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A pedotransfer function to evaluate the soil profile textural heterogeneity using proximally sensed apparent electrical conductivity

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ABSTRACT

Since soil texture is difficult to quantify, its determination is often restricted to the topsoil. To improve its mapping accuracy, observations of the apparent electrical conductivity (ECa) obtained from proximal soil sensors are increasingly being used due to its close relationship with soil texture under non-saline conditions. However, a single ECa measurement does not allow an unambiguous interpretation of both the topsoil texture and its vertical distribution, because of its bulk support over the entire profile. Therefore we selected 88 soil profiles with a 'pseudo-homogeneous' textural composition from a database containing 1500 profiles with nine textural fractions and the organic matter content analysed for every horizon. These profiles were revisited and the ECa was measured with an EM38DD sensor. With these data we obtained the following pedotransfer function (PTF): ECa-V = 16.2 + 1.314% clay, with $R^2 = 0.81$. This function allows converting a topsoil clay percentage into a reference ECa value measured with the vertical coil orientation (ECa-V), assuming standard temperature and moisture conditions and a dominance of mica clay minerals. The ratio between the observed ECa-V and this reference ECa-V value is a measure of the soil profile textural heterogeneity: if this ratio is near to one, the profile is quasi-homogeneous; a ratio exceeding one indicates the presence of a more conductive material deeper in the soil profile, and *vice versa*. To explore this idea we considered an intensively surveyed area of 3000 km^2 in Belgium with a wide soil textural variation. Based on our PTF, a regional-scale topsoil clay map was converted into a reference ECa-V map which was found to be a valuable aid in evaluating the soil profile textural heterogeneity by field-measured ECa-V data.

1. Introduction

The ability to characterize soil by its electrical properties has been studied intensively, originally to characterize mainly soil salinity under laboratory conditions (Richards, 1954). But also in non-saline soils, in-situ measurements of the apparent electrical conductivity (ECa) were found to be highly informative, mainly in respect to investigating variations in clay and soil organic matter (SOM) contents (Corwin and Lesch, 2005; McCutcheon et al., 2006). The advantage of measuring ECa is the ability to operate with mobile and non-destructive proximal soil sensors based on electromagnetic induction (EMI) (like the EM38, Geonics Inc., Mississauga, Ontario, Canada) or electrical resistivity (like the Veris 2000XA, Veris Tech., Salina, Kansas, USA). Both measurement principles integrate the response of a soil volume down to an effective depth, which typically extends to 1.2–1.6 m for agricultural purposes, depending on the inter-coil or inter-electrode distance (McNeill, 1980b, Sudduth et al., 2003).

The availability of mobile proximal soil sensors in combination with GPS referencing offers the opportunity to complement the limited density of direct soil samples, on which soil properties are analyzed in the laboratory, with high-resolution measurements reaching a density of one observation per m^2. Such a wealth of secondary information has triggered research about the creation of pedotransfer functions (PTFs) linking ECa with clay and/or SOM concentrations. Several studies report on such PTFs, mostly using a depth-weighted combination of soil properties (Domsch and Giebel, 2004; Sudduth et al., 2005). For EMI sensors this depth-weighting is based on the depth-sensitivity curve of McNeill (1980b).

At present, many countries possess coverage of soil maps, often with soil texture as a key variable, complemented with detailed soil databases. Institutions, like the European Commission or the UN-Food and Agriculture Organization, have contributed further in pooling and standardizing such databases (Nemes et al., 1999; Henderson et al., 2005). However, soil sampling of profile horizons is labour-intensive and therefore most soil studies focus on the topsoil only (Kerry and Oliver, 2007; Garten et al., 2007). It is our experience that the subsoil is often much more heterogeneous than the topsoil, both laterally and vertically, especially in arable land where the topsoil is regularly being mixed by tillage (Vitharana et al., 2006).

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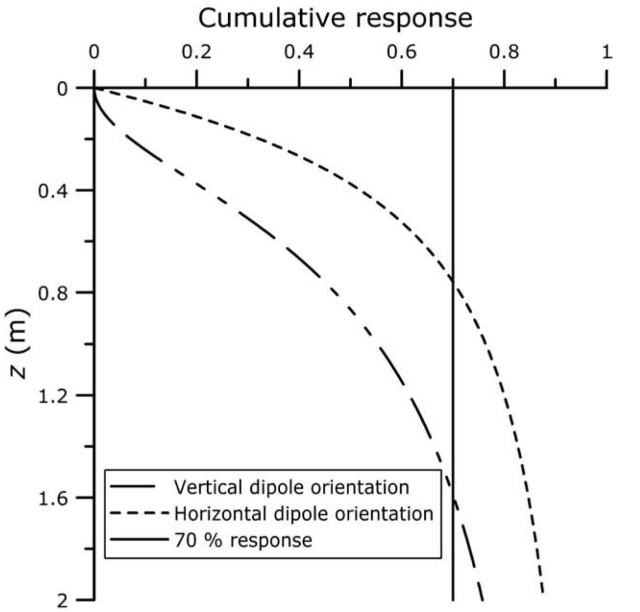

Fig. 1. Cumulative response of ECa as a function of *z* for the EM38 in the vertical and horizontal orientation.

