Acta Agriculturae Scandinavica Section B-Soil and Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: https://www.tandfonline.com/loi/sagb20

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Acta Agriculturae Scandinavica Section B-Soil and Plant Science, 2006; 56: 263–276

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ORIGINAL ARTICLE

Pedotransfer functions for estimating plant available water and bulk density in Swedish agricultural soils

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Abstract

Pedotransfer functions (PTFs) to estimate plant available water were developed from a database of arable soils in Sweden. The PTFs were developed to fulfil the minimum requirements of any agro-hydrological application, i.e., soil water content at wilting point (θ_{wp}) and field capacity (θ_{fc}), from information that frequently is available from soil surveys such as texture and soil organic carbon content (SOC). From the same variables we also estimated bulk density (ρ) and porosity (ε), which seldom are included in surveys, but are needed for calculating element mass balances. The seven particle-size classes given in the data set were aggregated in different ways to match information commonly gained from surveys. Analysis of covariance and stepwise multiple linear regression were used for quantifying the influence of depth, particle size class, textural class and soil organic carbon on the characteristic variables. PTFs developed from other data sets were also tested and their goodness-of-fit and bias was evaluated. These functions and those developed for the Swedish database were also tested on an independent data set and finally ranked according to their goodness of fit. Among single independent variables, clay was the best predictor for θ_{wp}, sand (or the sum of clay and silt) for θ_{fc} and SOC for ρ and ε. A large fraction of the variation in θ_{wp} and θ_{fc} is explained by soil texture and SOC (up to 90%) and root mean square errors (RMSEs) were as small as 0.03 m^3 water m^{-3} soil in the best models. For the prediction of ρ and ε in the test data set, the best PTF could only explain 40–43% of the total variance with corresponding RMSEs of 0.14 g cm^{-3} and 5.3% by volume, respectively. Recently presented PTFs derived from a North American database performed very well for estimating θ_{wp} (low error and bias) and could be recommended for Swedish soils if measurements of clay, sand and SOC were available. Although somewhat less accurately, also θ_{fc} could be estimated satisfactorily. This indicates that the determination of plant available water by texture and SOC is rather independent of soil genesis and that certain PTFs are transferable between continents.

Keywords: *Field capacity, organic carbon, pedotransfer function, soil database, soil moisture, water capacity, wilting point.*

Introduction

Spatially explicit information regarding soil hydraulic properties is increasingly needed for soil and water management issues related to agriculture. Soil water content is one of the most essential drivers for biological and chemical soil processes in the unsaturated zone and is therefore required for decision support models at regional, national and global scale as well as for farm management, e.g., in the context of precision agriculture or for spatially explicit ecosystem modelling at different scales.

The use of simulation models at adequate spatial resolutions is however often hampered by a lack of valid parameter values regarding soil hydraulic properties. Since sampling at high spatial resolution is often too costly, these properties have to be estimated from more readily available information. Providing that the level of accuracy achieved is adequate and that the range of applicability of the functional relationships is known, pedotransfer functions (PTFs; Bouma, 1989) can serve as a useful means for parameterizing simulation models (Wösten et al., 1990; Mayr & Jarvis, 1999). PTFs are developed with different methods and can be used for estimating soil water characteristics from particle size distribution and possibly carbon content, bulk density, cation exchange capacity, pH or clay mineralogy (see e.g., Rajkai et al., 1996, 2004;

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(Accepted 17 August 2005)

ISSN 0906-4710 print/ISSN 1651-1913 online
DOI: 10.1080/09064710500310170

Wösten et al., 2001; Wagner et al., 2004 and references cited therein). PTFs may be transferable between regions (Wagner et al., 2004) but their performance seems to be better when they are calibrated on soils with similar geographic and geological origin (Cornelis et al., 2001). For example, PTFs developed for Belgium (Vereecken et al., 1989) gave accurate predictions also for soils in Germany (Tietje & Tapkenhinrichs, 1993).

The variables included in soil surveys often differ between countries and, consequently, variables used to develop PTFs in one region may be missing for others. The transfer of these functions between regions may also be constrained by other factors and they may be valid only within the range of soil properties used for their derivation (Hutson & Cass, 1987; Wösten et al., 2001). For example, functions derived from a soil database with low variation in soil organic matter (SOM) are usually less sensitive to SOM (Puckett et al., 1985; Danalatos et al., 1994) than those derived from soils with high variation (e.g. Rawls et al., 2003). Unfortunately, PTFs previously developed for Swedish soils (Kritz, 1983; Rajkai et al., 1996) need bulk density as an input, but this property was not measured in the national Swedish soil survey of agricultural soils (Eriksson et al., 1997, 1999).

For spatial applications, simple empirical approaches to estimate soil water conditions are often used instead of more complex mechanistic models (Orlandini et al., 1996), and the simple approach can provide good approximations of point-scale experimental data for soil water (Evans et al., 1999). The available water capacity (AWC), the amount of water retained between field capacity and permanent wilting point, is a general soil indicator widely used to assess crop yield potentials and environmental risks (van Diepen, 1993; Akinremi & McGinn, 1997; Wassenaar et al., 1999; Cazemier et al., 2001). The permanent wilting point is usually defined as the water content below which plants wilt during the day and cannot recover overnight. Estimated in undisturbed soil cores, the 'permanent wilting point' is usually approximated by the water content determined at 1500 kPa tension. The definition of field capacity, the soil water content after a soil has been thoroughly wetted to saturation and allowed to drain for two to three days (Soil Survey Division Staff, 1993), is physically less stringent and is usually determined at 5 (UK), 10 (Netherlands) or 33 kPa tension (US), depending on prevailing hydrological conditions and tradition.

The objectives of the work presented here were to develop functions for estimating 1) AWC, i.e., soil water content at field capacity minus that at wilting point, from information that usually is available from surveys, soil texture and soil organic carbon concentration (SOC), 2) porosity, and 3) bulk density, which may not be available (e.g., in Swedish soil surveys) but is needed for applications focusing on element mass balances. Further, we tested existing PTFs (Kritz, 1983; Rawls et al., 1982, 2003; Rawls & Brakensiek, 1989) for use on Swedish soils. Finally, we also developed PTFs for Histosols and mineral soils rich in SOC.

Material and methods

Soil database

A Swedish soil database containing physical and chemical soil properties from 2392 soil layers (most frequently 10 cm thickness) representing 254 soil profiles at 126 sites was used (Jansson & Moon, 2001; Jansson & Karlberg, 2004). We selected all 170 arable profiles from 88 sites representing a wide range of soil texture, organic matter content and parent material. The geographical distribution of these profiles approximately corresponds to the distribution of arable land, decreasing sampling intensity from southern to northern Sweden. All records in the electronic database were cross-checked with those in the original publications, and only previously published profiles were included (Andersson & Wiklert, 1977a–c; Wiklert et al., 1983a–h). The variables in the database considered here are:

- seven particle-size classes (Swedish standards), clay (cl; <2 μm), fine silt (fsilt; from 2 μm to 6 μm), medium silt (msilt; from 6 μm to 20 μm), coarse silt (csilt; from 20 μm to 60 μm), fine sand (fsand; from 60 μm to 200 μm), medium and coarse sand (sa; from 200 μm to 2000 μm) and gravel (from 2 to 6 mm), which sum up to unity
- loss on ignition (LOI)
- bulk density (ρ)
- porosity (ε)
- water retention ($m^3\ m^{-3}$) determined at 1500 kPa and 10 kPa pressure head. This was measured in 5 to 10 cm high undisturbed soil cores (7 cm in diameter) and referred to as water content at wilting point (θ_{wp}) and field capacity (θ_{fc}), respectively. Comparable measurements for θ_{wp} and θ_{fc} were not available for all soils, since the pressures at which θ was determined differed between soils.

Particle size distribution was estimated using conventional methods based on H_2O_2 pretreatment to eliminate organic matter (Ljung, 1987). Size fractions ≤60 μm were determined by pipette sampling and by wet sieving for >60 μm.

