstyrrete undergrunnssjikt fra noen viktige norske jordbruksstrøk. Det er lagt vekt på å belyse sammenhenger mellom egenskapene, for derved å gjøre det mulig å estimere de mest etterspurte parametrene på grunnlag av tilgjengelige jordbeskrivelser. Slike beskrivelser er ofte begrenset, i beste fall til mekanisk analyse og glødetap, eller ikke sjelden til bare jordartsklasse og estimert moldinnhold.

*1. del:* Ligninger for å beregne moldinnhold på grunnlag av jordas glødetap og leirinnhold er utledet fra et datasett med 455 mineraljordprøver tatt fra ulike lokaliteter fordelt over hele landet, og fra et mindre datasett med 27 organiske jordprøver. En felles ligning basert på både glødetap og leirinnhold, gav god prediksjon av moldinnhold opp til ca. 8% i alle landsdeler. Ved høyere moldinnhold fikk man tilfredsstillende samsvar med den enkle sammenhengen: Moldinnhold = 0,9*glødetap - 1,2.

*2. del:* Materialtetthet, som brukes til å beregne jordas totale porevolum, ble målt ved hjelp av vannfylte væskepyknometre i 538 jordprøver med varierende moldinnhold opp til 20%. Prøvene var likt fordelt mellom tre jordgrupperinger (lettleire, mellomleire og silt). Sikre korrelasjoner ble funnet med både glødetap (negativ) og leirinnhold (positiv). Sistnevnte relasjon skyldes trolig samspillet mellom leirpartikler og vann, pga. vannmolekylenes dipolaritet. Det er kjent at dette gir en tilsynelatende økning i materialtettheten. Relasjonen ble derfor benyttet for å korrigere de målte verdiene. Dette resulterte i betydelig mindre avvik i den enkle regresjonen mellom materialtetthet og glødetap. Dessuten samsvarte verdiene ved lavt moldinnhold bedre med det som kan forventes for de vanligste jordmineralene (dvs. 2,65 g/cm$^3$ istedenfor 2,8).

*3. del:* Tørr jordtetthet ble målt i uforstyrrete sylinderprøver tatt med 10-15 cm dybdeintervall ned til 90 cm, fra 246 jordprofil på lokaliteter fordelt over hele Østlandet. Datasettet inneholdt tall for 467 matjordssjikt og 494 undergrunnssjikt, hvorav 166 ble klassifisert som grovsand/grus, 322 som finsand/silt, 313 som lettleire og 160 som mellomleire/stiv leire. Den beste multiple regresjonsligningen for jordtetthet ($R^2$=0,70) viste negativ virkning av mold- og siltinnhold, samt positiv virkning av grus- og leirinnhold og av dybdeøkning. De fire førstnevnte variabler er de samme som tidligere er blitt funnet å ha betydning for jordas «standard pakkingsgrad». Beregnete verdier av forventet jordtetthet presenteres for 11 vanlige norske jordarter, i tre dybder (15, 45 og 75 cm) og ved to nivå for matjordas moldinnhold (2,5 og 5,5%). Tilsvarende verdier er oppgitt for relativ pakkingsgrad, sett i forhold til den nevnte standarden. Disse verdiene tyder på at den nåværende pakkingsgraden hos norske jordarter er lavest i sandjord, etterfulgt av lett- og mellomleire, mens den er høyest i siltjord. Jordtettheten i organisk jord, som ble undersøkt i et mindre datasett med tall for 39 sjikt, viste en negativ, ikkelineær sammenheng med glødetap ($R^2$ = 0,95). Jordtettheten sank fra rundt 0,8 g/cm$^3$ ved 20% til 0,4 ved 50%, og videre til noe over 0,2 ved 80% glødetap.

