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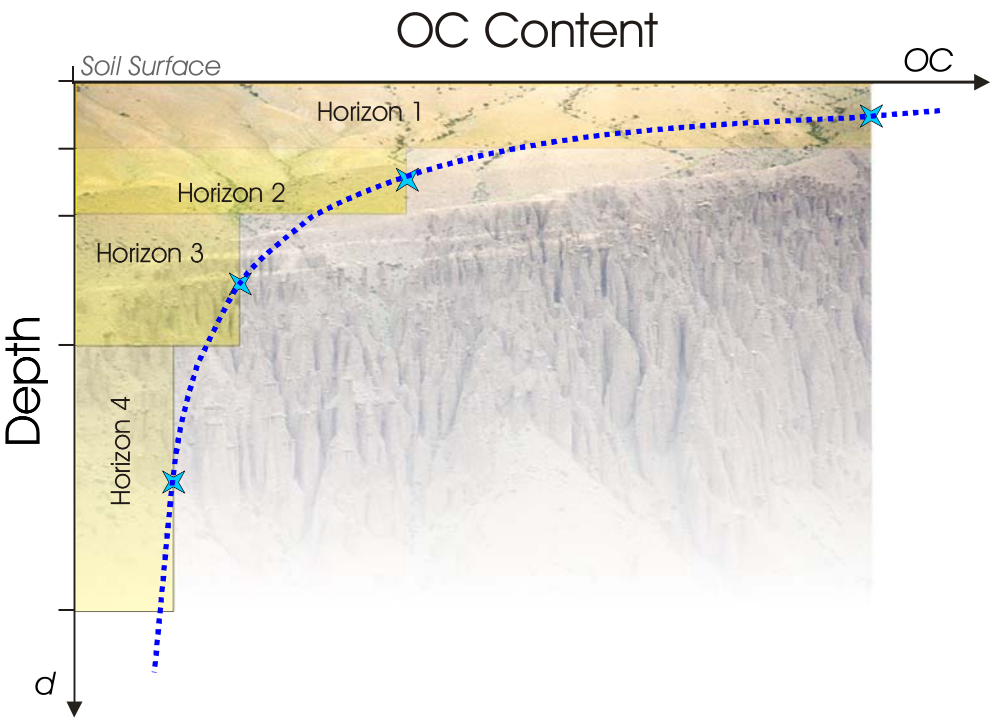
Distribution of Organic Carbon in Soil Profile Data

Roland Hiederer



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COVER PAGE:

The cover page shows the distribution organic carbon in pedological horizons of an idealized mineral soil and the regression curve through the mid-points of the horizon depths from logarithmically transforming the depth parameter.

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List of Acronyms

ACRONYM	TEXT
CV	Coefficient of Variation
HYPRES	Hydraulic Properties of European Soils
IPCC	Intergovernmental Panel on Climate Change
JRC	European Commission Joint Research Centre
ISRIC	International Soil Reference and Information Centre
OC	Organic carbon
PTF	Pedo-transfer function
PTR	Pedo-transfer rule
SC	Soil carbon
SD	Standard Deviation
SGDBE	Soil Geographic Database of Eurasia
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SPADE/M	Soil Profile Analytical Database of Europe, Measured profiles
WISE	World Inventory of Soil Emission Potentials

1 INTRODUCTION

Soil organic carbon (SOC) content has been estimated at pan-European scale for the soil layer from 0 to a depth of 30 cm (Jones *et al*., 2005). The methodology used to generate the data layer relied on a combination of a pedo-transfer rule (PTR) and pedo-transfer functions (PTF). The PTR has been developed based on PTR No. 21 of the PTR database of the *Soil Geographic Database of Eurasia* (SGDBE). The original conditions of the rule system have been revised and amended to accommodate organic soils and peat. The revised PTR for topsoil SOC content comprises 120 ordered conditions of combinations of 5 soil and environmental parameters with an output to one of 6 classes of SOC content. Differences in SOC content due to temperature differences are allowed for by the PTF on temperature variations with a continuous output. The methodology has been verified using measured data from soil profiles from sites across Europe, but the conditions and function parameters are only applicable to the topsoil layer.

Analyses of measured soil profiles suggests that the subsoil layer contains significant quantities of OC. The 30-100 cm depth layer is estimated to contain as much OC as the topsoil layer (Batjes, 1996; FAO, 2001; Jobbagy & Jackson, 2000). An approach was therefore explored how the existing methodology could be advanced to allow extending the SOC content to a depth of 100 cm. Rather then developing a PTR for subsoil SOC content it was investigated whether the rule-based system could be substituted by a function linking the SOC content of the topsoil to the subsoil. Where the influencing factors are discrete parameters, e.g. land cover classes, a function can be defined based on the statistical analysis of soil profiles for each factor class. Statistical methods have already been used to provide estimates of SOC content to a depth of 100 cm in large-scale databases, such as the maps on soil-water holding capacities from Reynolds, *et al*., 1999.

For the development of a PTF to estimate subsoil SOC content from the topsoil the factors influencing the relationship and the characteristics of the relationship depending on the factors will have to be determined. For this purpose three databases with measurements on soil profiles across Europe and one national profile database have been investigated. The main parameters influencing the change of SOC content with depth were taken from the literature. The study then evaluated the potential of the parameters to formulate a function relating topsoil to subsoil SOC content at any depth within the subsoil up to 100 cm.

2 VERTICAL DISTRIBUTION OF SOC

According to Batjes, 1996 the amount of OC located in the upper 30 cm of the global soil stratum amounts to almost 50% of the soil organic carbon in the layer 0-100 cm. When using the upper 200 cm as reference 29% (684–724 Pg C) of SOC is located in the upper 30 cm, 33% (778-824 Pg C) in the layer of 30–100 cm and 38% (914-908 Pg C) in the layer of 100–200 cm (Batjes, 1996). Jobbagy & Jackson, 2000 gave as estimates of the vertical distribution of soil organic carbon 64% (1,502 Pg C) for 0-100 cm, 21% (491 Pg C) for the depth layer 100-200 cm and 15% (351 Pg C) for the layer 200-300 cm.

A summary of estimates of SOC in the literature is given in Table 1.

Table 1: Global Soil Organic Carbon Estimates by Depth

Source	**C-Type**	**Depth Layer**						
		0-30 *cm*	**30-100** *cm*	**100-200** *cm*	**200-300** *cm*	**0-100** *cm*	**0-200** *cm*	**0-300** *cm*
Batjes, 1996	SC					2157–2293		
	SOC	684-724	778-824	914-908		1462–1548	2376-2456	
IPCC, 2001	SC					2011-2221		
Carter & Scholes, 2000	Total SC stock					1567		
Kasting, 1998	Global SC					1580		
FAO, 2001	SC						4156	
	SOC					1500	2456	
Jobbagy & Jackson, 2000	SOC			491	351	1502	1993	2344
Post *et al*, 1982						1395		

SC: Soil Carbon (organic and/or inorganic not necessarily specified)
SOC Soil Organic Carbon

The figures given in the literature and presented in the table refer to “soil carbon” and “soil organic carbon”. Although the two sources of carbon in the soil are not equivalent it is not always evident that they are distinguished. Some of the figures given for SC very likely refer to only carbon in organic material and do not include other forms of soil carbon.

2.1 Vertical Distribution of SOC in Topsoil and Subsoil

Studies of SOC frequently concentrate on the upper 30 cm of soil, in which organic material is concentrated and where processes of C mineralization and immobilization are more active. However, the large quantity of SOC stored in the subsoil layer is ignored when limiting estimates of total SOC pools to the upper layer.

The vertical distribution of SOC in mineral soils is a general decrease of OC content with depth. The decrease is non-linear and frequently modelled as an exponential function (Hilinski, 2001). According to the global soils database held at ISRIC in Wageningen, The Netherlands, for most mineral soils about the same amount of carbon is held in the 30-100 cm layer as in the 0-30 cm layer. Smith *et al*. (2000) fitted a quadratic equation to data from 22 soils from the global soils database of Batjes (1996) to derive this estimate.

A graphical representation of the values given by Batjes (1996) is shown in Figure 1.

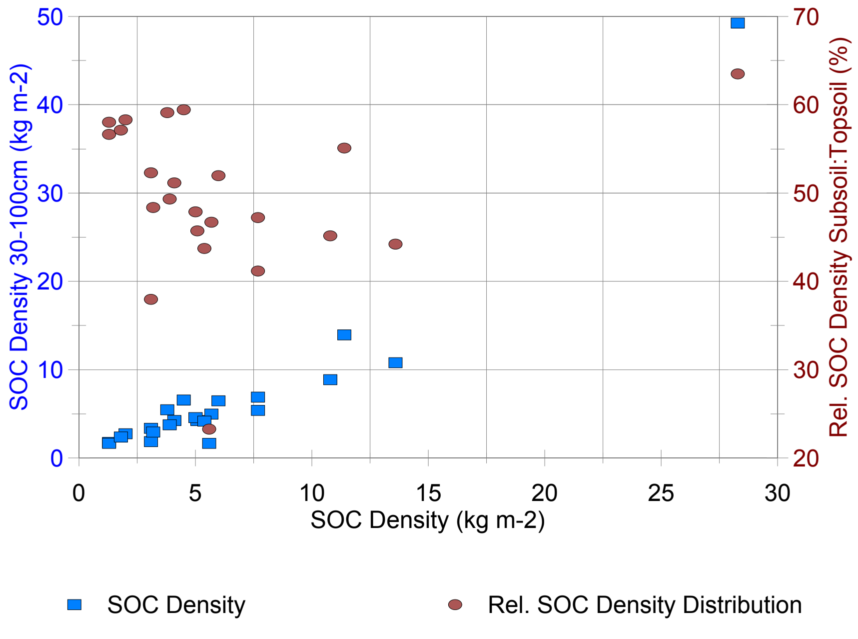


Figure 1: Relationship between Soil Organic Carbon Quantity in the 0-30 cm Topsoil Layer and the 30-100 cm Subsoil Layer (based on figures from: Batjes, 1996)

From the OC data aggregated by FAO soil classes the mean OC stock of the 30-100 cm subsoil layer was 50% of the amount of the 0-100 cm layer. For individual soil classes the fraction varies from 23% for *Podzoluvisols* to 64% for *Histosols*.

The data indicates an approximately linear relationship with a slope coefficient of 1 between the SOC quantity for the topsoil and the subsoil layers for mineral soil. For *Histosoils* the amount of SOC in the subsoil layer considerably outweighs the amount in the topsoil. The relationship in relative terms of the SOC quantity in the subsoil layer better illustrates the differences in topsoil to subsoil SOC quantity between mineral soils and *Histosoil*s. It also shows that *Podzoluvisols* and *Regosols* tend to have more OC in the topsoil than in the subsoil. Those findings are not surprising when considering the definition of the various soil classes in the FAO74 classification scheme.