This original database was extended by including topsoil layers from Histosols and mineral soils with organic matter contents ≥12% (Berglund, 1982, 1995a,b, 1996; Berglund et al., 1989; Berglund & Persson, 1996).

Classifications and calculations

The six fine-earth size fractions (≤2 mm) in the database were aggregated into three bulked fractions that sum up to unity (excluding gravel), clay ≤2 μm, 2 μm < silt ≤ 60 μm and 60 μm < sand ≤ 2000 μm, corresponding to the classification used by the British Soil Service. This classification differs only slightly from that of the US Department of Agriculture standards (clay ≤ 2 μm, 2 < silt ≤ 50 μm and 50 < sand ≤ 2000 μm). Thus, unlike particle size classes cl, fsilt, etc., which are weight fractions of all particles (including gravel), clay, silt and sand refer only to the fractions of fine earth (≤2 mm).

Textural classes were defined both according to international standards (FAO, 1990) and the Swedish nomenclature, where the soils are categorized into seven classes according to their clay content. In addition, each of these seven classes is divided into four sub-categories according to its concentration of organic matter (SOM) (Tables I and II).

Using the regression equations proposed in earlier works on Swedish soils for estimating SOM from LOI (Ekström, 1927; Berglund, 1995b) resulted in negative SOM-values for many soil layers where LOI was small. We therefore used the following rough approach for calculating SOM accounting for structurally water bound in clay lattices:

$$SOM = LOI^{*}(1 - 0.5^{*}clay) \quad (1)$$

According to this equation, the soils containing <12% SOM were considered as mineral soils. This threshold was chosen for matching the classification criteria in a recent national inventory of Swedish arable soils (Eriksson et al., 1997). Soil organic carbon (SOC) was assumed to be 58% of SOM according to Eriksson et al. (1997).

All soils containing ≥12% SOM were classified as 'organic' and a subset of 18 topsoil horizons, for which both LOI and SOC (dry combustion) measurements were available (Berglund et al., 1989; Berglund 1995a,b), was used for calculating SOC from LOI. This resulted in the following equation determined by linear regression ($R^2 = 0.96$):

$$SOC = 0.511^{*}LOI \quad (2)$$

The residual of this equation was judged to be normally distributed (Shapiro-Wilk and Kolmogorov-Smirnov test). Thus, our database for the development of the PTFs consists of 49 'organic' topsoil layers and 1620 mineral soil layers (mostly 10-cm intervals down to 1 m depth) with a wide range of soil textures and organic matter content (Figure 1; Tables I and II). The proportion of gravel varies between 0 and 59%.

Estimation of PTFs

Information regarding soil texture and organic matter differs between soil surveys and semi-quantitative methods are often used in farm surveys. Therefore, we aggregated the weight fractions of the mineral particles into size-classes, which correspond to information available from surveys. Multiple regressions models in the form of zero to third degree polynomials in 1 to 7 variables were then tested to estimate θ_{fc}, θ_{wp}, ε and ρ from different particle-size classes, textural classes, SOC, SOC classes and combinations thereof (Table III and Appendix).

PTF validation test

We tested four PTFs that had been developed for other soil databases for estimating θ_{fc} and θ_{wp} in our data set. One of these pairs of functions was developed for 284 topsoil layers in an investigation of seedbeds in Sweden (Kritz, 1983) and the other three were derived from data from the USA (Rawls et al., 1982, 2003; Rawls & Brakensiek, 1989). In one of these PTFs, which was developed using a regression tree modelling approach (Rawls et al., 2003), water content at field capacity was estimated at 33 kPa. We transformed this value to our reference (10 kPa) by extrapolation; the slope was calculated from the estimated θ at 1500 and 33 kPa, respectively.

An independent data set consisting of 120 layers (0 to 100 cm depth in 10 cm intervals) from 12 soil profiles from agricultural regions in Sweden (Johansson et al., 1985) was used for testing the PTFs developed here and those developed from other databases (Rawls et al., 1982, 2003; Kritz, 1983; Rawls & Brakensiek, 1989).

Statistical treatment

Analysis of variance, covariance and stepwise multiple linear regression analysis was used (SAS software, 1999–2000, SAS Institute Inc., Cary, NC, USA) to evaluate the effects of depth, soil textural class, particle size classes, SOC and SOC classes on θ_{fc}, θ_{wp}, ε and ρ. Only variables significant at the 5% level were included in the resulting PTFs.

Table I. Characteristics of textural classes in topsoil (a) and subsoil (b). In rows: Number of samples (n), mean values for clay, silt and sand content ($g\,g^{-1}$) loss on ignition (LOI, $g\,100g^{-1}$), soil organic carbon (SOC, $g\,100g^{-1}$), soil water content ($m^3\,m^{-3}$) at wilting point (θ_{wp}) and field capacity (θ_{fc}), soil dry bulk density (ρ) and porosity (ε). In columns: The different textural classes clay, silty clay (Sic), silty clay loam (Sicl), sandy clay (Sac), clay loam (Cllo), sandy clay loam (Sacl), loam, silt loam (Silo), sandy loam (Sal), silt (Silt), loamy sand (Losa) and sand sorted by descending clay content (from left to right) as well as overall weighted means over these classes (Overall). Mean refers to the average value within a textural class. Intercept and slope refer to the linear regression equations for estimating the independent variables (y) as a function of SOC; y = intercept + 0.01*slope*SOC (only slopes that differed significantly from 0 were considered). The class Organic (Org) stands for soils with SOM > 12%. For this class an exponential function was used for calculating ρ, ρ = intercept* exp(0.01*slope*SOC). The parameters presented here refer to models 11 and 12 in Table III.

a) Topsoil	Clay	Sic	Sicl	Cllo	Sacl	Loam	Silo	Sal	Silt	Losa	Sand	Overall	Org
n	56	41	38	21	11	27	27	80	4	22	10	337	49
Clay content	0.551	0.465	0.339	0.336	0.270	0.196	0.150	0.108	0.105	0.062	0.035	0.276	
Silt content	0.289	0.452	0.581	0.350	0.184	0.410	0.670	0.207	0.842	0.113	0.052	0.351	
Sand content	0.160	0.083	0.080	0.314	0.546	0.394	0.180	0.685	0.053	0.825	0.913	0.373	
LOI content	7.16	6.98	6.58	4.95	4.27	4.81	5.70	3.65	7.25	3.68	2.50	5.34	51.0
SOC content	2.98	3.11	3.18	2.42	2.17	2.54	3.06	2.01	3.99	2.08	1.42	2.61	24.3
$n\theta_{fc}$	36	28	23	13	4	25	21	69	0	21	8	248	48
θ_{fc} mean	0.409	0.431	0.419	0.359	0.343	0.358	0.415	0.288	—	0.245	0.155	0.348	0.582
θ_{fc} intercept	0.409	0.363	0.286	0.269	0.343	0.225	0.356	0.214	—	0.117	0.061	0.271	0.484
θ_{fc} slope	0	2.2	4.8	3.6	0	5.2	2.2	4	—	6.4	8.3	4.2	0.4
$n\theta_{wp}$	39	29	28	14	9	11	21	15	4	5	1	176	40
θ_{wp} mean	0.233	0.214	0.139	0.150	0.137	0.084	0.076	0.077	0.056	0.077	0.049	0.153	0.229
n_ρ	56	41	38	21	11	27	27	80	4	22	10	337	18
ρ mean	1.26	1.28	1.25	1.49	1.52	1.39	1.22	1.45	1.00	1.38	1.43	1.35	0.51
ρ intercept	1.63	1.7	1.53	1.77	1.52	1.76	1.44	1.67	1.00	1.58	1.6	1.63	1.10
ρ slope	−12.5	−13.2	−8.9	−11.6	0	−14.5	−7	−11	1	−9.7	−11.9	−11.1	−3.6
$n\varepsilon$	56	41	38	21	11	27	27	80	4	22	10	337	43
ε mean	0.518	0.513	0.524	0.437	0.423	0.463	0.531	0.443	0.620	0.468	0.450	0.485	0.741
ε intercept	0.400	0.369	0.403	0.336	0.423	0.345	0.455	0.365	0.620	0.399	0.386	0.387	0.628
ε slope	4	4.7	3.8	4.2	0	4.6	2.5	3.9	0	3.3	4.5	3.9	0.47