Our idea was to use the available and mapped topsoil properties and convert them by a PTF into reference ECa (ECa-ref) values assuming homogeneous soil textural conditions down to the measurement depth of ECa. These ECa-ref values could then be used to evaluate observed ECa (ECa-obs) values. Strong deviations in soil texture are likely to indicate a violation of the homogeneous profile assumption. In such a situation there is either a textural discontinuity (as observed by e.g. Saey et al., 2008) or man-induced soil structure and/or texture mixing disturbances. Given the rapidly increasing coverage of ECa-measured land (some western countries have extensive programmes of ECa measurements to support precision agriculture), the availability of ECa-ref values would allow a more absolute evaluation of ECa-obs and could be used to direct additional sampling and verification activities more efficiently by targeting deviations in expected ECa values.

The goals of this study were: (1) to establish a PTF between topsoil properties of soil profiles with 'pseudo-homogeneous' textural composition and ECa, resulting in ECa-ref values; (2) to evaluate the ratio of ECa-obs to ECa-ref as a measure of the degree of soil profile textural heterogeneity; and (3) to apply this idea to a regional soil texture map to create a regional-scale map of ECa-ref values. As a case study the province of East-Flanders in Belgium was used because this area has a wide variability of topsoil texture which has been mapped quantitatively.

2. Principle of operation and depth sensitivity of the EMI soil sensor

In our test case, ECa was measured using the EM38DD soil sensor. This is a dual-dipole sensor, which consists of two single EM38 units positioned perpendicular to each other, i.e. one instrument is oriented horizontally and the other vertically. In each unit, an alternating current passes through a coil, generating a primary electromagnetic field. This induces small eddy currents in the soil, which generate a secondary electromagnetic field that is sensed by a receiver coil located 1 m from the transmitter coil. The ratio of the secondary to the primary field provides a measure of the ECa of the soil (McNeill, 1980b; Cockx et al., 2007). Many factors contribute to the soil ECa, including the amount and connectivity of soil water, soil structure, dissolved electrolytes and the conductivity of the minerals (McNeill, 1980a; Hartsock et al., 2000). Generally, the ECa readings are influenced by all these factors, and the existing relationships are complex and interacting, but research has found that soil texture has a generally dominant effect (Corwin and Lesch, 2005; McBratney et al., 2005).

The two coil orientations of the EM38DD result in a different depth response. The cumulative response from the soil volume above depth z (in m) was given by McNeill (1980b), both for the vertical ($R_v(z)$) and the horizontal orientation ($R_h(z)$):

$$R_v(z) = 1-\left(4\cdot z^2+1\right)^{-0.5}, \tag{1}$$

$$R_h(z) = 1-\left(4\cdot z^2+1\right)^{0.5}+2\cdot z. \tag{2}$$

From these it can be deduced that 70% of the response is produced by the top 1.60 m for $R_v(z)$ and by the top 0.75 m for $R_h(z)$ (Fig. 1).

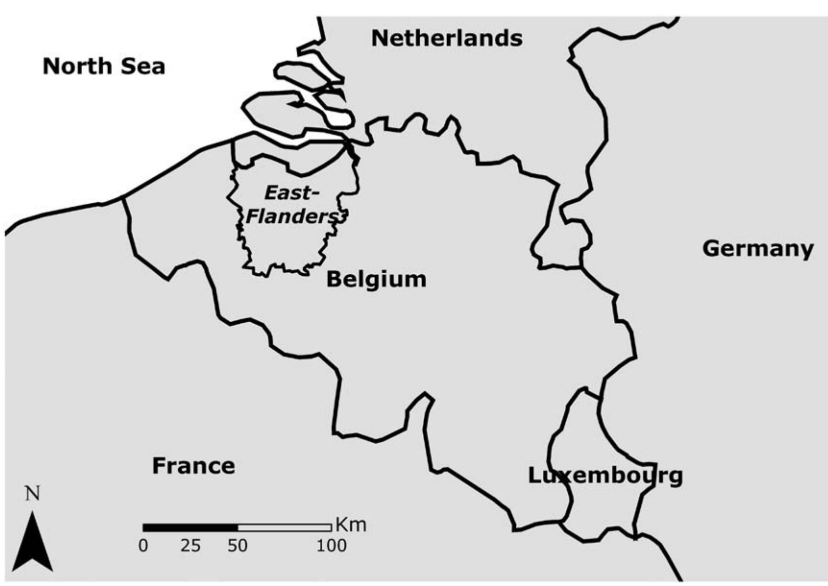

Fig. 2. Localization of the study area in Belgium.

3. Soil texture data base

The study was conducted over an area covering 3000 km^2 located in the north of Belgium: the province of East-Flanders (Fig. 2). Van Meirvenne and Van Cleemput (2005) found that within this province a large textural variability exists: 11 of the 12 textural classes of the USDA texture triangle are found (only the class 'sandy clay' is absent, Fig. 3).