2.2 Factors Influencing SOC Vertical Distribution

Based on published results there appear to be distinct differences in the distribution of SOC between the topsoil and the subsoil section depending on land use. The first 20 cm of the soil were found to contain between 33% (shrubland) and 50% (forest), with grass land in between with 42%, of the SOC relative to the layer of 0-100 cm (Jobbagy & Jackson, 2000). Globally, the concentration of the amount of SOC in the layer 0-20 cm ranged form 29% in cold and arid regions under shrubland to 57% for cold and humid forests.

At a global scale not only the amount of OC but also the specific characteristics of the exponential relationship of OC with depth in the profile were found to vary strongly with vegetation type (Jobbagy & Jackson, 2000). The variations are attributed to the vertical distribution of roots and to a lesser degree to climate and clay content. The decrease with depth is most pronounced under shrubs, followed by grassland and least prominent under forest. For forests (Arrouays & Pelissier, 1994) and grassland (Omonode & Vyn, 2006) a continuous function can be applied for the most part, while for arable land a sudden change in SOC can occur at the depth of the ploughed layer limiting the use of a function.

Climatic conditions seem to be the dominant factor determining SOC for the upper soil layer while for deeper soils clay content becomes increasingly influential. On a global scale SOC increases with precipitation and decreases with temperature (Post *et al*, 1982). For a sample of soils under forest in Finland the vertical distribution of SOC depends on soil fertility to support forest vegetation (Lisky & Westman, 1995). For the depth layer 50-100 cm the amount of SOC was found to vary from 7.7% to 22% relative to the layer of 0-100 cm. In a study of two mineral soils under forest in Germany the relative amount of soil organic matter in the subsoil layer was found to range from 45% to 75% of the total SOC for the whole profile (Rumpel *et al*, 2002).

The major conditions influencing SOC independently of climatic conditions are:

- *Land use / cover*
  Shrubland and arable land have the lowest rate of decrease of SOC with depth, forests the most pronounced with grassland in between.

- ***SOC content***
  Soils high in SOC show less of a decrease in OC with depth than soils low in OC.

- ***Soil depth***
  In shallow soils SOC decreases more rapidly with depth than in deeper soils.

- ***Clay content***
  For deep soils clay content is more closely related to SOC than for shallow soils.

Findings from other studies suggest that SOC decreases with depth in mineral soils, while it may increase with depth for organic soils.

3 ANALYSIS OF SOIL PROFILE DATASETS

The general assumption for the relationship describing SOC content and depth below the soil surface can be expressed in form of a linear function with a logarithmic transformation of soil depth and/or SOC content, as given by:

$$f(SOC) = m \times f(d) + b$$

where

f(*SOC*)	logarithmic transformation of SOC (or none)
d	depth of soil section from surface

The slope coefficient *m* and constant *b* of the function may depend on the factors influencing the character of changes in SOC content with depth, as expressed by

$$m, b = f(LC, SOC, D, C)$$

where

LC	Land cover
SOC	mean OC content of soil section
D	depth of soil
C	clay content of soil

For the analysis two segments of the soil profile were distinguished:

1. topsoil layer from 0-30 cm
2. subsoil layer from 30-100 cm

The depth range of the topsoil layer is defined by the separation of topsoil from subsoil in the typological database of the SGDBE. The lower limit of 100 cm for the subsoil layer was chosen because it allows more direct comparisons with other dataset, such as ISRIC-WISE or NRCS, but also because measured data at lower depth becomes scare. The soil profile databases used in the study were:

- SPADE/M: Soil Profile Analytical Database for Europe / Measured Data of the Soil Geographic Soil Database of Eurasia
- FF Level I and Level II: Forest Focus data from Soil Condition Survey from systematic and intensive monitoring sites
- ISRIC-WISE: International Soil Reference and Information Centre – World inventory of Soil Emission Potentials
- UK Soil Database for CO_2 Inventory

It was intended to include the HYPRES database (Hydraulic Properties of European Soils), but the database available to the study did not allow a proper evaluation of the profile data..

The limits of pedological horizons or layers of fixed height in a profile, as used by the FF Soil condition Survey, generally do not coincide with the depth ranges of the topsoil and subsoil. Hence, the soil parameters assigned to a layer have to be derived by approximation from the profile data. Estimates of SOC and clay content for reporting the layers were computed by a weighted linear interpolation using the relative coverage of a depth segment by a horizon as weighting factors.

3.1 Soil Profile Analytical Database of Europe / Measured Data (SPADE/M)

The SPADE/M database contains the results of measurements taken for pedological horizons of 496 profiles in Europe (Hiederer & Jones, 2006). The spatial coverage of measured profiles shows local concentrations and larger regions not covered by data, as shown in Figure 2.

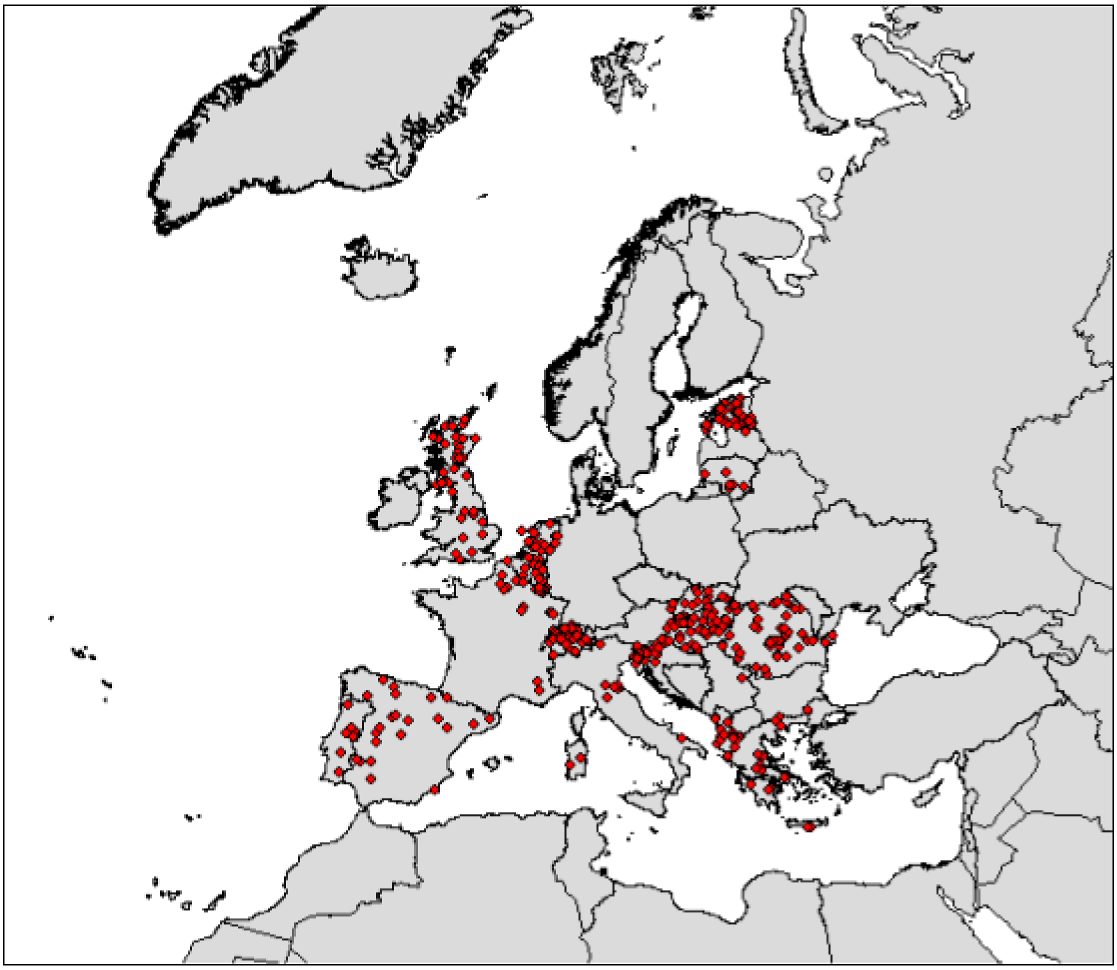


Figure 2: Spatial Distribution of SPADE/M Profiles

In the preparation of the PTR database of the SGDBE the profiles were intended to support the definition and the refinement of PTRs used to extend the range of parameters of the SGDBE. An effort was also undertaken to link the profiles to soil typological units, but this task was not completed at the time. The use of the data in multi-parameter or spatial analysis is hampered by the amount of missing entries in the description of the profiles and horizons. Information on profile depth and soil type is available for all profiles, although for 16 profiles the soil type is not specific. Geographic coordinates are given for 408 profiles, land use is identified for 399 profiles, SOC content is recorded for 398 and clay content for 393 profiles. With 139 different soil types a validation of attributing soil attributes based on soil name, as used by PTRs, is rather limited. There are 8 soil types with 10 or more profiles for one soil type (*Lc*: 10, *Od*: 10, *CMe*: 11, *Jeg*: 12, *Lgs*: 13, *Be*: 18, *Bd*: 21, *Lo*: 34), while for 96 soil types the frequency of profile data is 3 or less. Even with the very broadly defined vegetation classes the dataset lacks a broad basis to support identifying or confirming conditions of the PTR when discriminating soil characteristics by type at more than a general level. In the assessment of SOC content with depth the conditions affecting the relationship were therefore evaluated in separation.

3.1.1 SOC Content in Profile Horizons

The distribution of SOC content for the central depth of a sample horizon is depicted in Figure 3.

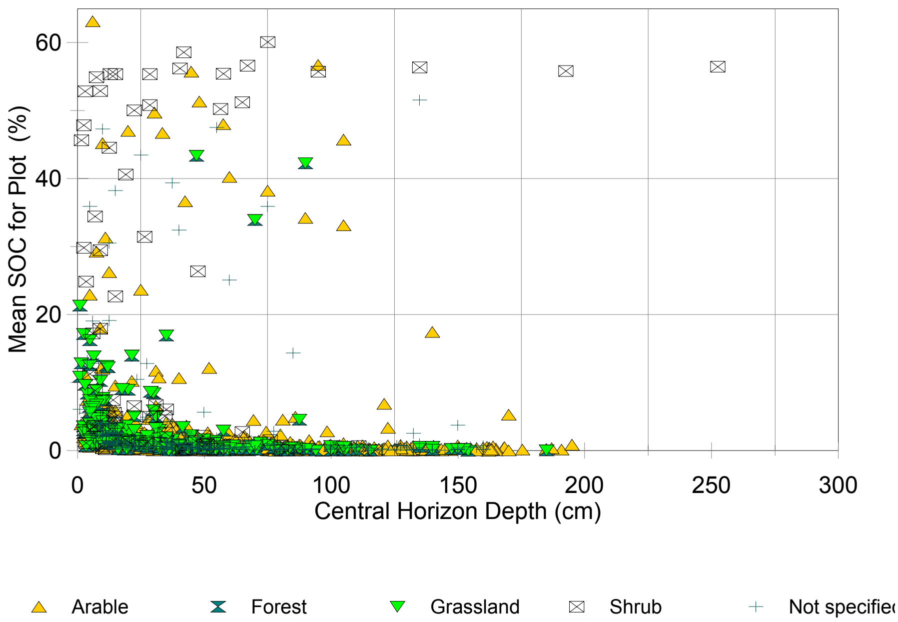


Figure 3: Horizon Depth vs. Soil Organic Carbon (SPADE/M)

The graph indicates the absence of a simple relationship for the decrease with depth in the profiles of the dataset. While a large majority of horizons show a decrease in occurrence with sampling depth, the distribution also suggests a different behaviour for horizons with high SOC as compared to those with a low SOC content. The inversion point is around a 20% SOC content. Below this value SOC generally decreases with depth, while it shows a tendency to increase above this value. The value coincides with the definition of *Histosols* in the FAO classification system (http://www.fao.org/AG/AGL/agll/prosoil/histo.htm). The soil organic matter (SOM) content of 30% used as one criterion to define *Histosols* represents approximately 18% organic carbon (conversion factor of 1.72, Buckman & Brady, 1960). The 18% SOC content threshold was subsequently used when processing SPADE/M profile data, because the changes of SOC content with depth appear to differ significantly around this value of SOC content.