b) Subsoil	Clay	Sic	Sac	Cllo	Sicl	Sacl	Loam	Silo	Silt	Sal	Losa	Sand	Overall
n	395	232	2	39	121	18	44	114	50	118	58	92	1283
Clay content	0.656	0.488	0.387	0.348	0.342	0.247	0.200	0.160	0.099	0.092	0.061	0.018	0.375
Silt content	0.289	0.459	0.133	0.349	0.589	0.197	0.399	0.713	0.844	0.265	0.110	0.054	0.384
Sand content	0.055	0.053	0.480	0.303	0.068	0.556	0.401	0.127	0.057	0.644	0.830	0.928	0.241
LOI	4.31	3.67	4.00	2.79	2.61	2.50	2.00	2.10	2.26	1.83	1.76	1.30	3.05
SOC	1.68	1.61	1.97	1.35	1.26	1.28	1.05	1.12	1.25	1.02	0.99	0.75	1.37
$n\theta_{fc}$	240	167	2	29	101	8	41	75	26	104	43	64	900
θ_{fc} mean	0.482	0.447	0.301	0.355	0.394	0.284	0.301	0.386	0.452	0.263	0.208	0.123	0.378
θ_{fc} intercept	0.423	0.368	0.301	0.355	0.394	0.285	0.301	0.365	0.295	0.225	0.126	0.021	0.325
θ_{fc} slope	3.2	4.6	0	0	0	0	0	1.9	12.3	3.7	7.4	15.6	5.1
$n\theta_{wp}$	303	141	2	14	69	12	25	98	50	36	24	29	803
θ_{wp} mean	0.297	0.253	0.158	0.184	0.181	0.136	0.135	0.096	0.067	0.065	0.035	0.027	0.203
θ_{wp} intercept	0.330	0.275	0.158	0.184	0.213	0.136	0.135	0.096	0.067	0.065	0.035	0.027	0.191
θ_{wp} slope	−2.0	−1.2	0	0	−2.5	0	0	0	0	0	0	0	−1.8
n_ρ	395	232	2	39	121	18	44	114	50	118	58	92	1283
ρ mean	1.32	1.41	1.63	1.57	1.51	1.56	1.65	1.47	1.31	1.53	1.53	1.51	1.43
ρ intercept	1.61	1.7	1.63	1.64	1.68	1.56	1.76	1.59	1.67	1.6	1.69	1.59	1.64
ρ slope	−17.2	−18.2	0	−5.3	−13.5	0	−10.7	−10.3	−29	−6.6	−16.8	−10.4	−14.8
$n\varepsilon$	395	232	2	39	121	18	44	114	50	118	58	92	1283
ε mean	0.520	0.486	0.391	0.415	0.445	0.417	0.385	0.456	0.520	0.423	0.426	0.433	0.47
ε intercept	0.431	0.390	0.391	0.415	0.393	0.417	0.359	0.417	0.39	0.405	0.368	0.408	0.41
ε slope	5.2	6	0	0	4.2	0	2.5	3.5	10.4	1.7	5.8	3.4	4.8

Table II. Mean soil water content ($m^3\ m^{-3}$) at wilting point (θ_{wp}) and field capacity (θ_{fc}), porosity (ε) and soil dry bulk density (ρ) for the textural and SOM classes according to the Swedish nomenclature for the classification of agricultural soils, i.e., lerfri ($\leq$2% clay), svagt lerig (2 to 5%), lerig (5–15%), LL (15–25%), ML (25–40), SL (40–60), mSL ($>$60% clay) and mf (SOM $<$2%), nm (2–3%), mm (3–6%), mr (6–12%). n is the number of samples for which measurement of θ_{wp}, θ_{fc}, ε and ρ were available. The values presented here refer to model 10 in Table III.

		n		θ_{wp}		θ_{fc}		ε		ρ	
Texture class	SOM class	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
lerfri	mf	0–2	17–52		0.020	0.185	0.141	0.449	0.426	1.455	1.531
lerfri	nm	0	0–3						0.472		1.387
lerfri	mm	0	0–2						0.455		1.425
lerfri	mr	0	0								
svagt lerig	mf	0–6	34–84		0.029	0.122	0.194	0.405	0.431	1.552	1.518
svagt lerig	nm	0–5	1–5		0.042	0.263	0.203	0.495	0.445	1.316	1.464
svagt lerig	mm	3–4	0–1	0.069		0.364	0.453	0.526	0.711	1.233	0.750
svagt lerig	mr	0	0								
lerig	mf	4–14	90–167	0.049	0.066	0.256	0.269	0.418	0.431	1.521	1.528
lerig	nm	6–45	32–46	0.067	0.064	0.267	0.396	0.438	0.510	1.469	1.310
lerig	mm	17–43	6–14	0.074	0.085	0.332	0.326	0.473	0.483	1.370	1.351
lerig	mr	11–14	3	0.059	0.034	0.428	0.486	0.574	0.572	1.088	1.110
LL	mf	0–1	62–74		0.118	0.316	0.351	0.392	0.418	1.600	1.577
LL	nm	1–4	8–12	0.121	0.119	0.339	0.368	0.448	0.439	1.450	1.506
LL	mm	14–26	4–12	0.095	0.106	0.361	0.356	0.458	0.428	1.412	1.499
LL	mr	7–9	0	0.104		0.393		0.526		1.218	
ML	mf	0	49–88		0.190		0.382		0.421		1.576
ML	nm	0–1	39–72		0.182	0.327	0.384	0.390	0.445	1.620	1.505
ML	mm	43–64	26–38	0.154	0.172	0.390	0.384	0.468	0.459	1.395	1.441
ML	mr	9–11	0	0.138		0.476		0.586		1.093	
SL	mf	0	53–88		0.260		0.433		0.460		1.479
SL	nm	0–1	90–155		0.269	0.324	0.426	0.442	0.469	1.420	1.460
SL	mm	32–53	66–80	0.234	0.259	0.404	0.442	0.491	0.507	1.347	1.338
SL	mr	17–18	18–25	0.211	0.205	0.454	0.612	0.552	0.716	1.175	0.705
mSL	mf	1	50–72	0.312	0.326	0.529	0.491	0.583	0.517	1.070	1.369
mSL	nm	1	96–123	0.304	0.319	0.463	0.483	0.603	0.515	1.000	1.343
mSL	mm	3–7	50–54	0.272	0.293	0.454	0.504	0.540	0.532	1.221	1.287
mSL	mr	7	9–13	0.225	0.255	0.382	0.591	0.639	0.719	0.881	0.675

Residuals were analysed graphically and tested for normality using the Shapiro-Wilk and Kolmogorov-Smirnov tests (proc univariate, SAS software). Root mean square error (RMSE) was used as a measure of model fit:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \tag{3}$$

where P_i and O_i are predicted and observed values, respectively, and n is the number of observations. The RMSE reflects a magnitude of the mean difference between observations and predictions but does not indicate if the estimate is biased. To quantify a systematic bias, we calculated also the mean bias error (MBE):

$$MBE = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \tag{4}$$

A positive value of MBE indicates over-prediction and a negative value indicates under-prediction.

Results and discussion

Depth affected the dependent variables significantly according to the analysis of covariance. This effect is probably related mainly to management (tillage of topsoil etc.) and to differences in SOM quality with depth. Therefore, we split the data set into topsoil (lower boundary 25 cm) and subsoil (below 25 cm depth) categories. In general, SOC and ε were greater in topsoil than in subsoil, whereas the relationship was the inverse for θ_{fc}, θ_{wp}, and ρ (Table I).