During the Belgian soil survey, which was conducted between 1947 and 1973, 4887 topsoil (0–30 cm) locations were sampled and additionally 1500 soil profiles were dug down to 1.5 m and sampled per horizon within this area. All samples were analysed for soil texture using the conventional sieve-and-pipette method and split into nine fractions: 0–2 μm (Fr_{0-2}), 2–10 μm (Fr_{2-10}), 10–20 μm (Fr_{10-20}), 20–50 μm (Fr_{20-50}), 50–100 μm (Fr_{50-100}), 100–200 μm ($Fr_{100-200}$), 200–500 μm ($Fr_{200-500}$), 500–1000 μm ($Fr_{500-1000}$) and 1000–2000 μm ($Fr_{1000-2000}$). Also the soil organic matter (SOM) content was determined by the Walkley and Black method.

The ECa equivalent texture for the entire soil profile was obtained by weighting each horizon with the EM38 depth response curve according to the horizon boundaries. For example, the weighted clay content, $Fr_{0-2,w}$, over the total soil profile was obtained from:

$$Fr_{0-2,w} = \frac{Fr_{0-2,H_1} \cdot (R(z_1)) + Fr_{0-2,H_2}(R(z_2) - R(z_1)) + \ldots + Fr_{0-2,H_n}\left(R\left(z_n = z_{\text{lower boundary}}\right) - R(z_{n-1})\right)}{1 - R\left(z_n = z_{\text{lower boundary}}\right)} \quad (3)$$

with z_i the depth of the lower boundary of horizon H_i ($i = 1,2,\ldots, n$), z_n the depth of the lower boundary of the deepest horizon of which textural data are available, $Fr_{0-2,H1}$the clay content of horizon H_i and $R(z_i)$ the cumulative EM38 response from the soil above z_i. To relate $Fr_{0-2,w}$ to the apparent electrical conductivity measured with the sensor in the vertical orientation (ECa-V), the vertical cumulative response function $R_v(z)$ (Eq. (1)) was used in Eq. (3). Similarly for the apparent electrical conductivity measured with the sensor in the horizontal orientation (ECa-H), Eq. (2) was used.

The lower boundary of the soil profile descriptions was mostly 1.5 m. However, the response of the measured ECa signal still has a contribution of the soil volume below 1.5 m. This is 32% for the vertical and 16% for the horizontal coil orientations, respectively (Fig. 1). Therefore, the relative response of each soil horizon between the depths z_1 and z_2 was calculated by dividing its response ($R(z_2) - R(z_1)$) by the total response from the top 1.5 m (R(1.5 m)) (representing 68% and 84% of the total ECa response, respectively).

4. Selection of soil profiles with 'pseudo-homogeneous' textural composition

To investigate the relationship between ECa and the soil textural composition, homogeneous soil profiles are required. Since texturally homogeneous soil profiles are extremely rare, we used a selection criterion to find profiles with 'pseudo-homogeneous' textural composition: the deviation in clay content (Fr_{0-2}) between the top- and subsoil horizons was set to be less than 10%. Out of the available 1500 profiles, only 88 met this criterion and Fig. 4 shows their locations. Somewhat to our surprise these profiles were distributed over the entire province, which indicated a good level of aerial representation.

All of the 88 soil profiles with 'pseudo-homogeneous' textural composition were revisited and a pooled soil sample was taken by taking three samples from the top- and subsoil within a 2.5 m radius in respect to the reported coordinates of the National Soil Survey. These samples were air-dried to analyze the SOM content. The 88 locations were also classified into pasture or arable to account for the influence of recent land use on the SOM. This distinction was made because we expected clearly different SOM concentrations between them (no other land uses were visited).

Five profiles were selected to represent the different soil regions of the province. Their topsoil samples were analysed for the cation exchange capacity (CEC) by the ammonium-acetate method (Schollenberger and Simon, 1945). The CEC values ranged between 15.8 and

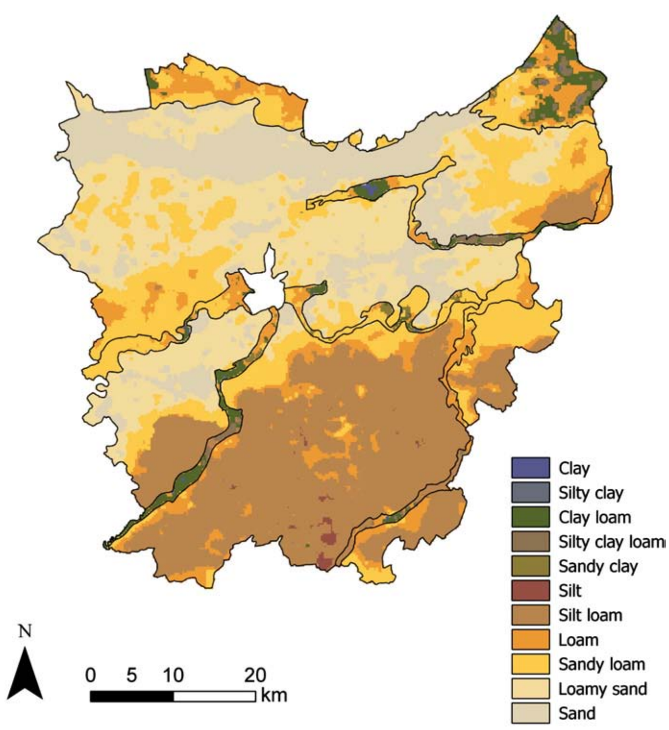

Fig. 3. Soil texture map of East-Flanders classified according to the USDA soil textural triangle (Van Meirvenne and Van Cleemput, 2005) (the city of Ghent was blanked).