*4. del:* Jordas porøsitet og vannholdende egenskaper ble målt for alle sjikt i datasettene som er nevnt ovenfor i del 3. Målinger omfattet vannretensjon ved 10, 100 og 1500 kPa for alle prøver. Målinger ved 2 og 300 kPa ble utført for representative deler av materialet, mens for resten ble det beregnet verdier på grunnlag av sammenhengene som ble funnet. Luftkapasitet ble beregnet ved 2 og 10 kPa i tillegg til kapasitetene for lett-tilgjengelig vann (10-100 kPa), sterkere bundet tilgjengelig vann (100-1500 kPa) og totalt tilgjengelig vann (10-1500 kPa).

Regresjonsligninger presenteres for totalt porevolum og vannretensjon ved ulike bindingstrykk, og for de nevnte kapasitetene, både for individuelle jordartsgrupper og for matjordssjikt og undergrunnssjikt hver for seg. Begge grupperingsmåter ga omtrent lik prediksjonsnøyaktighet. Virkningene av mold, jordtekstur og jordtetthet i ligningene er drøftet, og ligningenes gyldighet ble testet ved hjelp av et uavhengig datasett fra en tidligere undersøkelse. Dette bekreftet at ligningene som presenteres her passer i de fleste tilfellene. Beregnete verdier av luftkapasitet, tilgjengelig vannkapasitet og visnegrense er oppgitt for de samme 11 jordartene som er nevnt i del 3.

Når det gjaldt organisk jord ble det funnet at totalt porevolum og vannretensjonen ved ulike bindingstrykk, viste ikke-lineære sammenhenger med moldinnhold. Totalt tilgjengelig vannkapasitet økte nesten lineært fra ca. 25% ved 10% moldinnhold til ca. 50% ved 60% moldinnhold, men var nesten uendret deretter.

*Del 5:* Luftpermeabilitet ble målt ved jordas antatte feltkapasitet (10 kPa) i 745 av jordsjiktene som er nevnt i del 4. Mettet vannledningsevne ble ikke målt, men denne egenskapen ble beregnet på grunnlag av en tidligere etablert sammenheng med luftpermeabilitet. På grunn av den høye variabiliteten som disse egenskapene viser, ble det ikke forsøkt å relatere dem direkte med jordtekstur. Det ble istedenfor utledet ekponensielle regresjonsligninger mellom dem og jordas luftkapasitet. Disse ligningene stemmer godt overens med tidligere erfaring i både Norge og Danmark. De kan brukes sammen med ligningene gitt i del 4 for luftkapasitet. Beregnete verdier for både luftpermeabilitet og mettet vannledningsevne, presenteres for de samme 11 jordartene som nevnt ovenfor.

*Samlet konklusjon:* Viktige jordfysiske egenskaper kan estimeres for de vanligste dyrkete jordartene som finnes på Østlandet, på bakgrunn av jordtekstur og moldinnhold. Usikkerheten ved slike estimeringer er trolig i mange tilfeller ikke større enn den som gjelder ved direkte målinger. Bruk av beregnete verdier av jordfysiske egenskaper kan anbefales til en rekke formål. Det kan være aktuelt i forbindelse med kartlegging av jordas bruksegenskaper (f.eks. temakart) og til bruk i modellering. Eksempler av sistnevnte anvendelse er beregninger av vekstenes vannbalanse og produksjonspotensiale eller transport og eventuell utvasking av løste næringstoff eller miljøgifter.

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APPENDIX I: Regression equations for the influence of soil textural composition (SAND, SILT, CLAY, GRAVEL)[1], soil organic matter (SOM)[2] and dry bulk density (BD)[3] on total porosity and moisture retention.