Among single independent variables, clay was the best predictor for θ_{wp}, the coarse fractions (0.2 to 6 mm) for θ_{fc} and SOC for ε and ρ (models 1 and 2; Table III). SOC helps to create more stable aggregates; hence, a better structured soil. Thus, mostly the larger soil pores are affected by SOC and, thus, water holding properties in the wet range (Rawls et al., 2003), whereas θ_{wp} is affected only marginally (model 3; Table III). This concurs with general

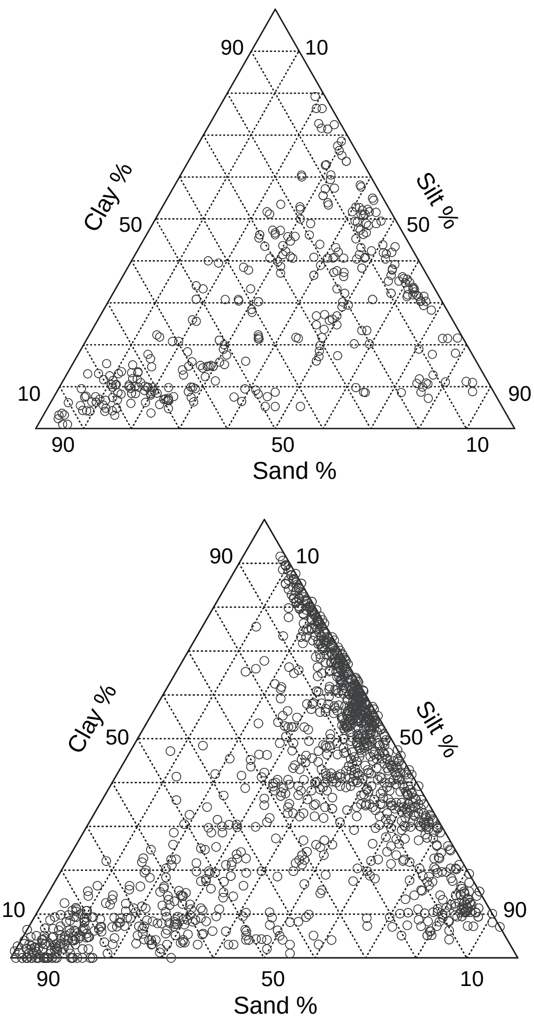

Figure 1. Percentage of clay ($\leq$2 μm), silt (2–60 μm) and sand (60–2000 μm) corresponding to fractions of the fine earth (< 2mm) in topsoil (A) and subsoil (B) layers. To use the diagram, locate the percentage of clay first and project horizontally inward. Do likewise for the percentage silt (down 30° left) or sand (up 30° left).

knowledge that soil water content at low matric suction is mainly determined by soil structure, which is strongly influenced by SOC. On the other hand, water content at high matric suction is mainly determined by soil texture. The relationships between particle size classes and θ_{wp}, θ_{fc} and the available water capacity of the soil (AWC; the difference between θ_{fc} and θ_{wp}) and between SOC and ρ are illustrated in Figure 2. θ_{wp} increases with clay and θ_{fc} decreases with sand content (or increases with clay and silt content since sand = 1 – clay–silt). AWC correlated positively with the silt content of the soils (Figure 2), which means that the soils in the lower right part of the texture triangle (silt, silt loam and silty clay loam) had the greatest AWCs (Figure 1; Table I). The slope of this linear relationship was almost identical for top- and subsoils but AWC in the subsoil was about 0.03 m^3 m^{-3} less than in the topsoil (Figure 2).

For the organic topsoils, particle sizes of the mineral components were only available for a few soils and PTFs were developed using only SOC. We could not detect a significant relationship between SOC and θ_{wp} at a 5% probability level. Thus, the mean value (0.229 m^3 m^{-3}) can be used as a predictor for θ_{wp} in these soils (Table I). SOC was positively correlated with θ_{fc} and ε and explained 33 and 60% of the variation in θ_{fc} and ε, respectively. Bulk density decreased exponentially with SOC and the coefficient of determination for this relationship was $R^2 = 0.87$. The slopes and intercepts of these functions are presented in Table I.

In general, most PTFs predict water content well at the dry end of the functions, near θ_{wp} and ε if ρ is an input variable, whereas prediction errors usually are large at intermediate moisture conditions such as at θ_{fc} (Cornelis et al., 2001). The correlation between ρ and θ_{fc} in our database was significant and *a priori* knowledge of ρ improved estimates of this characteristic parameter (Table III).

When the soils were grouped into the 12 textural classes according to international standards, textural class alone was a reasonably good predictor of the independent variables (model 11; Table III). The inclusion of SOC in addition to textural class into the PTFs increased goodness of fit, except for predicting θ_{wp} in the topsoil (model 12; Table III). According to analysis of covariance, textural class, SOC and also the interaction between textural class and SOC contributed significantly in explaining the observed variation in θ_{fc}, ε and ρ (Table I). The interactions between textural class and the particle fractions clay, silt and sand were not significant, which means that within each textural class, the particle size classes were of minor importance for estimating these four soil properties. Due to the interaction between textural class and SOC, we estimated the influence of SOC on θ_{fc}, ε, ρ and on θ_{wp} in the subsoil separately for each textural class. The resulting slopes and intercepts are presented in Table I.

Grouping the soils according to their clay and SOM content in line with Swedish standards (model 10; Table III), resulted in somewhat closer fit for predicting θ_{wp} but smaller R^2 and RMSE for θ_{fc}, ε and ρ compared with models developed from the textural classes and SOC (model 12; Table III). Although the interaction between SOM and the clay fraction was significant, the inclusion of this interaction in the PTF model reduced RMSE by less than

Table III. Measures of goodness-of-fit of the regression models for estimating water content at wilting point (θ_{wp}) and field capacity (θ_{fc}), porosity (ε) and soil dry bulk density (ρ) in topsoil and subsoil, i.e., R^2 and Root Mean Square Error (RMSE). Units for RMSE are in m^3 $100m^{-3}$ for θ and ε and in g cm^{-3} for ρ. The number of samples used for estimating the dependent variables is denoted by n. Parameter values for the regression models 1–9 are presented in the Appendix, those for model 10 in Table II and those for models 11–12 in Table I.

	θ_{wp}				θ_{fc}				ε				ρ			
	Topsoil $n=176$		Subsoil $n=803$		Topsoil $n=248$		Subsoil $n=900$		Topsoil $n=337$		Subsoil $n=1283$		Topsoil $n=337$		Subsoil $n=1283$	
Model	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
1) cl	0.81	3.20	0.85	4.2	0.43	6.7	0.53	8.8	0.16	6.2	0.19	7.2	0.13	0.17	0.12	0.21
2) sa+gravel	0.23	6.50	0.38	8.5	0.71	4.8	0.70	7.1	0.32	5.5	0.16	7.3	0.27	0.16	0.10	0.21
3) soc	ns	7.40	0.05	10.5	0.42	6.7	0.28	11.0	0.52	4.7	0.40	6.2	0.51	0.13	0.45	0.16
4) cl and soc	0.81	3.20	0.86	4.1	0.70	4.9	0.63	7.9	0.49	4.8	0.46	5.9	0.47	0.14	0.46	0.16
5) sa+gravel and soc	0.24	6.50	0.38	8.5	0.76	4.3	0.79	6.0	0.56	4.4	0.45	5.9	0.53	0.13	0.46	0.16
6) clay, sand and soc	0.83	3.1	0.86	4.1	0.80	3.9	0.79	6.0	0.56	4.5	0.48	5.8	0.53	0.12	0.49	0.16
7) Swedish size classes	0.85	2.90	0.89	3.6	0.90	2.8	0.85	5.1	0.73	3.5	0.63	4.9	0.72	0.10	0.62	0.14
8) International size classes	0.84	3.00	0.88	3.7	0.83	3.7	0.81	5.7	0.68	3.8	0.60	5.0	0.68	0.10	0.59	0.14
9) Internet. classes and ρ					0.86	3.4	0.90	4.0								
10) cl- and SOM classes	0.81	3.30	0.86	4.1	0.68	5.0	0.68	7.3	0.54	4.6	0.52	5.6	0.53	0.13	0.52	0.15
11) Textural classes	0.74	3.80	0.81	4.7	0.67	5.1	0.70	7.1	0.36	5.4	0.28	6.8	0.32	0.15	0.19	0.20
12) Textural classes and soc	0.74	3.80	0.79	4.8	0.78	4.1	0.78	6.1	0.59	4.2	0.55	5.4	0.59	0.12	0.55	0.15