The SPADE/M dataset contains plots with a SOC content >18% mainly on arable land and areas covered by shrub vegetation. On arable land the highest values of SOC content in the sampled horizons are reported for depths less than 100 cm. For plots under shrub the number of horizons with SOC content of approximately >30% increases with depth. In the interpretation of the distribution one should consider that the database contains only 6 horizons with data for SOC content >18% and a depth of the central horizon of more than 100 cm.

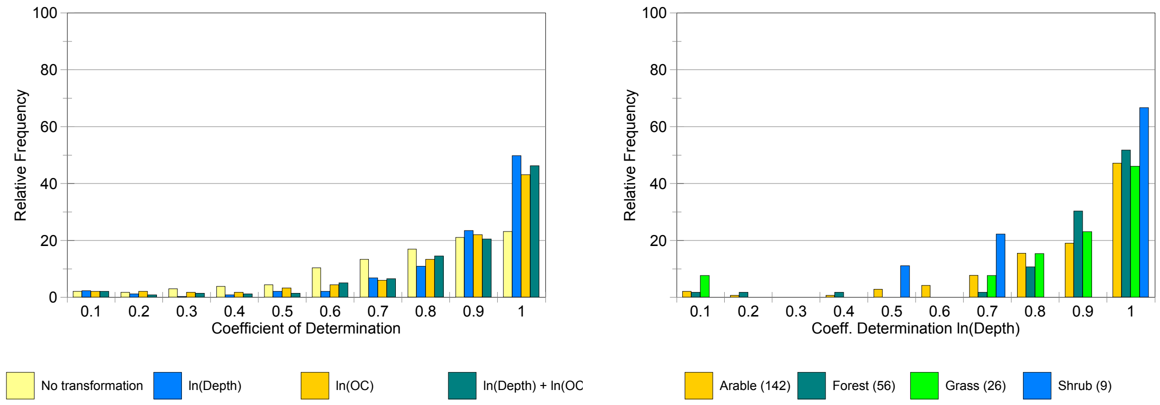
In the subsequent analysis profiles with data for less than 3 horizons within the depth range of 0-30 cm or 30-100 cm were excluded. Omitted were further profiles with abrupt and significant changes in SOC throughout the profile. Such changes are generally caused by organic horizons overlying mineral subsoil or vice versa. Profiles of this type would have confounded the results of changes in SOC content with depth. Abrupt changes in SOC content were identified by a standard deviation (SD) of 10 or more in the soil profile. The value was found to separate cases where organic and mineral horizons were mixed in the profiles dataset and coincides with the theoretical maximum for the SD of a mineral soil profile.

Conversely, included were also profiles with an incomplete description of the horizons. Of the 496 samples 218 samples fully describe profiles to a depth of 100 cm or more. However, only two profiles with a mean SOC content of >18% to a depth of 100 cm comply with this condition. Partially described profiles where therefore included in the analysis. The total number of samples was then 340 profiles with data to a depth of 100 cm or deeper (340 for the topmost 30 cm) and 9 profiles with a mean SOC content >18%. While increasing the number of profiles available for analysis the addition of incompletely described profiles potentially introduces uncertainties when computing the mean SOC content for the layer depth. However, the objective of the study was to analyse changes in SOC content with depth and the absence of a complete description of the soil profile was considered less detrimental to the task than a decrease in the number of profiles available for the analysis.

3.1.2 SOC Content and Depth Transformation

The values shown in Figure 3 only depict the distribution of the horizons, not necessarily the relationship between soil depth and SOC content, since one horizon's characteristics are not independent from other horizons of the same plot.

Evaluated were the 4 possible combination of a logarithmic transformation of mean SOC content and depth. For depth the central value of the horizon was used. The frequency distribution of the coefficient of determination (r^2) for profiles with a coverage by horizons of >=75% to a depth of 100 cm is shown in Figure 4.



a) Transformation Options *b) Land Use Classes for Depth Transformation*

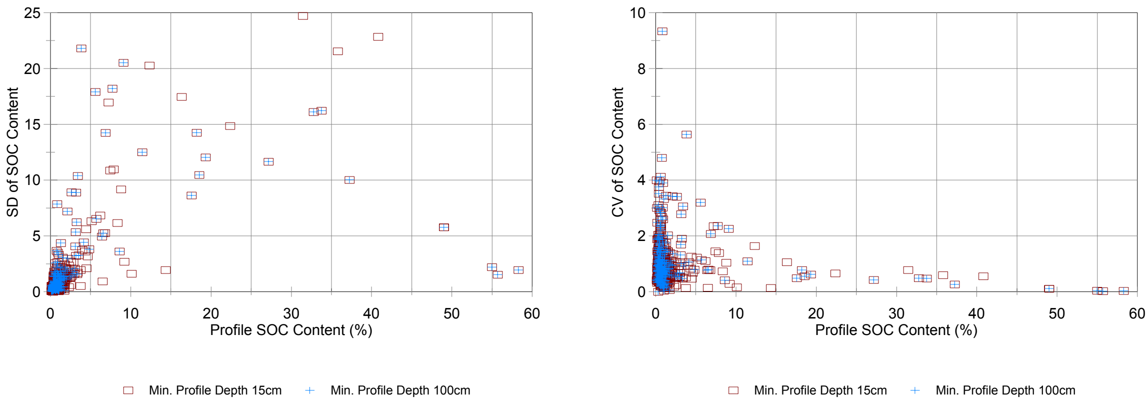
Figure 4: Frequency Distribution of Combinations of Logarithmic SOC and Central Horizon Depth Transformation and Transformation of Depth by Land Use (SPADE/M)

The results indicate that the change in SOC content with soil depths is better modelled when using a logarithmic transformation of soil depth and/or SOC content than when using non-transformed parameters. There is no noteworthy difference in the correlation of any of the relationships using a transformed depth or SOC content parameter. The ranking changes slightly for the relationships of the transformed parameters when setting stricter limits on the completeness of coverage of the profile, but a simple linear relationship does not model the situation to the same degree.

While the findings indicate that a non-linear relationship between SOC content and depth can be defined for more than 90% of the profiles in the database (r^2>0.5) the direction of the change is not indicated by the coefficient of determination, nor whether the relationship can be defined by one set of parameters or depends on other factors. The results only indicate that the relationship can be modelled by a linear function with logarithmically transformed parameters for individual profiles. Furthermore, the seemingly high number of close correlations is at least in part a consequence of the restricted number of observations, i.e. horizons by plot.

Also shown in the graph is the relative frequency of the coefficient of determination for the transformation of the depth parameter by the main land use classes. Notable is the distribution of the correlation fit for profiles under shrub. It should be noted that the distribution is based on only 9 profiles, which is considered insufficient to provide a consistent portrayal of the situation. The occurrence of low coefficients of determination for profiles under grass is also caused by a single profile where the SOC content in the subsoil changes from 34% to 4.6%.

Indicators of the dispersion of the SOC content within a profile are the standard deviation (SD) and the coefficient of variation (CV) of the SOC content horizon data. The relationships are presented in Figure 5.



a) SOC Content vs. SD *b) SOC Content vs. CV*

Figure 5: Relationship between Standard Deviation (SD) and Coefficient of Variation (CV) and Profile SOC Content with Varying Cover of Profile Depth (SPADE/M)

The relationship between the mean SOC content of the profile and the SD of the SOC contents of the horizons does not reveal a particular general trend. When including profiles with a minimum depth of 15cm in the analysis the dispersion of the SOC content values within a profile is highest for profiles with a mean SOC content of about 35%. In case only profiles with a minimum depth of 100 cm are included in the analysis the main dispersion is more prevalent in mineral soils with a decrease in SD towards higher mean SOC contents. One may conclude from those observations that deeper profiles are more homogeneous than shallower profiles with increasing mean SOC content of the profile. The affinity is not a consequence of a larger number of values sampled for deeper profiles when the sampling is based on pedological horizons, as in the case of SPEADE/M data.

For the relationship of the mean SOC content and the CV the larger relative spread of values within a profile for lower mean SOC contents than for profiles with higher contents is illustrated in the graph. There are no profiles in the dataset with a CV of >=1 for a mean SOC content of 12% and one for deeper soils of >=100 cm with a CV >0.5. The larger variations for profiles with a mean SOC content close to 0 have to be interpreted with the increasing sensitivity of the indicator to small changes. The decrease at the higher end is controlled by the limit in the SOC content to approx. 60%.

The data suggests that deeper soils tend to be either clearly mineral or organic, but not transitional. This results in a reduction in the number of profiles with a depth of 100 cm or more in the range of mean SOC contents between 10-35% from 37 to 4. A comparable effect would be achieved by limiting the SD to 10. As a consequence, when concentrating the analysis on profiles without abrupt changes in SOC content between horizons, the data are split into two distinct groups of mineral and organic soils and peat with diverse characteristics of the dispersion of SOC content within the profile by the mean SOC content.

3.1.3 Influence of Land Cover

In the SPADE/M dataset 17 classes of land cover information are defined for 397 plots. Those land cover classes were translated into the 4 classes of vegetation identified to influence the change of SOC content with depth on a global scale (Jobbagy & Jackson, 2000). These vegetation classes closely resemble the classes of land use employed in the pedo-tranfer rule (PTR) for SOC content in the 0-30 cm topsoil of the Soil Geographic Database of Eurasia (SGDBE).

The distribution of profiles according to the land cover classes for the soil segment 0-100 cm is as shown in Table 2.