| Dependent variable | Soil grouping | Equation |
|---|---|---|
| Total porosity | SAND | 74.5 + 2.9 * SOM - 0.20 * GRAVEL - 0.62 * SILT - 0.33 * SAND |
| | SILT | 40.1 + 3.1 * SOM - 0.38 * GRAVEL - 0.43 * CLAY + 0.06 * SILT |
| | LOAM | 25.8 + 3.1 * SOM + 0.21 * SILT - 0.13 * GRAVEL |
| | CLAY | 41.3 + 3.1 * SOM - 0.28 * SAND |
| | TOPSOIL | 40.7 + 1.9 * SOM + 0.09 * SILT - 0.17 * CLAY - 0.16 * GRAVEL |
| | SUBSOIL | 40.3 + 3.6 * SOM - 0.30 * GRAVEL - 0.10 * CLAY - 0.04 * SAND |
| Vol. % at saturation | SAND | 66.2 + 2.6 * SOM -0.19 * GRAVEL - 0.44 * SILT - 0.28 * SAND |
| | SILT | 39.5 + 2.6 * SOM - 0.34 * GRAVEL - 0.42 * CLAY + 0.08 * SILT |
| | LOAM | 41.7 + 2.8 * SOM - 0.13 * SAND - 0.15 * GRAVEL |
| | CLAY | 42.3 + 3.1 * SOM - 0.24 * SAND |
| | TOPSOIL | 39.4 + 1.7 * SOM + 0.06 * SILT - 0.11 * GRAVEL |
| | SUBSOIL | 35.3 - 0.29 * GRAVEL + 3.1 * SOM + 0.07 * SILT |
| Vol. % at 2 kPa (pF 1.3) | SAND | 26.1 + 1.8 * SOM + 0.28 * SILT - 0.18 * GRAVEL -5.0 * BD + 0.25 * CLAY |
| | SILT | 63.9 - 14.3 * BD - 0.18 * SAND - 0.16 * GRAVEL + 0.59 * SOM |
| | LOAM | 54.6 - 14.3 * BD - 0.30 * GRAVEL + 1.0 * SOM + 0.20 * CLAY |
| | CLAY | 60.9 - 18.5 * BD + 0.19 * CLAY - 0.24 * GRAVEL + 0.72 * SOM |
| | TOPSOIL | 42.0 - 0.18 * SAND + 1.7 * SOM - 0.23 * GRAVEL |
| | SUBSOIL | 62.0 - 0.22 * SAND - 12.7 * BD - 0.14 * GRAVEL + 0.91 * SOM |
| Vol. % at 10 kPa (pF 2.0) | SAND | 11.5 + 1.9 * SOM + 0.34 * SILT - 0.17 * GRAVEL + 0.24 * SAND |
| | SILT | 28.6 + 0.24 * SILT - 6.5 * BD + 0.94 * SOM - 0.15 * GRAVEL |
| | LOAM | 40.8 - 7.9 * BD - 0.36 * GRAVEL + 1.2 * SOM + 0.27 * CLAY |
| | CLAY | 51.8 - 14.3 * BD + 0.21 * CLAY - 0.32 * GRAVEL + 0.78 * SOM |