*ns: not significant ($p \leq 0.05$)

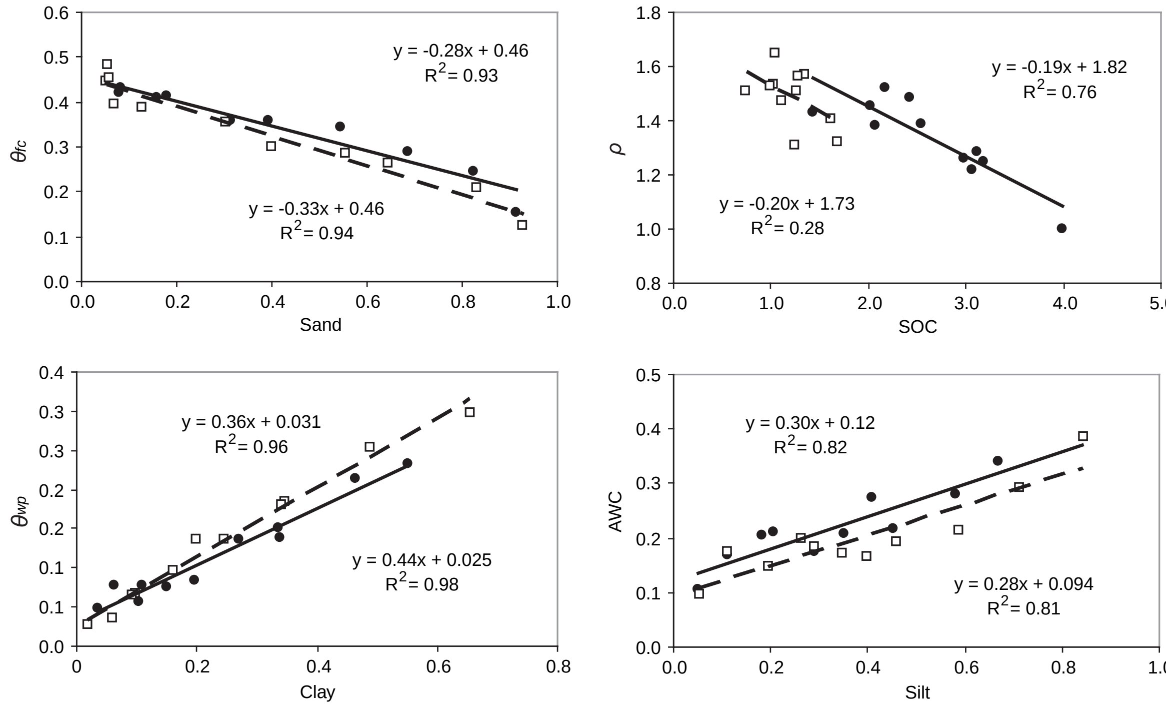

Figure 2. Relationship between particle size classes (averages for each soil textural class according to Table I), soil organic carbon (SOC) and other soil characteristic properties, i.e., between sand ($=1-$clay$-$silt; g g^{-1}) and water content at field capacity θ_{fc} (m^3 m^{-3}), between clay and water content at wilting point θ_{wp}, between silt and available water capacity (AWC) and between SOC and bulk density (ρ). Open and closed symbols refer to subsoil and topsoil, respectively. Slopes differed significantly between topsoil and subsoil only in the lower left plot.

5%. The means for the different clay- and SOM-groups are presented in Table II.

PTFs developed from the numerical values of the six fine-earth fractions and SOC without grouping resulted in the best model fit among the models tested here, when squares of the independent variables and also linear interactions between the variables were included in the regression (model 7, Table III). Including higher order interactions did not further reduce RMSE.

Aggregating the particle size classes into the three textural classes clay, silt and sand, and developing a PTF from clay, sand and SOC resulted in slightly higher RMSEs (model 6, Table III), but the inclusion of cubed terms as well as interactions between linear and quadratic terms improved the model significantly (model 8 in Table III). The resulting RMSEs were only slightly greater than those obtained for model 7, where all particle size classes were included (Table III).

The inclusion of ρ as a predictor for θ_{fc} improved the model fit further, whereas RMSE for estimating θ_{wp} could not be further reduced (model 9, Table III). The resulting transfer equations for models 1 to 9 including all variables that were significant at the 5% level are presented in the Appendix.

Validation

The models for estimating θ_{fc} and θ_{wp}, developed from other data sets (Rawls et al., 1982, 2003; Kritz, 1983; Rawls & Brakensiek, 1989), explained a relatively large portion of the variation in the measurements and resulted in reasonably low RMSE, but the estimates were more or less biased. The functions proposed by Rawls et al. (2003), which were developed from the US National Soil Characterization database performed much better than the others (Table IV) and had lower RMSEs than several of the models calibrated for our own data set. Clay, sand and SOC were used as the only regressors in these functions. The biases of the estimates were between 1.6 and 4.5% water content.

The estimations of θ_{wp}, θ_{fc}, ε and ρ using the different PTFs (models 1 to 6; Tables III and IV) for the independent validation data set resulted in model fits that could be expected from the calibration, i.e., large R^2 and small RMSE in the calibration corresponded generally to close model fit in the validation (Table V). Among the models calibrated for other databases (Table IV), also here the PTFs proposed by Rawls et al. (2003) performed best. For estimating θ_{wp} the model error was as low as for the best regression model calibrated for the Swedish database

Table IV. Results from four different pedotransfer functions developed from independent databases for estimating water content at wilting point (θ_{wp}) and field capacity (θ_{fc}) in topsoil and subsoil. The number of samples used for estimating the dependent variables is denoted by n. Model goodness-of-fit expressed as R^2, Root Mean Square Error (RMSE) and Mean Bias Error (MBE). Units for RMSE and MBE are in $m^3\ 100m^{-3}$.

	θ_{wp}						θ_{fc}					
	Topsoil $n=176$			Subsoil $n=803$			Topsoil $n=248$			Subsoil $n=900$		
Model	R^2	RMSE	MBE	R^2	RMSE	MBE	R^2	RMSE	MBE	R^2	RMSE	MBE
13) Rawls et al., 1982	0.72	3.90	12.7	0.80	4.8	7.1	0.72	4.7	15.6	0.77	6.2	13.9
14) Rawls & Brakensiek, 1989	0.72	3.90	12.7	0.80	4.8	7.1	0.64	5.3	−2.2	0.70	7.0	−3.3
15) Rawls et al., 2003	0.81	3.20	4.5	0.87	3.9	1.6	0.75	4.4	−4.1	0.75	6.5	−4.3
16) Kritz, 1983	0.82	3.10	2.6	0.82	4.5	−0.2	0.62	5.5	5.6	0.14	12.0	3.4

and the model bias was even lower. The estimation errors for θ_{fc}, ε and ρ were least for models 8 and 9 (Table V).

Normality tests revealed that the studentized residuals of models 6, 15 and 16 may not have been normally distributed for estimates of θ_{wp} in the topsoil and those of models 6 and 7 for estimates of θ_{fc} in the topsoil. For all other models the distribution of the residuals did not differ significantly from the normal distribution. The trend in the residual plots of model 15 disappeared when excluding some extreme soils with clay contents above 60% (Figure 3). This should be considered when applying model 15, which is developed for a database with much lower representation of heavy clay soils. The residual plot for model 7 suggests that the trend in residuals should be of minor importance for most applications, despite a slight deviation from normal distribution of the residuals (Figure 3).