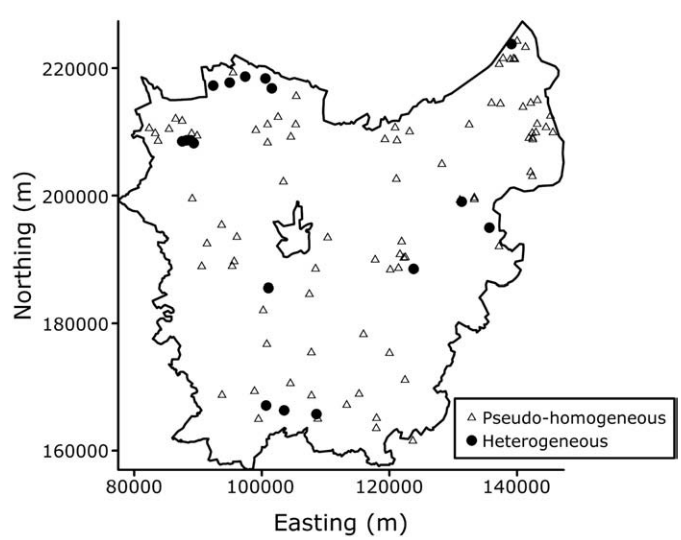

Fig. 4. Localization of the 88 soil profiles with 'pseudo-homogeneous' textural composition and 17 soil profiles with heterogeneous textural composition inside East-Flanders.

35.9 cmol(+) kg^{-1} clay, with an average of 21.8 cmol(+) kg^{-1} clay. These moderate CEC values all indicated by a dominance of mica (illite) clay minerals, typically having a CEC between 15 and 40 cmol (+) kg^{-1} (Hillel, 1998).

5. ECa measurements

At each of the 88 revisited soil profiles with ‘pseudo-homogeneous’ textural composition, ECa was measured with an EM38DD soil sensor. To avoid instrument drift (Robinson et al., 2004) a precise calibration procedure was performed at each of these 88 locations. Six ECa measurements were taken by the manually operated EM38DD sensor within a small area of 2.5 m radius, both in the vertical (ECa-V) and in the horizontal (ECa-H) orientation. The mean of these six ECa-V and ECa-H measurements was attributed to the central coordinates of this location.

Since measurements were conducted under different field conditions, both the ECa values were standardized to a temperature of 25 °C, using the following temperature standardization equation (Slavich and Petterson, 1990):

$$ECa_{25} = ECa \cdot \left(0.447 + 1.4034 \cdot \exp\left(-\frac{T}{26.815}\right)\right) \quad (4)$$

with ECa_{25} the standardized ECa at a temperature of 25 °C and T the soil temperature in degrees Celsius measured at a depth of 20 cm at each location. The temperature standardization coefficients were considered to be insensitive to the exact depth of soil temperature measurements, as reported by Sheets and Hendrickx (1995).

To minimize the influence of a strongly varying soil water content on the conductivity measurements, soil water tension was measured with mobile field tensiometers (Feldtensiometer, Umwelt Gerate Technik Müncheberg, Germany). At each of the 88 locations, three tensiometers were inserted to the depths 0.3, 0.6 and 0.9 m below the soil surface. Only when a near to field capacity moisture tension was observed, ECa measurements were taken.

Table 1 provides the descriptive statistics of the particle size fractions of the 88 soil profiles with ‘pseudo-homogeneous’ textural composition as taken from the soil database weighted by the vertical response curve (hence the subscript ‘w’). Most textural fractions showed a large spread, except the very coarse sand fractions (>500 µm) which contained rarely a few grains. The weighted clay fraction ranged from 0.2 to 56.5% with a coefficient of variation (CV) of 94%, which is quite large. The fraction with the largest CV (127%) was the 200–500 µm fraction. The texture class which corresponded to the mean values of the three major textural fraction was loam (according to the USDA soil texture triangle), indicating the central positions of these mean values. The corresponding ECa measurements and SOM measurements showed also a large variation, although less. The ECa values ranged from very low (5–9 mS m^{-1}) to values close to 100 mS m^{-1}. Their distributions had a CV between 62 and 68% with the mean ECa-V value being slightly larger than the mean ECa-H. The SOM contents indicate rather moderate SOM contents, without the presence of e.g. boggy or peaty conditions.

Table 1
Descriptive statistics of profile weighted textural fractions ($Fr_{-,w}$) determined with the vertical response curve (Eq. (1)) for the 88 soil profiles with ‘pseudo-homogeneous’ textural composition and the recently observed ECa and SOM (m: mean, s^2: variance).