| | TOPSOIL | 23.5 - 0.22 * SAND + 2.1 * SOM - 0.29 * GRAVEL + 11.3 * BD |
| | SUBSOIL | 50.9 - 0.27 * SAND - 6.6 * BD - 0.16 * GRAVEL + 1.2 * SOM |
| Vol. % at 100 kPa (pF 3.0) | SAND | - 1.2 + 0.65 * CLAY + 1.8 * SOM - 0.14 * GRAVEL + 0.14 * SILT + 5.2 * BD |
| | SILT | 5.4 + 1.9 * SOM + 0.76 * CLAY - 0.09 * SAND - 0.15 * GRAVEL + 6.7 * BD |
| | LOAM | 20.6 - 1.2 * SOM - 0.30 * GRAVEL + 0.37 * CLAY |
| | CLAY | 36.4 - 7.6 * BD + 0.25 * CLAY - 0.35 * GRAVEL + 0.73 * SOM |
| | TOPSOIL | -12.2 +0.48 * CLAY + 2.2 * SOM + 0.11 * SILT - 0.23 * GRAVEL + 15.5 * BD |
| | SUBSOIL | 7.8 + 0.42 * CLAY - 0.11 * SAND + 2.1 * SOM + 6.9 * BD - 0.12 * GRAVEL |
| Vol. % at 300 kPa (pF 3.5) | SAND | - 1.5 + 0.71 * CLAY + 1.4 * SOM - 0.11 * GRAVEL + 4.0 * BD + 0.07 * SILT |
| | SILT | - 0.2 + 0.79 * CLAY + 1.6 * SOM - 0.04 * SAND + 5.6 * BD - 0.11 * GRAVEL |
| | LOAM | 15.2 + 1.0 * SOM - 0.23 * GRAVEL + 0.50 * CLAY - 0.04 * SILT |
| | CLAY | 17.8 + 0.40 * CLAY - 3.2 * BD - 0.19 * GRAVEL + 0.80 * SOM + 0.07 * SILT |
| | TOPSOIL | -10.8 + 0.57 * CLAY + 1.7 * SOM - 0.18 * GRAVEL + 12.5 * BD + 0.05 * SILT |
| | SUBSOIL | 1.9 + 0.55 * CLAY - 0.06 * SAND + 1.7 * SOM + 5.6 * BD - 0.09 * GRAVEL |
| Vol. % at 1500 kPa (pF 4.2) | SAND | - 3.4 + 1.0 * SOM + 0.31 * CLAY - 0.08 * GRAVEL + 4.2 * BD |
| | SILT | - 5.4 + 0.37 * CLAY + 0.82 * SOM + 4.8 * BD |
| | LOAM | - 11.3 + 0.48 * CLAY + 8.3 * BD + 0.70 * SOM - 0.07 * GRAVEL |
| | CLAY | - 11.5 + 0.47 * CLAY + 10.2 * BD - 0.15 * GRAVEL |
| | TOPSOIL | - 7.2 + 0.37 * CLAY + 0.65 * SOM + 7.3 * BD - 0.07 * GRAVEL |
| | SUBSOIL | - 5.7 + 0.54 * CLAY + 4.8 * BD - 0.05 * GRAVEL |