Conclusions

Among single independent variables, clay was the best predictor for θ_{wp}, sand ($=1-$silt$-$clay) for θ_{fc} and SOC for ρ and ε. A high portion of the variability in θ_{wp} and θ_{fc} could be explained by soil texture and SOC (up to 90%) and root mean square errors (RMSEs) were $\leq 0.03\ m^3$ water m^{-3} soil in the best models. For the prediction of ρ and ε in the validation data set, the best PTF could only explain 40 to 43% of the total variability with corresponding RMSEs of 0.14 g cm^{-3} and 5.3% by volume, respectively.

The PTFs presented by Rawls et al. (2003) for estimating θ_{wp} performed well (low RMSE and bias)

Table V. Measures of goodness-of-fit of the PTFs for predicting water content at wilting point (θ_{wp}) and field capacity (θ_{fc}), porosity (ε) and. soil dry bulk density (ρ) in the independent data set (120 samples, 24 from topsoil and 96 from subsoil; Johansson et al., 1985), i.e., R^2, Root Mean Square Error (RMSE) and Mean Bias Error (MBE). Units for RMSE and MBE are in $m^3\ 100m^{-3}$ for θ and ε and in g cm^{-3} for ρ.

	θ_{wp}			θ_{fc}			ε			ρ		
Model	R^2	RMSE	MBE	R^2	RMSE	MBE	R^2	RMSE	MBE	R^2	RMSE	MBE
1) cl	0.82	4.1	−3.1	0.51	6.9	0.8	0.27	6.0	0.8	0.18	0.16	−0.02
2) sa+gravel	0.35	7.7	−2.4	0.70	5.4	3.5	0.10	6.6	1.8	0.08	0.18	−0.04
3) soc	0.17	8.6	−6.2	0.20	8.8	−5.2	0.32	5.8	−2.3	0.30	0.15	0.07
4) cl and soc	0.83	3.9	−2.4	0.53	6.7	−0.8	0.40	5.4	−0.2	0.32	0.15	0.07
5) sa+gravel and soc	0.36	7.6	−2.5	0.72	5.2	1.9	0.32	5.7	<0.1	0.30	0.15	0.01
6) clay, sand and soc	0.83	3.9	−3.1	0.74	5.1	1.5	0.40	5.4	−0.1	0.36	0.15	0.01
7) Swedish classes num	0.85	3.7	−0.6	0.64	6.0	−3.4	0.16	6.4	−6.3	0.22	0.16	0.10
8) International classes num	0.84	3.7	−2.8	0.75	4.9	1.3	0.43	5.3	−0.4	0.40	0.14	0.18
9) International classes and ρ				0.91	3.0	1.1						
10) cl- and SOM classes	0.81	4.1	−2.1	0.68	5.6	0.7	0.38	5.5	−0.4	0.36	0.15	0.02
11) Textural classes	0.79	4.3	−2.8	0.70	5.4	2.2	0.23	6.1	1.6	0.18	0.17	−0.04
12) Textural classes and SOC	0.79	4.3	−2.8	0.71	5.3	1.1	0.36	5.6	0.2	0.36	0.15	0.01
13) Rawls et al., 1982	0.75	4.8	3.6	0.72	5.3	15.3						
14) Rawls & Brakensiek, 1989	0.75	4.8	3.6	0.65	5.9	−1.1						
15) Rawls et al., 2003	0.84	3.7	−0.5	0.72	5.2	−2.5						
16) Kritz, 1983	0.77	4.5	−2.6	0.20	8.8	2.9						

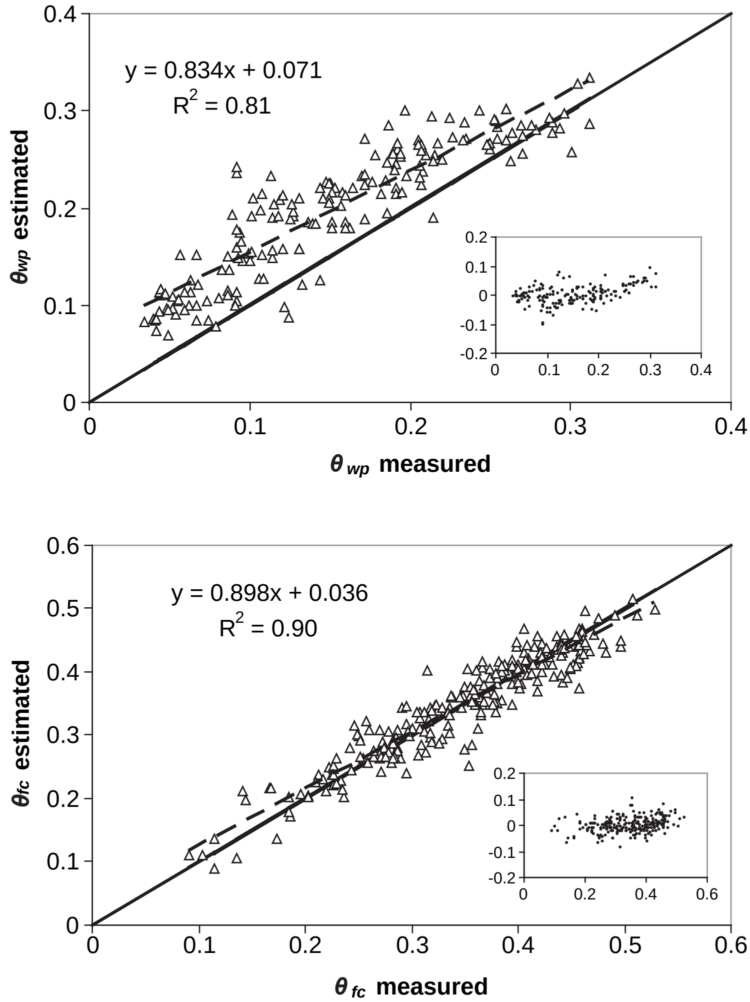

Figure 3. Measured and estimated water content at wilting point θ_{wp} ($m^3\ m^{-3}$) and at field capacity θ_{fc} ($m^3\ m^{-3}$) using models 15 and 7 (Table III; Appendix), respectively. Differences between the regression line (dashed) and the 1:1 line (continuous) illustrate model bias. Inserted small graphs show residuals plotted against measured θ_{fc}.

for the validation data and could be recommended for Swedish soils with clay contents below 60% if measurements of clay, sand and SOC are available. From the same regressor variables, θ_{fc}, ε and ρ can be estimated preferably using model 6 or 8. If ρ is known, θ_{fc} and ε can be estimated with greater accuracy (model 9). Although with somewhat lower accuracy, θ_{fc} could also be estimated satisfactorily using the PTF presented by Rawls et al. (2003), which indicates that the determination of plant available water by texture and SOC is quite independent of soil genesis and that certain PTFs are transferable between continents.

Acknowledgements

We would like to thank Jan Eriksson for help with Figure 1. Financial support from the Swedish Farmers' Foundation for Agricultural Research and the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) is acknowledged.

References

Akinremi, O. O., & McGinn, S. M. (1997). Regional simulation of fall and spring soil moisture in Alberta. *Canadian Journal of Soil Science*, *77*, 431–442.

Andersson, S., & Wiklert, P. (1977a). Studier av markprofiler i svenska åkerjordar. Del II. Norrbottens-, Västerbottens-, Västernorrlands- och Jämtlands län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 104*.

Andersson, S., & Wiklert, P. (1977b). Studier av markprofiler i svenska åkerjordar. Del III. Gävleborgs-, Kopparbergs- och Värmlands län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 105*. (In Swedish)

Andersson, S., & Wiklert, P. (1977c). Studier av markprofiler i svenska åkerjordar. Del IV. Älvsborgs-, Göteborgs- och

Bohus län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 106*. (In Swedish)

Berglund, K. (1982). Beskrivning av fem myrjordsprofiler från Gotland. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 125*. (In Swedish)

Berglund, K. (1995a). Optimal drainage depth of five cultivated organic soils. *Swedish Journal of Agricultural Research*, *25*, 185–196.