Table 2: Distribution of Soil Profiles by Land Cover Class under Two Treatments for Soil Segment 0-100 cm

Land Cover	**Treatment Conditions**		**Change**
	Profile Cover: >30% SD: no limit	**Profile Cover: >75% SD: <10**	**%**
Arable	169 (58.3%)	137 (64.0%)	-18.9
Forest	69 (23.8%)	50 (23.4%)	-27.5
Grassland	41 (14.1%)	24 (11.2%)	-41.5
Shrub	11 (3.8%)	3 (1.4%)	-72.7
TOTAL	**290**	**214**	**-26.2**

The treatment applied to the data affects not just the number of profiles, but also the distribution of the profiles for the land cover classes in different ways. Overall the number of profiles is lowered by approx. one quarter by requiring a data coverage to a depth of >=75cm and limiting profiles to those with a SD of the samples <10. Least affected by the condition are profiles on arable land, while most affected are those under shrub. The factor reducing the number of profiles is not so much caused by limiting the SD of the SOC content within a profile, but by the condition that the profile data has to cover a depth of >75cm. The correlation of land cover type and soil profile depth is illustrated in Figure 6.

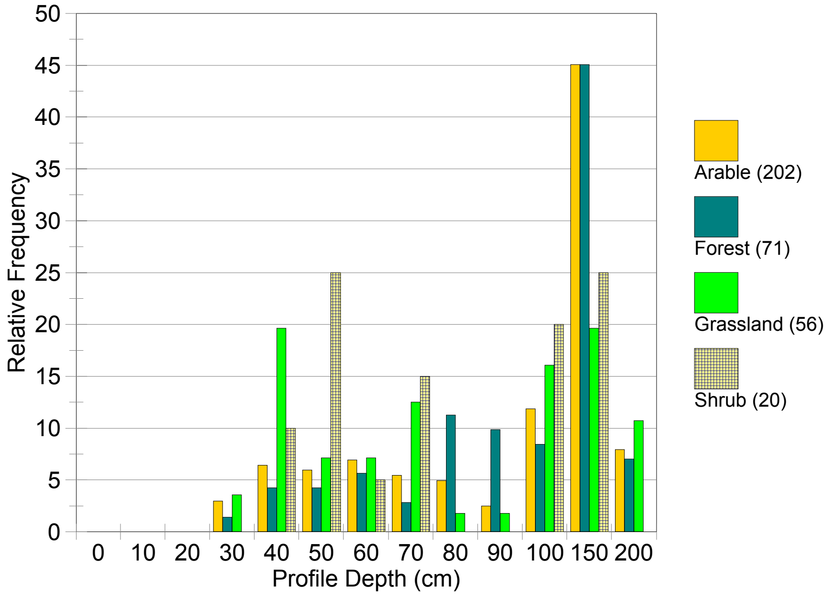


Figure 6: Frequency Distribution of Land Cover Types by Profile Depth (SPADE/M)

The graph indicates a prevalence of arable and forest land to occur on soils with a depth of more than 100 cm. By contrast, grassland and shrub can more regularly be found on shallower soils. The presence of those land cover types in the pool of profiles is therefore more strongly reduced by the processing conditions than for other land cover types.

The relative frequency of slope coefficients *m* less than 1 for the relationship of mean SOC content and depth by land cover type is presented in Figure 7.

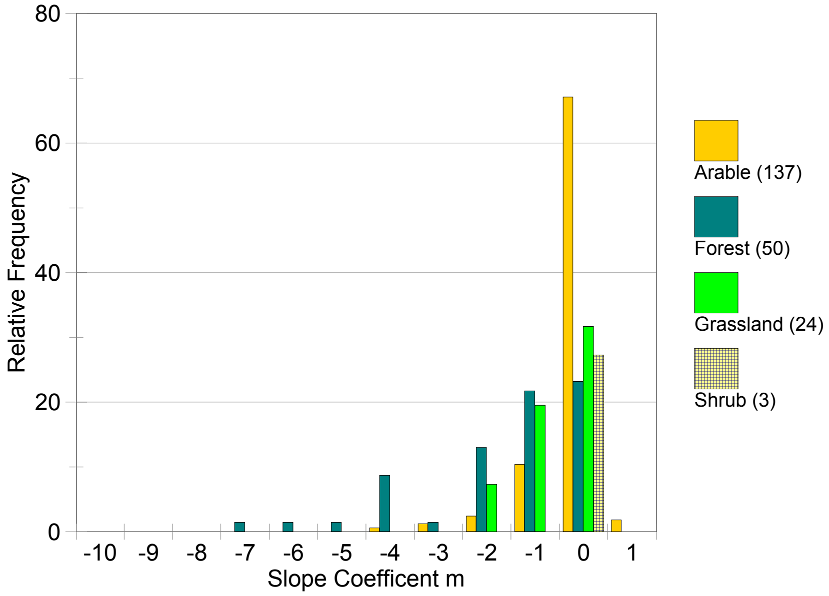


Figure 7: Frequency Distribution of Relative Occurrence of Slope Coefficient m by Land Cover Type (SPADE/M)

The number of profiles within each category differs from the total number of profiles due to data requirements for computing the slope coefficient (min. 3 horizons in profile). The frequency distribution of slope coefficients indicates for profiles on arable land a prevalence of values between -1 and 0. For profiles in forests slope coefficients below -1 and to -4 are more frequent than for other vegetation types. Profiles under grassland follow the tendency found for those in forests, but to a lesser degree. Not shown are slope coefficients >1. Only 6 profiles fall into this range and not much information on a relationship of the slope coefficient and land cover type could be gained from plotting the data.

It could be argued that some land cover types favour the development of OM in the soil, and thus SOC content, more than others and that as a consequence different coefficients for SOC content with depth can be defined based on the type of land cover. This is a circuitous argument, because the land cover type is not necessarily independent from the SOC content in the profile. When certain land cover types favour the development of higher SOC content or are favoured to be associated with such soils, a correlation between the type of vegetation and the rate of change in SOC may still be observed, although this is not a dependency, but could just as well be a result of a land management decision. The dataset clearly indicates a relationship of SOC content with depths as a function of the mean SOC content in the profile, regardless of the land cover type. A differentiation of the relationship by land cover type is restricted to the topsoil layer.

3.1.4 Influence of Mean SOC Content in Soil Layers

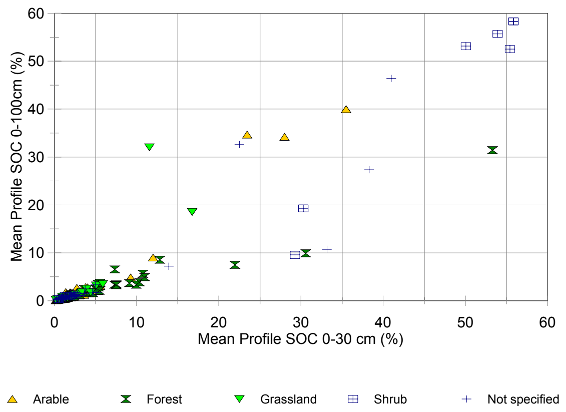
For horizon information to be used to describe changes in OC content with depth some conditions had to be set:

- A section must be covered with sample data to at least 75%. Thus, excluded from the analysis are data from horizons, where the lower limit does not exceed 75cm. For horizons starting above the lower depth limit but reaching to deeper levels, the soil attribute is assigned to the central horizon depth. The central depth is used even when the value is lower than the lower depth range of the soil section. This approach was found preferable to limiting the depth to a fixed value and assigning a soil attribute to the lower depth limit when the central horizon depth was actually below that position. Using a threshold of 75% for data coverage allows including horizon information, which may still pertain to a soil segment, such as measuring to a depth of 80 cm for the soil section 0-100 cm.
- To compute the slope and constant for a depth segment it should be covered by at least 3 points. The function can be fully defined by two points, but this was found to give at times spurious results.
- A limit of 10 for the standard deviation of SOC contents of the horizons included in estimating properties of a soil layer is applied to avoid including in the analysis profiles with discontinuities.
- The lower end of a horizon is set to 300 cm where no specific value is given to include the 112 plots with a deep but unspecified lower horizon in the analysis.

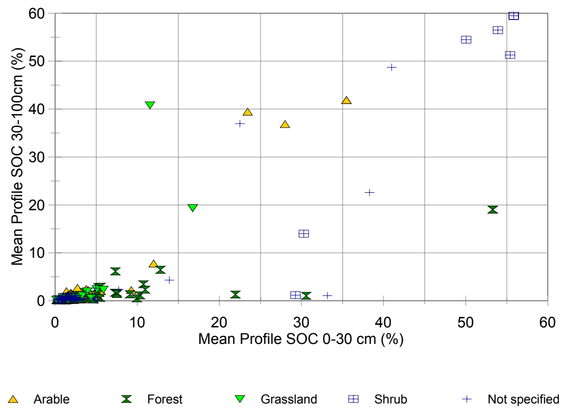
Further conditions restricting the use of the profiles may apply depending on the particular aspect investigated and are generally self-evident, e.g. including only plots with a land cover type in the analysis of the influence of land cover on SOC content.

As a first step the relationship of the mean SOC content of the 0-30 cm topsoil (SOC_{TOP}) and the 30 – 100 cm subsoil (SOC_{SUB}) was determined as well as to the combined topsoil and subsoil segment (SOC_{0-100}).

The results are graphically depicted in Figure 8.



a) Topsoil vs Profile SOC Content



b) Topsoil vs. Subsoil SOC Content

Figure 8: Relationship between Mean SOC Content of Topsoil and Subsoil and Combined Soil Segment (SPADE/M)

As could be expected from the analysis of the change in SOC content with depth, the relationship differs for soils with a mean SOC content of less than approximately 15-20% for the soil segment 0-100 cm from those with a higher mean SOC content. For a linear regression the x-coefficient for the relationship of the mean SOC content in the topsoil versus the soil segment 0-100 cm was found to be:

$$SOC_{0-100}^{\min} = 0.542 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.87, 268 dF)}$$

y-offset set to 0: $SOC_{0-100}^{org} = 1.034 \times SOC_{TOP}^{org}$ (r^2: 0.69, 8 dF)

y-offset calculated: $SOC_{0-100}^{org} = 0.799 \times SOC_{TOP}^{org} + 10.7$ (r^2: 0.76, 7 dF)

For a linear regression of the topsoil versus the subsoil mean SOC content the parameters found were:

$$SOC_{SUB}^{\min} = 0.323 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.52, 260 dF)}$$

For organic soils in the profile data it was found to be:

y-offset set to 0: $SOC_{SUB}^{org} = 0.830 \times SOC_{TOP}^{org}$ (r^2: 0.33, 16 dF)

y-offset calculated: $SOC_{SUB}^{org} = 0.948 \times SOC_{TOP}^{org} - 4.8$ (r^2: 0.34, 15 dF)

The results support the previous proposition that there is a marked difference in the relationship of mean SOC contents between mineral and organic soils. For a regression with a y-offset forced to 0 the difference on the x-coefficient for mineral and organic soil or peat is significant at a 95% confidence level. The regression parameters separated by land cover type are given in Table 3.