		Minimum	Maximum	m	s^2
ECa-V	(mS m^{-1})	9	106	39	581
ECa-H	(mS m^{-1})	5	97	32	487
$Fr_{0-2,w}$	(%)	0.2	56.5	17.5	272.0
$Fr_{2-10,w}$	(%)	0.0	19.0	5.6	22.9
$Fr_{10-20,w}$	(%)	0.0	15.5	6.5	23.3
$Fr_{20-50,w}$	(%)	1.1	64.4	25.4	305.5
$Fr_{50-100,w}$	(%)	1.6	44.1	18.3	97.6
$Fr_{100-200,w}$	(%)	0.2	70.3	22.7	575.2
$Fr_{200-500,w}$	(%)	0.1	23.1	4.0	26.0
$Fr_{500-1000,w}$	(%)	0.0	1.0	0.1	0.0
$Fr_{1000-2000,w}$	(%)	0.0	0.5	0.0	0.0
SOM (0 m–0.3 m)	(%)	0.4	13.8	3.8	8.1

Table 2
Pearson correlation coefficients between the two ECas and the profile weighted textural fractions ($Fr_{-,w}$) and SOM content.

	n	ECa-V	ECa-H
$Fr_{0-2,w}$	88	0.899**	0.919**
$Fr_{2-10,w}$	88	0.830**	0.866**
$Fr_{10-20,w}$	88	0.648**	0.661**
$Fr_{20-50,w}$	88	0.199	0.135
$Fr_{50-100,w}$	88	−0.500**	−0.561**
$Fr_{100-200,w}$	88	−0.714**	−0.694**
$Fr_{200-500,w}$	88	−0.644**	−0.627**
$Fr_{500-1000,w}$	69	−0.235*	−0.233
$Fr_{1000-2000,w}$	12	−0.230	0.092
$Fr_{0-10,w}$	88	0.894**	0.917**
$Fr_{0-20,w}$	88	0.881**	0.901**
ESOM (0 m–0.3 m)	88	0.652**	0.702**

*Significant at 5% level of significance.
**Significant at 1% level of significance.

6. Pedotransfer function

The Pearson correlation coefficients between the ECa measurements and the weighted textural fractions and top SOM content are given in Table 2. A continuous sequence was found starting with the largest positive correlation with $Fr_{0-2,w}$ (r = 0.899 with ECa-V), over weak correlations with the silt fractions (r = 0.199 for $Fr_{20-50,w}$ with ECa-V) to a moderately large negative correlation with the sand fractions (r = −0.714 for $Fr_{100-200,w}$ with ECa-V). As mentioned before the very coarse sand fractions were not found in all samples. Obviously, the compositional nature of soil textural fractions (they sum to 100%) is linked to this observation: the more clay, the less silt and sand. So all these fractions cannot be considered as independent variables. Aggregations of two or more fractions ($Fr_{0-10,w}$ and $Fr_{0-20,w}$) did not improve the correlation compared to the $Fr_{0-2,w}$ fraction. The SOM had a moderately strong correlation (0.652 with ECa-V). Similar results were found with ECa-H.

A multiple linear regression analysis was conducted using S-PLUS (Insightful Corporation, Seattle, USA) to identify the best linear combination of predictors (weighted textural fractions and top SOM) that correlate maximally with the predicted variable, i.e. ECa-V. We used a stepwise removing procedure where the least influencing predictor variable was removed in turn. However, the compositional nature of the textural fractions violates the assumption of independent variances and covariances which could result in a bias (Duffera et al., 2007). Therefore we decided to exclude the sand fractions (>50 µm) from the multiple linear regression analysis (Vitharana et al., 2008). So our starting model contained the following variables:

$$\text{ECa-V} = \beta_0 + \beta_1 \cdot Fr_{0-2,w} + \beta_2 \cdot Fr_{2-10,w} + \beta_3 \cdot Fr_{10-20,w} + \beta_4 \cdot Fr_{10-50,w} + \beta_5 \cdot SOM + \varepsilon \quad (5)$$

with β_i the coefficient of the ith predictor variable (i = 1,..., 5) and ε the difference between the predicted and observed value of ECa-V. A similar analysis was conducted for ECa-H.

The 88 soil profiles were split in two classes: the arable fields (53 profiles) and the pasture fields (35 profiles) to account for the effect of land use on the SOM content.

For ECa-V both land use types resulted in only one significant predictor variable: $Fr_{0-2,w}$. Therefore both land use classes were pooled. This resulted in the PTF for ECa-V:

$$\text{ECa-V} = 16.2 + 1.314 \cdot Fr_{0-2,w} \quad (6)$$

Table 3
Fitting parameters the regression model for ECa-V (Eq. (5)) obtained with the stepwise multiple linear regression analysis (s: standard error; t: Student's-t-test of significance, p: probability level).

	Value	s	t-statistic	p-value
Intercept	16.2	1.7	9.814	0.0000
$Fr_{0–2,w}$	1.314	0.069	19.091	0.0000

with a R^2 of 0.81 and a residual standard error of 10.6 mS m^{-1}. Table 3 provides some of the fitting parameters of this model.

For ECa-H besides $Fr_{0–2,w}$ also the land use specific SOM was identified as a significant variable:

$$\mathrm{ECa{-}H} = 7.2 + 1.098 \cdot Fr_{0\text{–}2,w} + 1.494 \cdot I_1 \cdot \mathrm{SOM} + 1.339 \cdot (1 - I_1) \cdot \mathrm{SOM} \quad (7)$$

where:

$$I_1 = \begin{cases} 1 & \text{if landuse = arable} \\ 0 & \text{if landuse = pasture} \end{cases}$$

with a R^2 of 0.86 and a residual standard error of 8.4 mS m^{-1}. The fitting parameters are given in Table 4.