[1] SAND (0.06-2 mm), SILT (0.002-0.06 mm), CLAY (<0.002 mm): weight % of fine earth (<2 mm)
GRAVEL (2 mm) : weight % of whole sample

[2] SOM: weight % of fine earth (<2 mm)

[3] BD: Mg/$m^3$

APPENDIX II: Regression equations for the influence of soil textural composition (SAND, SILT, CLAY, GRAVEL)[1], soil organic matter (SOM)[2] and dry bulk density (BD)[3] on air capacity and available water .

| Dependent variable | Soil grouping | Equation |
|---|---|---|
| Air capacity at 2 kPa (pF 1.3) | SAND | 51.5 - 0.31 * SILT - 20.0 * BD - 1.4 * SOM + 0.12 * GRAVEL |
| | SILT | 26.5 + 0.16 * SAND - 16.6 * SAND - 16.6 * BD - 0.86 * SOM + 0.11 * GRAVEL |
| | LOAM | 26.6 - 13.9 * BD + 0.26 * GRAVEL - 0.68 * SOM |
| | CLAY | 19.0 - 8.7 * BD + 0.22 * GRAVEL -0.09 * CLAY |
| | TOPSOIL | 44.8 + 0.09 * SAND - 24.6 * BD - 1.4 * SOM + 0.22 * GRAVEL - 0.08 * SILT |
| | SUBSOIL | 28.0 + 0.18 * SAND - 17.4 * BD - 0.93 * SOM + 0.08 * GRAVEL |
| Air capacity at 10 kPa (pF 2.0) | SAND | 69.7 - 0.36 * SILT - 27.4 * BD - 1.8 * SOM + 0.12 * GRAVEL |
| | SILT | 36.9 + 0.20 * SAND - 22.3 * BD - 0.95 * SOM + 0.12 * GRAVEL |
| | LOAM | 39.2 - 20.3 * BD + 0.33 * GRAVEL - 0.89 * SOM |
| | CLAY | 27.4 - 12.6 * BD + 0.29 * GRAVEL - 0.10 * CLAY |
| | TOPSOIL | 61.0 + 0.13 * SAND - 34.4 * BD - 1.7 * SOM + 0.27 * GRAVEL - 0.08 * SILT |
| | SUBSOIL | 39.0 + 0.22 * SAND - 23.5 * BD - 1.2 * SOM + 0.10 * GRAVEL |
| Readily available water (pF 2-3) | SAND | 9.1 - 2.8 * BD + 0.19 * SILT - 0.40 * CLAY - 0.06 * GRAVEL + 0.30 * SOM |
| | SILT | -45.7 + 0.93*SILT +0.79 * SAND - 13.8 * BD - 1.1 * SOM |
| | LOAM | 19.6 - 7.6 * BD -0.07 * GRAVEL - 0.11 * CLAY |
| | CLAY | 14.0 - 7.3 * BD + 0.05 * SAND |
| | TOPSOIL | 12.5 - 0.26 * CLAY + 0.12 * SILT - 3.7 * BD - 0.06 * GRAVEL |
| | SUBSOIL | 28.5 + 0.16 * SILT - 0.27 * CLAY - 14.2 * BD - 1.0 * SOM |
| Weakly available water (pF 3-4.2) | SAND | 3.8 + 0.37 * CLAY + 0.72 * SOM + 0.13 * SILT - 0.06 * GRAVEL |
| | SILT | 54.8 + 0.94 * SOM - 0.50 * SAND - 0.42 * SILT - 0.12 * GRAVEL |
| | LOAM | 29.5 - 8.1 * BD - 0.23 * GRAVEL + 0.56 * SOM |
| | CLAY | 28.6 - 12.7 * BD - 0.13 * CLAY + 1.4 * SOM + 0.14 * SILT |
| | TOPSOIL | 5.1 - 0.11 * SAND + 1.6 * SOM - 0.16 * GRAVEL + 8.9 * BD |
| | SUBSOIL | 5.3 + 0.12 * SILT + 1.7 * SOM - 0.05 * GRAVEL |
| Total available water (pF 2-4.2) | SAND | 8.5 + 0.29 * SILT + 1.3 * SOM - 0.11 * GRAVEL |
| | SILT | 35.4 + 0.23 * SILT - 12.5 * BD - 0.31 * CLAY - 0.14 * GRAVEL |
| | LOAM | 52.1 - 16.3 * BD - 0.29 * GRAVEL + 0.50 * SOM - 0.21 * CLAY |
| | CLAY | 58.6 - 22.1 * BD - 0.24 * CLAY + 1.1 * SOM - 0.19 * GRAVEL |
| | TOPSOIL | 14.2 + 0.23 * SILT + 1.2 * SOM - 0.18 * GRAVEL - 0.13 * CLAY |
| | SUBSOIL | 30.7 + 0.27 * SILT - 0.28 * CLAY - 12.0 * BD + 0.96 * SOM - 0.09 * GRAVEL |
| Total available water (alternative equations excl. BD) | SAND | same equation as above |
| | SILT | 15.6 + 0.25 * SILT - 0.26 * GRAVEL + 1.1 * SOM - 0.45 * CLAY |
| | LOAM | 20.2 + 2.0 * SOM - 0.35 * GRAVEL + 0.10 * SILT - 0.23 * CLAY |
| | CLAY | - 0.3 + 3.3 * SOM + 0.26 * SILT |
| | TOPSOIL | same equation as above |
| | SUBSOIL | 10.7 + 0.28 * SILT - 0.29 * CLAY + 2.2 * SOM - 0.19 * GRAVEL |

[1] SAND (0.06-2 mm), SILT (0.002-0.06 mm), CLAY (<0.002 mm): weight % of fine earth (<2 mm) GRAVEL (2 mm) : weight % of whole sample

[2] SOM: weight % of fine earth (<2 mm)

[3] BD: $Mg/m^3$