Table 3: Parameters of Linear Regression between SOC Content of Topsoil, Soil Segment 0-100 cm and Subsoil (SPADE/M)

Regression Analysis Land Use Type	Slope Coeff.	Coeff. Determi-nation	Lower Limit (95%)	Upper Limit (95%)
		TOP vs. 0-100		
Arable <18% OC	0.615	0.88	0.590	0.639
Forest <18% OC	0.497	0.85	0.459	0.536
Grass < 18% OC	0.545	0.92	0.508	0.582
Non-Classified	0.498	0.90	0.467	0.528
		TOP vs. SUB		
Arable <18% OC	0.4384	0.62	0.408	0.476
Forest <18% OC	0.277	0.49	0.222	0.331
Grass < 18% OC	0.343	0.73	0.290	0.396
Non-Classified	0.274	0.61	0.234	0.315

It should be noted that the seemingly linear relation of mean SOC content between the two layer depths does not imply a linear change of SOC with depth. It does, however, indicate the potential of estimating the mean SOC content in the 0-100 cm soil segment by the mean SOC content in the first 30 cm. The variations in the x-coefficient for various depths in the profile down to 100 cm can be estimated from the correlation between the slope of the relationship of SOC content and depth with the mean SOC content of a profile.

The results of the analysis of comparing the mean topsoil SOC content to the soil segment 0-100 cm is subject to restrictions imposed by including the topsoil data in the dependent variable. Subsequently, when comparing the mean topsoil SOC content to the subsoil the relationship becomes less well defined. One reason is that the analysis is based on all profiles regardless on the soil type. Therefore, included are also profiles, where the soil type indicates a clear distinction in the SOC content between the horizons of a profile. The profiles where an organic topsoil (>18% SOC content) is aligned to a mineral subsoil (<12% SOC content) are classified as *Podzols*. Of the 21 profiles classified as *Podzols* 8 show an organic layer, which extends at time no more than 2cm. The inverse condition, i.e. a mineral horizon over an organic horizon, is not present in the profiles in the dataset.

When restricting the variation in SOC content between profile horizons to a SD of 10 the regression coefficient for all profiles regardless of the mean SOC content and a y-offset of 0 is 0.956, with a coefficient of determination (r^2) of 0.90. The high value for the coefficient of determination is somewhat misleading, since the few profile data for organic soils and peat control the x-coefficient of the regression and the fit although a significant difference in the x-coefficient depending on soil type has been established.

Consequently, given the diverse characteristics of the SOC content with depth between mineral and organic soils it seems to be improper to combine the profile data of mineral and organic soils into a single population and to determine the relationship between the topsoil and subsoil SOC content by using a linear regression. Instead, for the analysis of SOC content and depth mineral soils should be treated separately from organic soils and peat. While there is a clear distinction in the relationship for profiles with a mean SOC content <12% and >20%, the situation for soils with mean SOC contents in-between is not evident from the data.

The evaluation of the slope coefficient of the relationship between SOC content and depth and the mean SOC content of the soil segment is based on a linear function with a logarithmic transformation of depth and no transformation for SOC content. For each profile *i* it can be formulated for a depth *d* as:

$$SOC_{i,d} = m_i \times \ln(d) + b_i$$

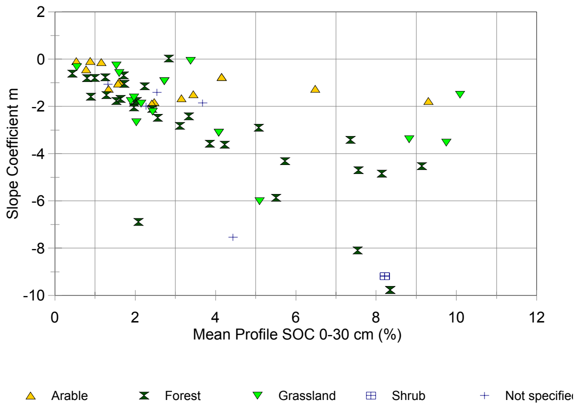
Using any other combination of transforming SOC content and/or depth resulted in comparable performance describing SOC content and depth in individual profiles, but no relationship could be found between the coefficients and the mean SOC content of either topsoil or subsoil.

The relationship between the coefficients and the mean SOC content of a given soil segment *S* can be formulated as:

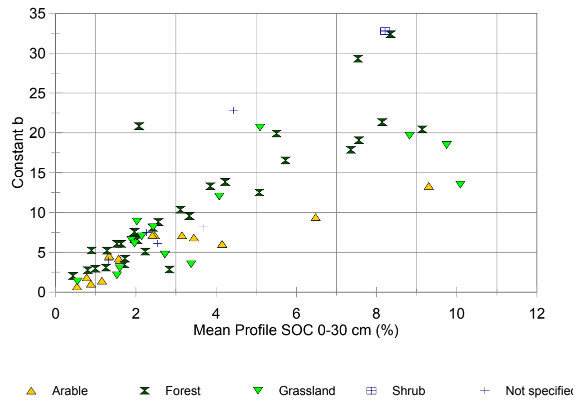
$$m_i = m_S \times SOC_S + b_S$$

The relationship between the y-offset, when used, and the mean SOC content of a given soil segment is formulated accordingly.

A graphical presentation of the relationship between the mean SOC content of the topsoil and the regression parameters is given in Figure 9.



a) Topsoil SOC Content vs. Coefficient



b) Topsoil SOC Content vs. Constant

Figure 9: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Soil Section 0-30 cm by Land Cover Type (SPADE/M)

The range of SOC content values covered by the analysis is unavoidably restricted to mineral soils, because in the dataset organic soils and peat have less than 3 horizons for that depth. From the graph a distinctly different relationship between SOC content and depth for soils on arable land and forest can be perceived. In soils under forest SOC content decreases at a much more rapid rate than on arable land (difference in x-coefficient significant at 95% confidence level).

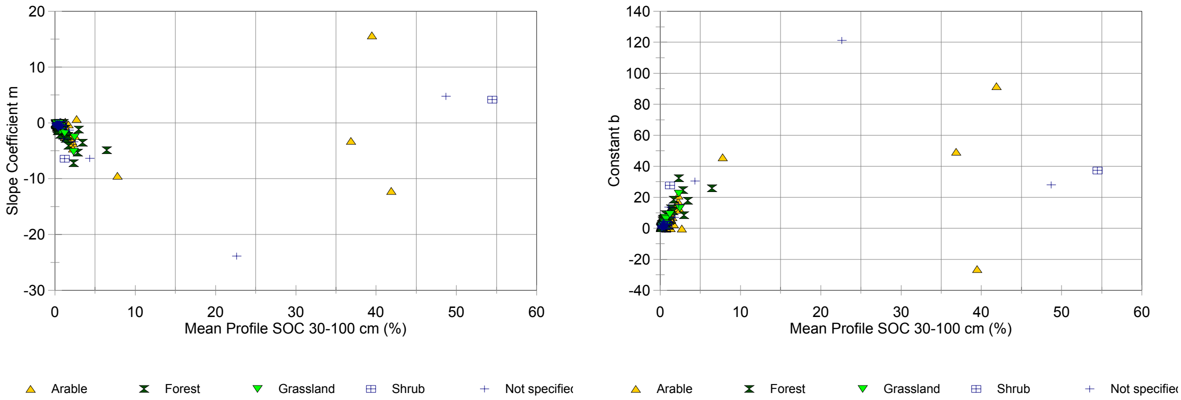
The regression parameters for soils on arable land and under forest are:

$$m_{TOP}^{arable} = -0.147 \times SOC_{TOP} - 0.623 \text{ (r}^2\text{: 0.30, 12 dF)}$$

$$m_{TOP}^{forest} = -0.674 \times SOC_{TOP} - 0.532 \text{ (r}^2\text{: 0.57, 29 dF)}$$

Soils under grassland occupy an intermediate condition and with the variability in values are not sufficiently distinct from either. For soils under shrub only one profile is available and thus no comments on a correlation of SOC content and depth in relation to land cover type can be pronounced.

For the subsoil segment the coefficient of the correlation between SOC content and depth is shown in Figure 10.



a) Subsoil SOCC Content vs. Coefficient *b) Subsoil SOC Content vs. Constant*

Figure 10: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Soil Section 30-100 cm by Land Cover Type (SPADE/M)

The relationship between the x-coefficient of the correlation of SOC content and depth for soil on arable land and under forest observed for the topsoil is also discernable for the subsoil section. With data for 18 profiles under grassland a correlation could also be defined for this land cover type. The regression x-coefficients for soils with a mean SOC content <18% in the soil segment by land cover type are:

$$m_{SUB}^{arable} = -1.153 \times SOC_{SUB} + 0.147 \text{ (CI}_{95}\text{: -1.297 to -1.008, r}^2\text{: 0.71, 103 dF)}$$

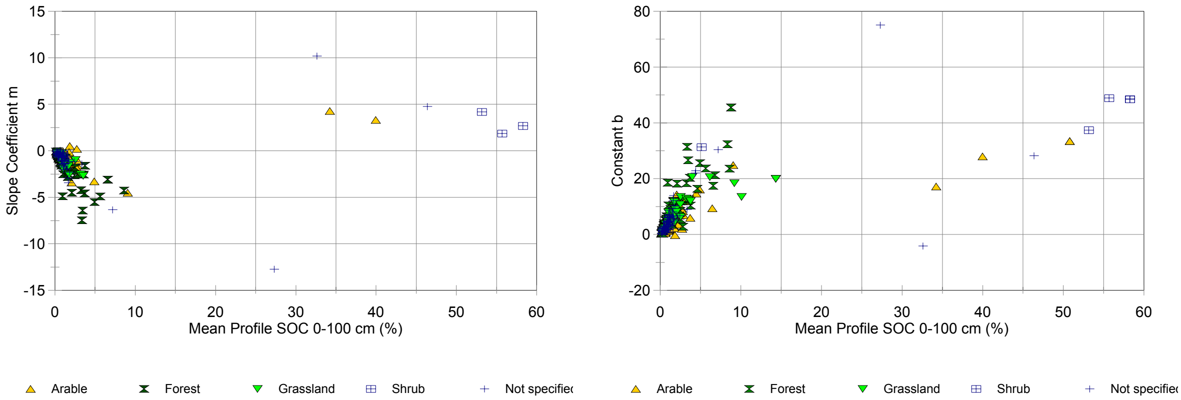
$$m_{SUB}^{forest} = -0.998 \times SOC_{SUB} - 0.317 \text{ (CI}_{95}\text{:-1.291 to -0.706, r}^2\text{: 0.55, 39 dF)}$$

$$m_{SUB}^{grass} = -1.655 \times SOC_{SUB} + 0.198 \text{ (CI}_{95}\text{: -2.139 to -1.171, r}^2\text{: 0.77, 16 dF)}$$

$$m_{SUB}^{all} = -1.168 \times SOC_{SUB} + 0.010 \text{ (CI}_{95}\text{: -1.298 to -1.038, r}^2\text{: 0.62, 189 dF)}$$

In the profile data the x-coefficient of SOC content and depth for grassland appears distinct from those of other land cover types. The difference is significant at a 90% confidence level, but not at 95%. For the 6 profiles of organic soils and peat no specific relationship with land cover can be differentiated, regardless of whether the profile with a mean SOC content of 22% was included or not.