Berglund, K. (1995b). Properties of cultivated gyttja soils. *International Peat Journal*, *6*, 5–23.

Berglund, K. (1996). Cultivated organic soils in Sweden: properties and amelioration. Swedish University of Agricultural Sciences, Department of Soil Sciences. *Reports and Dissertations*, *28*, 39 pp.

Berglund, K., & Persson, L. (1996). Water repellence of cultivated soils. *Acta Agriculturae Scandinavica*, *46*, 145–152.

Berglund, K., Miller, U., & Persson, J. (1989). Gyttjejordar, deras sammansättning och egenskaper. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 160*. (In Swedish)

Bouma, J. (1989). Using soil survey data for quantitative land evaluation. *Advances in Soil Science*, *9*, 177–213.

Cazemier, D. R., Lagacherie, P., & Martin-Clouaire, R. (2001). A possibility theory approach for estimating available water capacity from imprecise information contained in soil databases. *Geoderma*, *103*, 113–132.

Cornelis, W. M., Ronsyn, J., van Meirvenne, M., & Hartmann, R. (2001). Evaluation of pedotransfer functions for predicting the soil moisture retention curve. *Soil Science Society of America Journal*, *65*, 638–648.

Danalatos, N. G., Kosmas, C. S., Driessen, P. M., & Yassoglou, N. (1994). Estimation of the draining soil moisture characteristics from standard data as recorded in soil surveys. *Geoderma*, *64*, 155–165.

Ekström, G. (1927). Klassifikation av svenska åkerjordar. Sveriges Geologiska Undersökning, Stockholm, Serie C, No 345, Årsbok 20. (In Swedish)

Eriksson, J., Andersson, A., & Andersson, R. (1997). Current status of Swedish arable soils. *Report 4778*. Naturvårdsverket Förlag, Stockholm (in Swedish with English summary and legends).

Eriksson, J., Andersson, A., & Andersson, R. (1999). Texture of agricultural topsoils in Sweden. *Report 4955*. Naturvårdsverket Förlag, Stockholm (in Swedish with English summary and legends).

Evans, S. P., Mayr, T. R., Hollis, J. M., & Brown, C. D. (1999). SWBCM: a soil water balance capacity model for environmental applications in the UK. *Ecological Modelling*, *121*, 17–49.

FAO. (1990). Guidelines for soil profile description. Soil Resources Development and Conservation Service, Land and Water Development Division, FAO, Rome.

Hutson, J. L., & Cass, A. (1987). A retentivity function for use in soil-water simulation models. *Journal of Soil Science*, *38*, 105–113.

Jansson, P-E., & Karlberg, L. (2004). Coupled heat and mass transfer model for soil-plant-atmosphere systems. Royal Institute of Technology, Departmentof Civil and Environmental Engineering, Stockholm, 431 pp. (ftp://www.lwr.kth.se/CoupModel/CoupModel.pdf).

Jansson, P-E., & Moon, D. S. (2001). A coupled model of water, heat and mass transfer using object orientation to improve flexibility and functionality. *Environmental Modelling & Software*, *16*, 37–46.

Johansson, W., Gustafsson, E-L., & McAfee, M. (1985). Description of physical properties of twelve cultivated soils. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 148*.

Kritz, G. (1983). Physical conditions in cereal seedbeds: a sampling investigation in Swedish spring-sown fields. Sveriges Lantbruksuniversitet, Institutionen för Markventenskap, *Rapporter från Jorbearbetningsavdelningen Nr 65* (in Swedish.)

Ljung, G. (1987). Mekanisk analys. Beskrivning av en rationell metod for jordartsbestämning. Institutionen för markvetenskap, avdelningen för lantbrukets hydroteknik, Uppsala, Sweden (in Swedish). (In Swedish)

Mayr, T., & Jarvis, N. J. (1999). Pedotransfer functions to estimate soil water retention parameters for a modified Brooks-Corey type model. *Geoderma*, *91*, 1–9.

Orlandini, S., Mancini, M., Paniconi, C., & Rosso, R. (1996). Local contributions to infiltration excess run-off for a conceptual catchment scale model. *Water Resources Research*, *32*, 2003–2012.

Puckett, W. E., Dane, J. H., & Hajek, B. F. (1985). Physical and mineralogical data to determine soil hydraulic properties. *Soil Science Society of America Journal*, *49*, 831–836.

Rajkai, K., Kabos, S., van Genuchten, M. T., & Jansson, P-E. (1996). Estimation of water-retention characteristics from the bulk density and particle-size distribution of Swedish soils. *Soil Science*, *161*, 832–845.

Rajkai, K., Kabos, S., & van Genuchten, M. T. (2004). Estimation of the water retention curve from soil properties: comparison of linear, non-linear and concomitant variable methods. *Soil and Tillage Research*, *79*, 145–152.

Rawls, W. J., Brakensiek, D. L., & Saxton, K. E. (1982). Estimation of soil water properties. *Transactions of ASAE*, *25*, 1316–1320.

Rawls, W. J., & Brakensiek, D. L. (1989). Estimation of soil water retention and hydraulic properties. In H. J. Morel-Seytoux (Ed.), Unsaturated Flow in Hydrological Modeling – Theory and Practice. pp. 275–300. NATO ASI Series C: Mathematical and Pysical Sciences, Vol. 275, Kluwer Academic Publishers.

Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M., & Bloodworth, H. (2003). Effect of organic carbon on soil water retention. *Geoderma*, *116*, 61–76.

Soil Survey Division Staff. (1993). *Soil Survey Manual, handbook 18*, Soil Conservation Service, US Department of Agriculture, US Government Printing Office Washington, DC.

Tietje, O., & Tapkenhinrichs, M. (1993). Evaluation of pedotransfer functions. *Soil Science Society of America Journal*, *57*, 1088–1095.

van Diepen, C. A. (1993). Two alternative methods for evaluating crop yield potential in the European Community. *Geoderma*, *60*, 359–376.

Vereecken, H., Maes, J., Feyen, J., & Darius, P. (1989). Estimating the soil moisture retention characteristic from texture, bulk density and carbon content. *Soil Science*, *148*, 389–403.

Wagner, B., Tarnawski, V. R., & Stöckl, M. (2004). Evaluation of pedotransfer functions predicting hydraulic properties of soils and deeper sediments. *Journal of Plant Nutrition and Soil Science*, *167*, 236–245.

Wassenaar, T., Lagacherie, P., Legros, J. P., & Rounsevell, M. (1999). Modelling wheat yield responses to soil and climate variablity at the regional scale. *Climate Research*, *11*, 209–220.

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983a). Studier av markprofiler i svenska åkerjordar.

Del I. Ultunajordar. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 132*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983b). Studier av markprofiler i svenska åkerjordar. Del V. Skaraborgs län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 130*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983c). Studier av markprofiler i svenska åkerjordar. Del VI. Örebro och Västmanlands län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 131*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983d). Studier av markprofiler i svenska åkerjordar. Del VII. Uppsala län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 133*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983e). Studier av markprofiler i svenska åkerjordar. Del VIII. Stockholms-, Södermanlands- och Östergötlands län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 134*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983f). Studier av markprofiler i svenska åkerjordar. Del IX. Hallands-, Jönköpings-, Kronobergs-, Kalmar- och Gotlands län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 135*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983g). Studier av markprofiler i svenska åkerjordar. Del X. Malmöhus och Kristianstads län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 136*. (In Swedish)

Wiklert, P., Andersson, S., Weidow, B., Karlsson, I., & Håkansson, A. (1983h). Studier av markprofiler i svenska åkerjordar. Del XI. Kristianstads län. Swedish University of Agricultural Sciences, Department of Soil Sciences, Division of Agricultural Hydrotechnics. *Report 137*. (In Swedish)

Wösten, J. H. M., Schuren, C. H. J. E., Bouma, J., & Stein, A. (1990). Functional sensitivity analysis of four methods to generate soil hydraulic functions. *Soil Science Society of America Journal*, *54*, 832–836.