So for both ECa variables, the $Fr_{0–2,w}$ was found to be the most important variable explaining 81% of the variability of the ECa-V signal (Fig. 5). Due to its stronger response to the topsoil (recall Fig. 3), the prediction of ECa-H requires, besides $Fr_{0–2,w}$, also knowledge of the topsoil SOM content (and land use type). Both variables succeed in explaining 86% of the variation in ECa-H. However, to evaluate the soil profile textural heterogeneity or between the top- (0 m–0.3 m) and subsoil (0.3 m–1.5 m), we focussed on ECa-V. Moreover this variable is independent from land use.

7. Identifying the soil profile textural heterogeneity with reference ECa-V values

Eq. (6) can be used to convert topsoil $Fr_{0–2}$ measurements into reference ECa-V values (ECa-ref), assuming the soil texture to be homogeneous over the entire profile. These values can then be compared with measured ECa-V values (ECa-obs) to evaluate the soil profile heterogeneity in terms of soil texture.

To evaluate the value of our PTF, we selected 17 soil profiles with subsoil $Fr_{0–2}$ values differing more than 10% from the topsoil $Fr_{0–2}$ from our database of East-Flanders. Their locations are indicated on Fig. 4. At these 17 locations, the ECa-V was measured in the same way as at the 88 soil profiles with 'pseudo-homogeneous' textural composition. These ECa-obs values are given in Table 5 together with the ECa-ref values obtained from their topsoil $Fr_{0–2}$ which was input in Eq. (6). Eleven ECa-obs values exceeded the ECa-ref and six were smaller. We propose to use the ECa ratio, defined as $\frac{\text{ECa-obs}}{\text{ECa-ref}}$, as a measure of the soil profile textural heterogeneity (Table 5). An ECa ratio of 1 would theoretically imply a perfectly homogeneous profile, a value exceeding one would indicate a subsoil with more conductive material (e.g. more clay), whereas an ECa ratio smaller than one would indicate the inverse. Moreover, the magnitude of the ECa ratio could indicate the degree of soil profile textural heterogeneity, as the $Fr_{0–2}$ profiles given in Fig. 6 show. The 17 heterogeneous profiles were grouped into three classes according to their ECa ratio: <1, between 1 and 2 and >2. Fig. 6a shows the $Fr_{0–2}$ analysed in the profiles with an ECa ratio >2. These high ratios were associated with a strong textural discontinuity with an increase in $Fr_{0–2}$ of at least 40% compared to the topsoil within a depth of 1.2 m. The profiles in Fig. 6b had an ECa ratio between 1 and 2. No general trend in $Fr_{0–2}$ could be observed in these profiles, they all fluctuated around a more or less stable $Fr_{0–2}$ content in the top 1 m. Some horizons contained more, other less, but a clear dominant pattern was absent. The profiles of Fig. 6c had an ECa ratio smaller than 1. Generally these profiles showed a continuous decrease of $Fr_{0–2}$ down to at least 1.2 m. Sometimes the $Fr_{0–2}$ content increased somewhat below this depth. Obviously the ECa ratio is influenced by both the magnitude of change in $Fr_{0–2}$ and the depth at which these changes occur. Nevertheless the 17 examples showed the potential of the ECa ratio to evaluate the soil profile textural heterogeneity of a

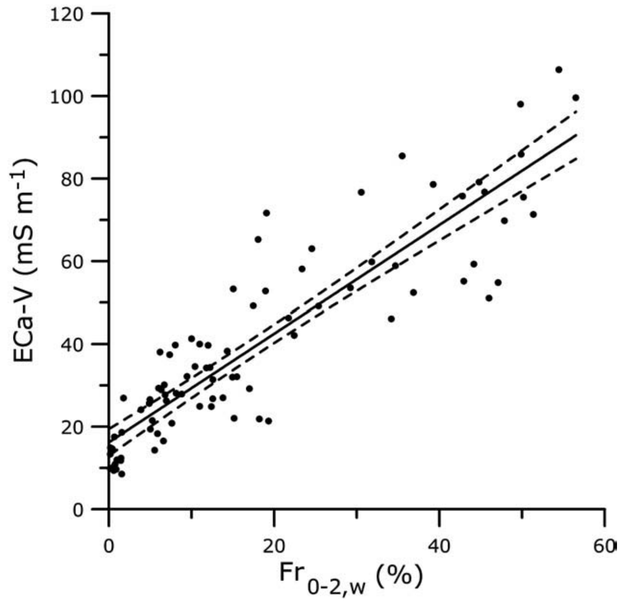

Fig. 5. The 88 measurements of ECa-V of the 'pseudo-homogeneous' soil profiles and the profile weighted clay contents, $Fr_{0–2,w}$, with the fitted regression ECa-V = 16.2 + 1.314 $Fr_{0–2,w}$ (full line) and its 95% confidence interval (dashed curves).

Table 4
Fitting parameters the regression model for ECa-H (Eq. (7) obtained by the stepwise multiple linear regression analysis (s: standard error; t: Student's-t-test of significance, p: probability level).