The relationship between the average SOC content to a depth of 100 cm and the slope and constant for the model function using all profiles with a coverage of >=75% of the soil section with data are given in Figure 11.



a) Profile SOC Content vs. Coefficient *b) Profile SOC Content vs. Constant*

Figure 11: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Soil Section 0-100 cm by Land Cover Type (SPADE/M)

For the 21 profiles the distribution across the four land cover classes is as follows: Arable: 139, Forest: 50, Grassland: 24, Shrub: 6 and for non specified land cover 52. For the complete segment the differentiation in the change in SOC content with depth between profiles on arable land and under forest of the topsoil is blurred by the indistinct relationship within the subsoil layer. For profiles with high values for $SOC_{0\text{-}100}$ the dataset contains suitable data only for profiles under arable land (2) and shrub (3).

The variables describing a linear relationship between the SOC content and depth with the mean SOC content of the soil segment covering the soil section 0-100 cm are defined separately for mineral and organic soils as:

$$m_{SOC<18}^{arable} = -0.515 \times SOC_{0-100} - 0.139 \text{ (CI}_{95}\text{: -0.591 to -0.439, r}^2\text{: 0.57, 135 dF)}$$

$$m_{SOC<18}^{forest} = -0.676 \times SOC_{0-100} - 0.844 \text{ (CI}_{95}\text{:-0.882 to -0.470, r}^2\text{: 0.48, 48 dF)}$$

$$m_{SOC<18}^{grass} = -0.680 \times SOC_{0-100} - 0.270 \text{ (CI}_{95}\text{: -0.909 to -0.451, r}^2\text{: 0.63, 22 dF)}$$

$$m_{SOC<18}^{all} = -0.699 \times SOC_{0-100} - 0.189 \text{ (CI}_{95}\text{: -0.778 to -0.620, r}^2\text{: 0.54, 261 dF)}$$

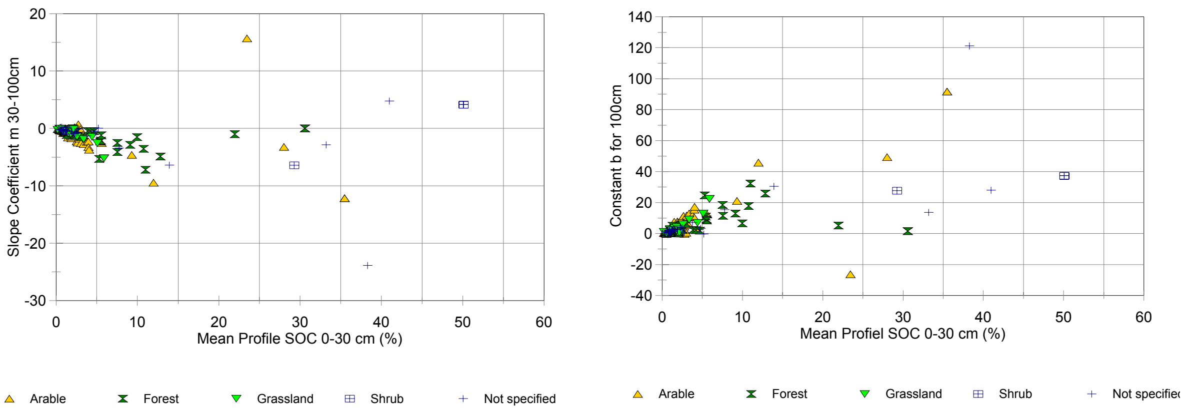
$$m_{SOC\geq 18}^{all} = -0.180 \times SOC_{0-100} + 12.7 \text{ (CI}_{95}\text{: -0.398 to +0.038, r}^2\text{: 0.47, 5 dF)}$$

When using the complete soil segment of 0-100 cm no significant differences in the slope coefficient of the relationship between SOC content and depth can be identified for any specific land cover type. A significant difference exists for the coefficient of profiles on arable land from the combined profiles.

For soils with a SOC content of >18% only 7 profiles could be included in the analysis. Although the mean profile SOC content and the slope coefficient of the correlation between SOC content and depth shows a coefficient of determination of 0.47 there may not be a correlation at all at a 95% confidence level. To better evaluate the issue data from more profiles are needed.

Noticeable in the subsoil section is one profile with a mean SOC_{100} content of 27.3%. The profile is fully described by horizons and shows a continuous decrease in SOC with depth from 38.3% (0-30 cm) to 14.4% (70-100 cm). There is no abrupt change indicated by the standard deviation for the profile (SD = 8.9). For the profile no information on soil type or land cover is available. This profile was not included when computing the effect of mean SOC content on the slope coefficient and constant but left in the graph to illustrate that there are situations outside the general conditions.

When associating the mean SOC content of the topsoil section to the slope coefficient of the relation between SOC content and depth for the subsoil section the situation illustrated in Figure 12 was found.



a) Topsoil SOC Content vs. Subsoil Coefficient *b) Topsoil SOC Content vs. Subsoil Constant*

Figure 12: Relationship between Mean SOC Content for Topsoil and Model Slope Coefficient and Constant for Subsoil by Land Cover Type (SPADE/M)

The results of the regression analysis of the topsoil mean SOC content with the slope coefficient of the change on SOC content in the subsoil were:

a) for $SOC_{30} \leq 18\%$

$$m_{SOC<18}^{arable} = -0.661 \times SOC_{SUB} + 0.349 \text{ (CI}_{95}\text{: -0.731 to -0.591, r}^2\text{: 0.78, 101 dF)}$$

$$m_{SOC<18}^{forest} = -0.461 \times SOC_{SUB} + 0.297 \text{ (CI}_{95}\text{:-0.514 to -0.318, r}^2\text{: 0.67, 37 dF)}$$

$$m_{SOC<18}^{grass} = -0.380 \times SOC_{SUB} + 0.149 \text{ (CI}_{95}\text{: -0.514 to -0.246, r}^2\text{: 0.71, 15 dF)}$$

$$m_{SOC<18}^{all} = -0.463 \times SOC_{SUB} + 0.173 \text{ (CI}_{95}\text{: -0.510 to -0.417, r}^2\text{: 0.69, 185 dF)}$$

b) for $SOC_{30} > 18\%$

$$m^{all}_{SOC\geq18} = -0.222 \times SOC_{SUB} + 4.9 \text{ (CI}_{95}\text{: -1.220 to 0.777, r}^2\text{: 0.03, 8 dF)}$$

The result of the regression analysis displays some differentiation in the slope coefficient between land cover types. The decrease in the slope coefficient of the relationship between SOC content and depth in the subsoil with an increase in the mean SOC content in the topsoil is more pronounced for soils on arable land and under grass than for soils under forest. The differences for forest soils are not enough to reject the hypothesis that there is no difference at the 95% confidence level, but are at a confidence level of 90%.

The analysis of the conditions found in the topsoil and subsoil of the profiles suggests that changes in SOC content occur for soils under forest mainly in the topmost 30 cm. For grassland the changes in the subsoil are more pronounced than for soils under forests or on arable land. The description of the relationship of SOC content and depth by a first order polynomial, albeit with a transformation of one axis, does not allow representing the differences in the behaviour found between the topsoil and the subsoil when describing the relationship for the complete soil segment from 0-100 cm. Given the nature of the differences they are compensated for when integrating all profile horizons. To better describe the relationship of SOC content with depth a higher-order polynomial could be convenient. Yet, with a limited number of horizons describing the changes in SOC content with depth only a simplistic function can be used.

The slope coefficient of the function decreases significantly with a decrease in the average SOC content and shows a tendency to increase for soils with a SOC content above 30%. Therefore, the two situations encountered are treated separately for soils with a mean SOC content above or below 18%:

a) for $SOC_{30} \leq 18\%$

$$m^{\min}_{SUB} = -0.464 \times SOC^{\min}_{TOP}, \; b^{\min}_{SUB} = 0.173 \times SOC^{\min}_{TOP}$$

Since the regression was calculated with 0 as y-offset the SOC content at any depth in the subsoil section relative to the mean SOC content of the topsoil section can be estimated by:

$$\Rightarrow SOC(d)^{\min}_{SUB} = -0.464 \times SOC^{\min}_{TOP} \times \ln(d) + 0.173 \times SOC^{\min}_{TOP}$$

b) for $SOC_{30} > 18\%$ the relationship can only be approximated by using the slope coefficient of the complete soil section from 0-100 cm related to the topsoil SOC content:

$$m^{org}_{0-100} = +0.012 \times SOC^{org}_{TOP} + 3.704, \; b^{org}_{0-100} = 0.858 \times SOC^{org}_{TOP} - 5.390$$

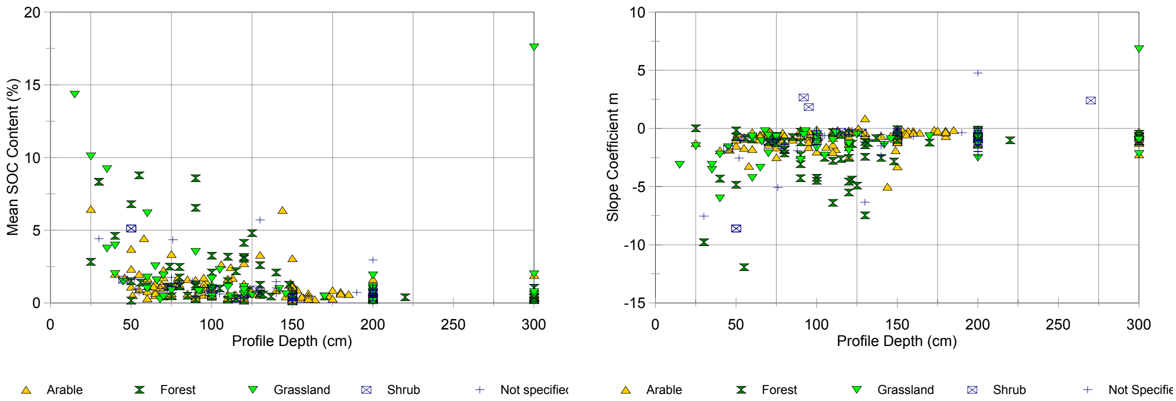
The profiles for organic soils and peat are not sufficiently comprehensive to establish a correlation between SOC content and depth for those soils with any confidence. The findings suggest that under the circumstances it would be preferable to use a constant slope coefficient independent of SOC content of the topsoil. The function for estimating subsoil SOC content at a given depth from the topsoil SOC content is then:

$$\Rightarrow SOC(d)_{SUB}^{org} = 3.704 \times \ln(d) + 0.858 \times SOC_{TOP}^{org} - 5.390$$

The separation of the soils in mineral and organic and peat leaves some uncertainty as to the changes in SOC content with depth for soils with a mean SOC content of 12 to 25%.