Wösten, J. H. M., Pachepsky, Y. A., & Rawls, W. J. (2001). Pedotransfer functions: bridging the gap between available basic soil data and missing hydraulic characteristics. *Journal*

Appendix A

Coefficients of multiple linear regression models for predicting soil water content ($m^3\ m^{-3}$) at wilting point (θ_{wp}) and field capacity (θ_{fc}), porosity (ε) and soil dry bulk density (ρ) as function of particle size classes[§] ($g\ g^{-1}$) and soil organic carbon (SOC; $g\ 100g^{-1}$) in top- and subsoil. Models 1 to 9 have the general form $y = X\beta$, where y is the response vector, X is the matrix of regressor variables and β is the vector of regression coefficients. For example, the pedotransfer equation for projections of θ_{wp} according to model 8 is: $\theta_{wp} = 0.0078 + 0.3303$ clay $+ 0.0587$ soc*clay $+ 0.0124$ soc*sand − 0.0104 soc^2*clay. Only variables that improved fit significantly at the 5% level were included in the stepwise regression models. Indicators for model goodness-of-fit are presented in Tables III and V.

	θ_{wp}		θ_{fc}		ε		ρ	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Model 1:								
intercept	0.0284	0.0368	0.2699	0.2433	0.4488	0.4210	1.4336	1.5427
cl	0.3790	0.4048	0.3247	0.3742	0.1304	0.1301	−0.3139	−0.2734
Model 2:								
intercept	0.1919	0.2475	0.4560	0.4723	0.5353	0.4981	1.2182	1.3764
sa+gravel	−0.1472	−0.2579	−0.2476	−0.3397	−0.1271	−0.1017	0.3233	0.2178
Model 3:								
intercept	0.0788	0.1236	0.1870	0.2582	0.3774	0.3953	1.6384	1.6444
SOC	0.0202	0.0429	0.0580	0.0684	0.0348	0.0434	−0.0945	−0.1195
Model 4:								
intercept	0.0284	0.0140	0.1103	0.1625	0.3697	0.4057	1.6693	1.5994
cl	0.3790	0.5050	0.5165	0.4565				0.1111
SOC		0.0144	0.0754	0.0742	0.0403	0.0235	−0.1168	−0.0787
SOC*cl		−0.0504	−0.1193	−0.0997	−0.0098	0.0308	0.0391	−0.0857
Model 5:								
intercept	0.2172	0.2343	0.3749	0.4030	0.4089	0.4170	1.5815	1.6270
sa+gravel	−0.1599	−0.2507	−0.2045	−0.3018	−0.0554	−0.0624	0.1171	0.0965
SOC	−0.0072	0.0084	0.0259	0.0422	0.0375	0.0520	−0.1078	−0.1608
Model 6:								
intercept	0.0086	0.0379	0.4384	0.3692	0.3843	0.3901	1.6333	1.6552
clay	0.4473	0.4352		0.0784		0.0408		
sand			−0.3839	−0.296				−0.0561
SOC				0.0355	0.0448	0.0570	−0.1233	−0.1525
SOC*clay	−0.0157	−0.0213						−0.0533
SOC*sand	0.0123	−0.0118	0.0796	0.0314	−0.0204	−0.0435	0.0433	0.1160

Appendix *(continued)*

	θ_{wp}		θ_{fc}		ε		ρ	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Model 7:								
intercept	−0.0108	0.0016	0.3058	0.0843	0.3676	0.4004	1.6597	1.8451
SOC	0.0329				0.0296	−0.1157	−0.0992	
cl	0.4184	0.9424	0.3467	0.4947	−0.3542	−0.4232	1.1983	
fsilt			−1.2230					
msilt	−0.2277			−0.3899		−0.6073	−0.4920	0.7419
csilt			0.2148	0.4583		0.5631		
fsand								−0.3153
sa			−0.9503	−0.0858		0.2698		−0.8756
SOC^2	−0.0067		−0.0056	0.0031				−0.0085
cl^2		−0.5815			0.5433	0.5273	−1.6143	−0.5142
$fsilt^2$		−0.4894	2.1581	1.0266		0.8117		−3.2046
$msilt^2$				1.2814		1.2041		−3.0954
$csilt^2$						−0.8551	−0.9803	
$fsand^2$				0.1731	0.1166		−0.3110	
sa*sa			0.6917		0.1235	−0.3594	−0.3034	0.8585
SOC*cl		−0.0267				0.1899		−0.1667
SOC*fsilt	−0.0392		0.1500				0.1290	0.2948
SOC*msilt	0.0843		0.1125	0.1479		0.3171		−0.5905
SOC*csilt						0.1706		
SOC*fsand			0.0731			0.1243		
SOC*sa	0.0199		0.0925	0.1098		0.1916		−0.1332
cl*fsilt					1.1129	0.4869	−3.6227	
cl*msilt						0.5348		
cl*csilt		−0.443						−1.3805
cl*fsand		−0.5526	−0.8518					1.3858
cl*sa		−0.5379	0.7817					
fsilt*msilt						−0.7612		3.9677
fsilt*csilt								−3.0093
fsilt*fsand		0.8502						
fsilt*sa			2.6232					
gmj*csilt					1.0732			
gmj*fsand								
gmj*sa				1.7050				3.6864
csilt*fsand				0.2419	0.2636			−1.2682
csilt*sa		1.1309	1.1974			−1.8692		
fsand*sa			0.3312					
Model 8:								
intercept	0.0078	−0.0114	0.3907	0.4063	0.4115	0.4998	1.4290	1.3762
SOC				0.0044	0.0409	0.0823	−0.1456	−0.2184
clay	0.3303	0.7502				−0.9261		2.3444
sand		0.0627	−0.3610	−0.3040		−0.0682	0.4405	0.1419
SOC^2			0.0101	0.0235				
SOC*clay	0.0587	−0.0237		−0.0781			0.4024	
SOC*sand	0.0124		0.1269			−0.2657		0.6128
$clay^2$		−0.3439		0.2227		1.9390		−4.7358
clay*sand				−0.2448	−0.6089	0.4127	0.6069	−0.8757
$sand^2$		−0.0524						
SOC^3				−0.0020		−0.0019		0.0057
SOC^2*clay	−0.0104		−0.0168		−0.0031	0.0359		−0.1069
SOC^2*sand			−0.0230			0.0234		−0.0627
SOC*$clay^2$						−0.2411	−0.5150	0.6248
SOC*$sand^2$						0.1751		−0.3825
$clay^3$			0.2640		0.2276	−0.8169		1.9286
$clay^2$*sand		−0.6673						
$sand^2$*clay				0.5845				
$sand^3$							−0.3253	
Model 9								
intercept			0.4055	1.5835				
clay			−0.3170					
sand				−1.0939				

Appendix *(continued)*

	θ_{wp}		θ_{fc}		ε		ρ	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
ρ				−1.4303				
clay^2				0.1669				
sand^2				0.7891				
ρ^2				0.5659				
sand^3			−0.2263	−0.5321				
ρ^3				−0.0870				
SOC*clay				−0.2261				
SOC*ρ			0.0943					
Clay*sand			−1.7687					
Sand*ρ			−0.1232	0.4959				
SOC^2*clay				0.0167				
clay^2*ρ			0.4323					
sand^2*SOC			0.1075	0.0700				
sand^2*clay				−0.7048				
ρ^2*SOC			−0.0553					
SOC^2*sand^2			−0.0156					
SOC^2*clay^2			−0.0077					
clay^2*sand^2				1.9390				
sand^2*ρ^2				−0.1278				
ρ^2*SOC*clay				0.0701				

[§] clay (≤2 μm) and sand (60–2000 μm) correspond to fractions of fine earth (<2mm) and cl (<2 μm), fsilt (2–6 μm), msilt (6–20 μm), csilt (20–60 μm), fsand (60–200 μm), sa (0.2–2 mm) and gravel (2–6 mm) correspond to fractions of all particle sizes (including gravel).