	Value	s	t-statistic	p-value
Intercept	7.2	1.8	3.886	0.0002
$Fr_{0–2,w}$	1.098	0.075	14.724	0.0000
SOM if arable	1.494	0.755	1.980	0.0510
SOM if pasture	1.339	0.430	3.113	0.0025

Table 5
Comparison between ECa-obs and ECa-ref and their ratio of 17 soil profiles with heterogeneous textural composition.

ECa-obs	ECa-ref	ECa ratio
(mS m^{-1})	(mS m^{-1})	–
69.4	22.1	3.14
58.5	19.2	3.04
57.7	21.3	2.71
43.5	20.3	2.15
63.8	31.5	2.03
66.9	35.9	1.86
76.6	44.0	1.74
31.8	22.5	1.42
85.1	62.3	1.37
51.7	39.3	1.32
91.5	70.0	1.31
35.4	36.9	0.96
37.4	43.5	0.86
29.3	35.0	0.84
34.0	41.5	0.82
42.2	53.8	0.77
28.6	53.8	0.53

location with a single topsoil Fr_{0-2} determination and a few ECa-V measurements.

8. A regional ECa-ref map

Van Meirvenne and Van Cleemput (2005) used 4887 topsoil samples to map the Fr_{0-2}, Fr_{2-50} and $Fr_{50-2000}$ fractions of the province of East-Flanders, Belgium, using stratified compositional block kriging with variogram stratification (Boucneau et al., 1998). The seven strata used were taken from a generalized 1/100.000 soil texture map and represented the major soilscapes of the province. Compositional kriging was used to ensure that the three textural fractions summed to 100% within each interpolated block. This was done by simultaneously minimizing the sum of the prediction error variances taking the unbiasedness, non-negativity and constant sum constraints into account into the kriging system (Walvoort and De Gruijter, 2001). The block size was 250 m by 250 m. Fig. 3 shows these results classified according to the USDA soil textural triangle.

We converted the topsoil Fr_{0-2} data into an ECa-ref map (Fig. 7) by applying our PTF (Eq. (6)). A large spread in ECa-ref values was found due to the large differences in topsoil Fr_{0-2} across the study area. High ECa-ref values (>45 mS m^{-1}) were attributed to the two polder areas in the north, the alluvial rims of rivers and where Tertiary clayey sediments surface (visible as locally increased values in south-eastern part). In the silty and sandy loam areas (central to southern parts), moderate ECa-ref values (25–45 mS m^{-1}) were mapped, while low ECa-ref values (<25 mS m^{-1}) were associated with the fine and medium sand areas covering most of the northern half of the province.

We found this map to be a valuable aid in evaluating field-measured ECa values, which are increasingly becoming available. By