3.1.5 Influence of Depth of Soil Stratum

The relationship between the profile mean SOC content and the depth of the soil stratum for mineral soils and the slope coefficient for all profiles are presented in Figure 13.



a) Profile Depth vs. SOC Content *b) Profile Depth vs. Slope Coefficient*

Figure 13: Mean SOC Content for Profile and Change in Model Slope Coefficient with Depth of Profile (SPADE/M)

For mineral soils the profile data show a tendency towards higher mean SOC content values and shallower profiles. This trend would appear to be prevalent for soils in forests and under grassland. When restricting the profiles to those with a standard deviation of <10 for the horizon SOC content the trend is no longer discernable. One may conclude from the observation that in the dataset forest and grassland are found more frequently on soils with higher variations of SOC in the profile than arable land

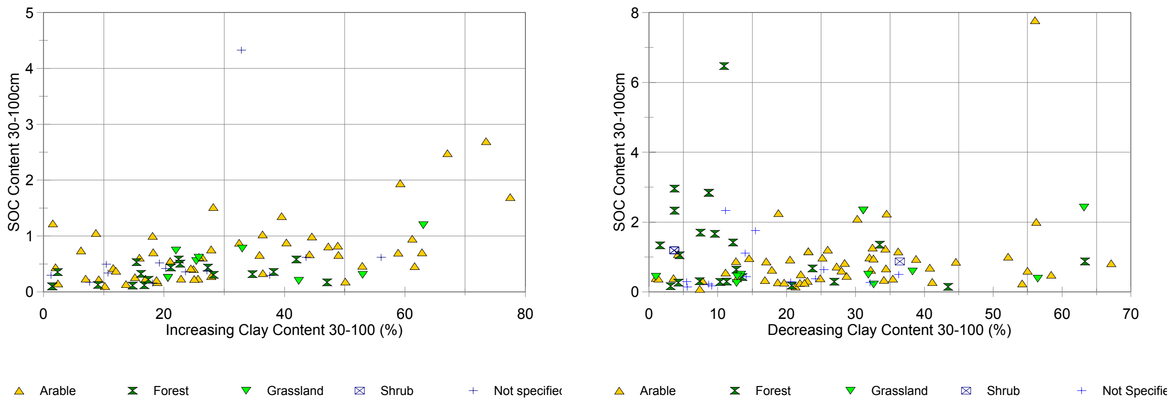
and on shallower soils. This could be attributed to land management practices of establishing land uses according to soil characteristics rather than a dependency of SOC content on land cover type and depth. With the very limited number of organic soils (7) no relationship between SOC content and profile depth could be identified.

A general relationship between the model slope coefficient and profile depth could not be substantiated. As it is the case of the relationship between profile depth and mean SOC content there would appear to be a decrease in the slope coefficient of the relationship of SOC content and depth up to a profile depth of 150 cm. No such trend was apparent for any other vegetation type.

When restricting the analysis to the soil segment 0-100 cm and a SD of <10 the data do not provide sufficient evidence to define a relationship between SOC content and profile depth, neither for mineral nor for organic soils. Such a relationship seems to be more prevalent for mineral soils under grassland than for the other land cover types, but becomes only relevant when analysing subsoil properties at depths lower than 100 cm.

3.1.6 Influence of Clay Content

It has been found that the SOC content is influenced by the amount of clay in the soil, in particular at lower depths and for deeper soils. A comparison in the subsoil segment between the clay and SOC content for profiles with an increasing clay content with depth in the subsoil and those with a decrease is given in Figure 14.



a) Increasing Subsoil Clay Content vs. SOC

b) Decreasing Subsoil Clay Content vs. SOC

Figure 14: Relationship Between Increasing and Decreasing Clay and SOC Content in Profile Subsoil Section

The graphs plot data from the 187 subsoil profiles, of which 88 show an increase in clay content with depth and 99 profiles show a decrease. For the subsoil the SOC content shows a weak tendency to increase with clay content for profiles where the clay content increases. The tendency seems to be most prevalent for profiles taken on arable land, whereas for profiles taken under forests or grassland no particular relationship could be found. While the data point towards a relationship between an increase in subsoil clay content and SOC content in the subsoil when the clay content exceeds 50%, the coefficient of determination for the general relationship is only 0.33.

A relationship between the clay content in the subsoil and SOC content for profiles with a decrease in clay content could not be substantiated by the profile data. Rather it would appear that for the profiles taken in forests SOC content decreases with clay content. However, the data do no provide sufficient evidence that such a trend exists.

Not investigated in any detail could be the additional influence of profile depth on the relationship due to the limited number of data. The dataset contains 12 profiles with a lower end of the profile of <100 cm and where the clay content increases in the subsoil section (9 for profiles with a decrease in clay content). Even when analysing the data to a depth of 300 cm no particular influence of the profile depth on the relationship of clay on the SOC content in the subsoil was found.

The lack of identifying any relation of clay content with the coefficient characterizing the change in SOC content with depth does not as such corroborate the absence of a relationship between the parameters. It only implies that no reliable relationship can be established based on the available data. There may well be such a relationship for a specific soil type. To identify any relationships for specific soils and land cover types data form more profiles would be needed.

3.1.7 SOC Content by Major Soil Category

The mean SOC content in the topsoil and subsoil sections by FAO85 Level I soil category are given in Table 4.

Table 4: SOC Content by Soil Category (SPADE/M)

Soil FAO85	Arable			Forest			Grass			Shrub			ALL		
	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles
Acrisol				2.2	0.4	2							2.2	0.4	2
Cambisol	**1.6**	**0.6**	16	**4.2**	**0.9**	11	2.3	0.5	6				**2.6**	**0.7**	49
Chernozem	1.8	1.2	8										1.8	1.2	8
Podzoluvisol	1.8	0.4	4	1.9	0.4	2							1.8	0.4	6
Rendzina	1.5	0.5	1	1.8	0.4	1							1.6	0.5	2
Gleysol	1.3	0.8	3				5.1	2.4	1				2.5	1.2	8
Phaeozem	**2.4**	**1.2**	15				4.6	1.8	2				**2.7**	**1.3**	17
Fluvisol	**1.4**	**0.9**	10				2.4	0.7	1				**1.4**	**0.8**	16
Kastanozem	4.7	3.0	3										4.7	3.0	3
Luvisol	**1.1**	**0.3**	28	2.0	0.4	5	1.9	0.9	5	1.5	0.7	1	**1.5**	**0.4**	51
Greyzem				3.1	0.4	1							3.1	0.4	1
Histosol	20.3	27.5	3				11.6	40.8	1	49.1	47.1	5	**35.0**	**38.9**	12
Podzol	1.7	0.7	6	14.3	4.4	6	1.8	0.4	1	29.3	1.2	1	**9.6**	**1.9**	18
Arenosol	0.4	0.2	3	1.4	0.3	5							**0.8**	**0.3**	12
Regosol	0.8	0.2	1										0.8	0.2	2
Solonetz	2.1	1.0	2										1.8	0.9	3
Andosol				10.4	5.0	3							11.3	4.8	4
Vertisol	1.5	0.9	9							0.6	0.3	1	**1.4**	**0.9**	11
Planosol	0.4	0.2	1	2.1	0.6	1							1.2	0.4	2
Xerosol	0.9	0.4	1							1.3	0.9	1	1.1	0.6	2
Solonchak	1.0	0.8	2				1.2	0.4	1				0.9	0.5	5
All	**2.1**	**1.5**	**116**	**5.1**	**1.5**	**37**	**3.1**	**3.1**	**18**	**30.9**	**26.5**	**9**	**4.3**	**2.8**	**234**

bold: defined by 10 or more profiles

The table provides the mean topsoil and subsoil SOC content for 21 soil classes by main land use type. When including profiles without land use information the total number of profiles is 234. The number of profiles assigned to a soil category varies considerably between the categories, but also between land uses. By far the most profiles are available for *Luvisol* (51) and *Cambisol* (49). For all other soil categories less than 20 profiles could be analysed for topsoil and subsoil SOC content. Most soil classes are found for arable land (18), followed by forest (10), grass (8) and shrub (5).

The variability of the mean topsoil and subsoil SOC contents between land uses for a given soil class and the low number of observed data available for most combinations makes specifying any general trends rather uncertain. The mean SOC contents for shrub areas, where one profile extensively shifts the whole ratio, illustrate this. Given the variability between land uses the selective geographic positioning of the profiles may further introduce bias into estimating a ratio between topsoil and subsoil SOC content. The mean of all profiles indicates that the subsoil SOC content is 65% of the topsoil SOC content. However, when using only mineral soil layers the ratio drops to 35% while parity is achieved for soils with organic layers. Very similar results are obtained when selecting profiles based on the soil category, i.e. when separating *Histosols* from other soil types (33% without *Histosols*, 111% for *Histosols* alone). Soils with potentially distinct differences in SOC content between the topsoil and the subsoil, such as *Podzols*, show more divergent ratios and should be treated separately.

3.2 Forest Monitoring Soil Survey Data

A rarely used source of information on soils from ground sampling is available from the long-term monitoring programme of air pollution effects on forests. The monitoring activity and the network of plots is implemented for Member States of the European Union under Council Regulation (EEC) No 3528/86 and Regulations (EEC) No 1696/87 and (EC) No 1091/94. "*Regulation (EC) No. 2152/2003 of the European Parliament and of the Council of 17 November 2003 concerning monitoring of forests and environmental interactions in the Community (Forest Focus)*"[1]. Forest Focus continues from the previous regulations as a Community scheme for harmonized, broad-based, comprehensive and long-term monitoring of European forest ecosystems. It is linked to one of the six *International Cooperative Programmes* (ICPs) concerned with the *Assessment and Monitoring of Air Pollution Effects on Forests* (ICP Forests), which acts under the *Working Group on Effects* of the "*Convention on Long-range Transboundary Air Pollution*" (CLRTAP) of the programme for the environment of the "*United Nations Economic Commission for Europe*" (UNECE). The monitoring activity collects data at two distinct levels serving different needs:

- systematic network of observation points (Level I);
- network of observation plots for intensive and continuous monitoring (Level II).

Data sampled at the plots are reported independently and stored using comparable data models, but different tables in the Forest Focus Monitoring Database at the JRC.