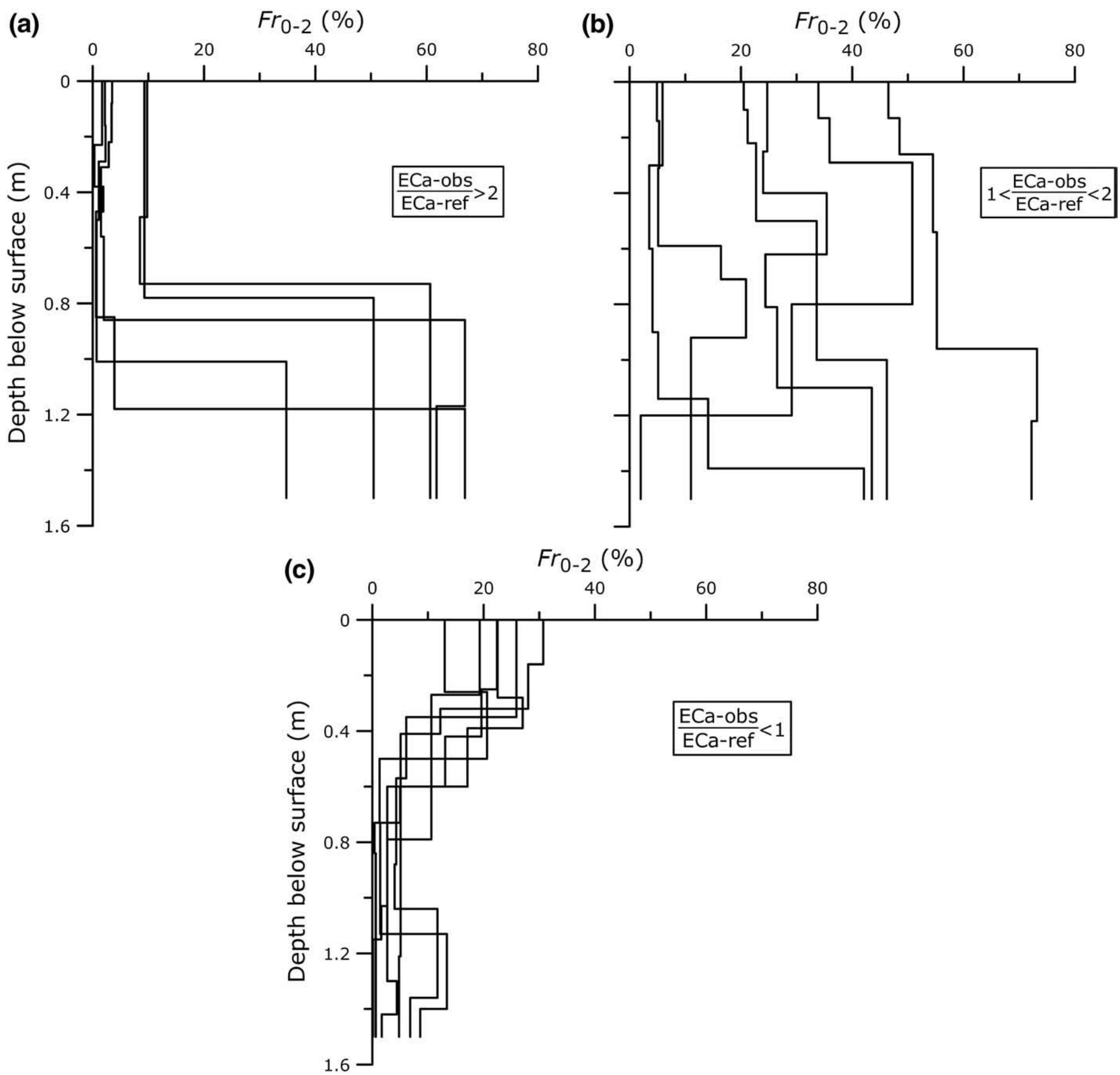

Fig. 6. Fr_{0-2} as a function of depth for 17 soil profiles with a heterogeneous textural composition classified on the base of the $\frac{ECa\text{-}obs}{ECa\text{-}ref}$ ratio: 5 profiles having a ratio >2 (a), 6 profiles having a ratio between 1 and 2 (b) and 6 profiles having a ratio <1 (c).

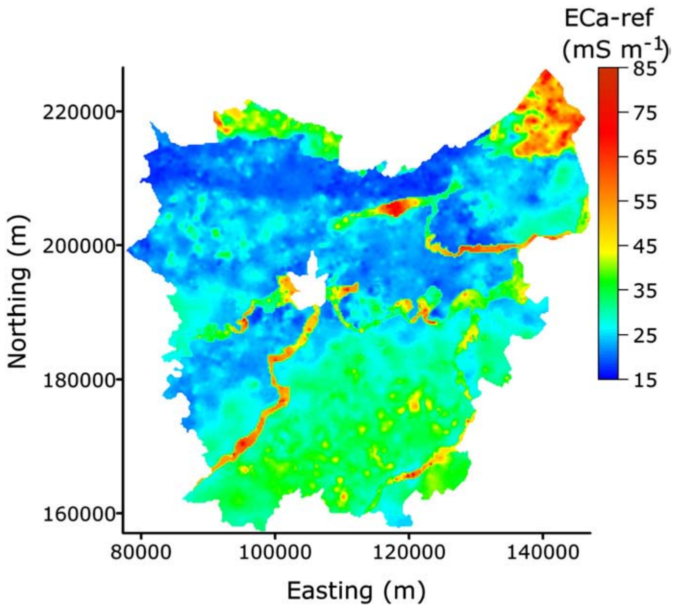

Fig. 7. ECa-ref of the province of East-Flanders, Belgium.

using the ECa ratio a measure of the soil profile textural heterogeneity compared to the topsoil texture is provided.

9. Conclusions

We concluded that:

1. Out of the nine textural fractions considered, as well as some combinations thereof, and the SOM content, Fr_{0-2} is the variable which is most strongly related to both ECa-V and ECa-H.
2. A multiple regression analyses indicated that ECa-V was best predicted by Fr_{0-2}, while ECa-H was best predicted by a combination of Fr_{0-2}, the topsoil SOM content and the land use type. Therefore ECa-V is found to be more suitable to evaluate the soil profile textural heterogeneity because the Fr_{0-2} fraction was routinely determined during soil surveys and can be considered to be reasonably stable over time, independent from land use.
3. A PTF is proposed to relate ECa-V and the Fr_{0-2} fraction:

   $$\text{ECa-V} = 16.2 + 1.314 \cdot Fr_{0-2}$$

   with $R^2 = 0.809$ and a residual standard error of 10.6 mS m^{-1}.
4. This PTF allows to obtain reference ECa-V values at a temperature of 25 °C and at field capacity moisture conditions from a determination of the topsoil Fr_{0-2} content assuming that the clay mineralogy is dominantly mica (with a CEC between 15 and 40 cmol(+) kg^{-1} clay).
5. The ECa-ref values can be combined with measured ECa values into an ECa ratio which can be used as an indication of the soil profile heterogeneity, either due to a textural variability or due to a man-induced disturbance. This ECa ratio is influenced by both the magnitude of change and the depth profile of Fr_{0-2}. This shows the potential of evaluating the soil profile textural heterogeneity of a location with a single topsoil Fr_{0-2} determination and a few ECa-V measurements.
6. The ECa-ref values can be mapped by converting existing soil texture maps using our PTF. These maps provide a guide in evaluating field-measured ECa-V values in respect to the soil profile textural heterogeneity, but their value depends on the quality of the soil textural inventory and is subject to the model uncertainty of our PTF.

We provided a study case where these findings were used to create a reference ECa map showing realistic ECa-ref values with a range which was far beyond the standard error of the PTF model. This map was found to be valuable in supporting the evaluation of ECa-V field surveys, which are increasingly becoming available.

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