3.2.1 Soil Condition Survey Data

The soil parameters to be assessed and the methods to be used for collected data at Level I and Level II plots are defined in Sub-Manual III of the ICP Forests Manual (UN/ECE, 2006)[2]. Particularities of the sampling specifications are:

1. **Organic and Mineral Layer**
   The forest soil condition survey distinguishes between an upper organic layer and an underlying mineral soil layer. The organic layer is defined based on the FAO definition (FAO, 1990a, Guidelines for soil description, 3rd (revised) edition). The organic layer is further divided into horizons of litter, fermentation horizon and/or humus. The litter horizon includes not yet decomposed dead plant material. Other soil sampling surveys use a different approach by removing any not decomposed organic material from the sample, e.g. when sampling on arable land. Those differences in the sampling method of organic material can introduce variations when the Forest Focus data are compared to those collected from other surveys.

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[1] OJ L 324, 11.12.2003, p. 1-8

[2] http://www.icp-forests.org/pdf/Chapt_3a_2006(1).pdf

2. **Differentiation within Organic Layer**
   The organic material is mainly reported as a single layer, although for 16 plots in the Level II data more than 2 organic layers are reported. For all plots with multiple organic layers the information is insufficient to define the change in SOC content with depth according to the selection conditions. As a consequence of having a single value of OC for the organic layer, the character of the changes of OC with depth is generally not well defined for the upper section of the soil.

3. **Sampling within Layers of Fixed Thickness**
   The purpose of the soil assessed at the sites of the sample plots was not to fully describe the soil profiles but to provide an appreciation of the soil conditions present at a plot. This purpose of the data collection impacts on the nature and completeness of the data recorded in the datasets. On Forest Focus plots soil parameters are sampled within layers of a fixed depth. The Sub-Manual for soil sampling stipulates for the mineral layer depths of 0-10 cm, 10-20 cm, 20-40 cm and 40-80 cm. The depth of the soil layer is not recorded, although in few cases data from depths below 80 cm were included in the profile data. As a consequence the soil properties for the lowest layer are assigned to the mean layer depth of 60 cm. In order to allow any analysis of the subsoil layer the minimum data coverage of the subsoil layer was set to 75%.

4. **Organic Carbon and Bulk Density**
   For the organic layer the OC content (g kg^{-1}) and the dry weight of the layer (kg m^{-2}) are recorded in the database, but not the layer thickness. It is thus straightforward to compute OC quantities for the organic layers, although not bulk density or SOC density (no figure to compute volume). For the mineral layers the OC content is recorded together with bulk density (kg m^{-3}). Measurements of bulk density are mandatory only for the 0-10 cm layer and OC for the 0-10 cm and the 10-20 cm layer. Assessing the parameters for other layers is optional.

3.2.2 Pre-Processing Data

The distinctiveness of the sampling approach for Forest Focus soil data from a standard description of a soil profile by pedological horizons requires specific care to be taken when comparing data between surveys. Level II data contains significantly more data on the subsoil section and is used to exemplify the conditions found when preparing the data for comparison with information provided by a survey based on identifying pedological profile.

Treatment of Organic Layer in Depth Analysis

Since the relationship between SOC content and depths is non-linear and also dependent on the total amount of SOC in the soil section the presence of an organic layer in soil section will influence the character of the relationship even when restricting the analysis to the mineral layer. This influence has been further evaluated.

a) Identify Organic Layer

Before the organic layer can be processed it has to be identified. Separating the organic form the mineral layer in the data is not quite as evident as it may at first seem. The most obvious choice is to filter any O or H layers. However, this leads to some inconsistencies with the FAO definition for organic soil material, which defines the material as organic for OC contents between 12 and 20%, depending on clay content and the status of water saturation. (FAO, http://www.fao.org/docrep/W8594E/w8594e0b.htm#organic%20soil%20material).

In the Level II dataset 75 layers are defined as mineral with an OC content of >12% and 24 with an OC content exceeding 20%, with a maximum of 41%. At least the layers with a mean OC content of >20% should have been classified as organic layers. For the layers with a mean OC content of >12% but <20% the character of the soil cannot be determined without adequate information on the clay content and water saturation. Conversely, there are 130 layers defined as organic with an OC content <20% and 57 layers with an OC <12%, the lowest with 2.1% OC content. While it may be argued that organic layers other than those defined as O or H layers can be recorded for a plot, any layer with an OC contents of <12% should be classified as mineral. With 14% of Level II profiles containing non-compliant organic and mineral layers including these profiles in the evaluation of the relationship of SOC content and depth would introduce inconsistencies into the results.

b) Estimation of Height of Organic Layer

Without information on the height of the organic layer in the data the position of the mineral layers within the profile cannot be determined accurately and therefore had to be estimated. Such information is not recorded in the dataset and in the absence of data on bulk density cannot be computed from the available data.

An approximation of the height of the organic layer can be found by using a representative figure for bulk density. In the Level II data set values of bulk density are given for 40 organic layers (O and H) of 18 plots. The average value for those layers is 0.18 g cm^{-3}. Of the 40 layers 4 have OC contents below 20%. For one plot with 3 organic layers with varying OC content identical values of 0.42 g cm^{-3} were reported, while all other layers had values of <0.2 g cm^{-3}. Those plot values were disregarded and the mean bulk density of the remaining organic layers was 0.13 g cm^{-3}. This value was used to estimate the height of the organic layers.

In the absence of adequate information on clay content and water status the layers cannot be re-classified according to the FAO definition; neither can the OC values be adjusted. With the height of the organic layer estimated by a fixed value for bulk density applied should be a limit to the profiles, where the OC content values are below the corresponding value used to estimate bulk density. Otherwise the height of the organic layer would be largely overestimated and the position of the mineral layers in the soil section would shift to deeper levels and obscure any trend in the changes of OC content with depth. The minimum OC content of the organic layers to include the profile in the analysis was therefore set to 20%. Any data on saturated organic layers (H) with depth information attached were also included in the analysis. When a layer did not conform to the conditions the whole profile was excluded from the analysis rather than only the layer. No restrictions of limiting the OC content were applied to the mineral layers, for which a depth was assigned.

c) Effect of Treatment of Organic Layer Height

The consequences of including the OC content of the organic layer(s) and shifting the mineral layers on the relationship between OC content and depth in the profile was investigated using the following approaches to treat the layer data:

1. Use only mineral layer information (M layers) for SOC content and depth.
2. Shift mineral layers by estimated depth of O and H layer, but use only SOC content from mineral layers.
3. Shift mineral layers by estimated depth of O and H layer and including O and H layers when computing mean OC content.

Varied was further the effect of treating the uppermost section of the soil by eliminating a fixed depth of 5cm. The value of 5cm was chosen because it was quoted in the database as the nominal depth for the organic layer and is the smallest height of a mineral layer. A value of 2.5cm was included to allow some measure of appraising where changes in the topmost section occur.

Consistency of the SOC content changes with depth in the profiles is provided by limiting the standard deviation of the SOC content in the pedological horizons or sampling layers. Because the variation within the profile can be expected to vary significantly depending on the treatment of the organic layer in the profile various thresholds of the standard deviation were include in the analysis.

The outcome of the treatment applied to define the profile structure was evaluated based on two indicators:

- the number of profiles compliant with the conditions and
- the coefficient of a linear regression by pairing the mean profile SOC content with the slope coefficient *m* of the function relating SOC content to depth, referred to as the x-coefficient of the SOC depth slope.

The latter indicator is used because the change in SOC content with depth is strongly correlated to the mean SOC content in a profile and because the mean SOC content varies substantially with the treatment of the organic layer in the profile. As a consequence, any significant effects of the treatment of the organic layer and variations of the processing parameters on the indicator implies that the relationship between SOC content and depth depends on the choice of the treatment and thresholds. This seemingly obvious deduction signifies that the unavoidable treatment of the organic layer data may very much restrict comparing the results obtained form the Forest Focus Soil Condition database with those sampled by other soil surveys.

The outcome of the various options of treating the organic layer on the number of profiles and the coefficient of the SOC depth slope are given in Table 5.

Table 5: Effect of Treating Organic Layer on Number of Profiles and x-Coefficient of the SOC Depth Slope

Use Height and OC Content of O/H Layer(s)	Use Height of O/H Layer(s)	Start of Profile from Top	Limit for Std. Dev. of Profile OC Content	No. of Profiles Compliant with Conditions	Regression on Coeff. of OC Slope Coeff.
N	**N**	0	100	576*	-0.566
			20	576*	-0.566
			12	576*	-0.544
			6	564	-0.474
		2.5	100	575*	-0.546
			20	575*	-0.546
			12	575*	-0.526
			6	564	-0.462
		5.0	100	575*	-0.480
			20	575*	-0.480
			12	575*	-0.480
			6	573	-0.441
N	**Y**	0.1	100	374	-0.664
			20	374	-0.664
			12	373	-0.589
			6	364	-0.507
		2.5	100	374	-0.671
			20	374	-0.671
			12	372	-0.671
			6	364	-0.511
		5.0	100	371	-0.682
			20	371	-0.682
			12	369	-0.602
			6	362	-0.542
Y	**Y**	0	100	387	-0.825
			20	374	-0.973
			12	110	-0.444
			6	11	-0.369
		2.5	100	387	-0.986
			20	376	-1.224
			12	244	-0.824
			6	170	-0.364
		5.0	100	383	-1.038
			20	375	-1.289
			12	303	-0.815
			6	258	-0.450

** 1 profile removed from comparison due to anomalous arrangement of layers within profile.*

The table shows a significant difference in the number of profiles found to comply with the conditions set and the relationship between the slope coefficient of change in SOC with depth and the SOC content in the soil section.

The main results of the analysis are:

1. **Use only mineral layer information (M layers) for OC content and depth**

   When the information of the organic layers is not used the largest number of profiles passes the pre-processing conditions set. The number of profiles varies very little over the range of standard deviations limits. Notable is a general decrease in the coefficient of the SOC depth slope when lowering the topmost depth level of information. This behaviour can be expected in the presence of a non-linear relationship between SOC content and depth.

2. **Shift mineral layers by estimated depth of O and H layer, but use only OC content from mineral layers**

   When taking the height of the organic layer into account to estimate the start of the mineral layers below the surface the number of profiles is considerably less than when ignoring the organic layers. The main reason is that this particular approach to pre-processing excludes all profiles where the presence of an organic layer is indicated, but no information on the layer weight is provided in the data. The number of profiles remains quite stable regardless of the restrictions set on the start of the layer or the variation of SOC content values within the profile. Contrary to the trend found when ignoring the organic layer information the coefficient of the regression further decreases when lowering the depth of the topmost layer. In the presence of an organic layer on top of mineral layers lowering the surface actually raises the top of the mineral layer when the height of the organic layer is more than the height of the slice removed from the section. As a consequence, the coefficient of the SOC content to depth relationship increases when the data contains a non-linear relationship between SOC content and depth.

3. **Shift mineral layers by estimated depth of O and H layer and including O and H layers when computing mean OC content**

   When including the estimated height and SOC content of the organic layers in the combination results in a markedly more complex effect on the number of profiles covered and the coefficient of the OC depth. For a better assessment of the interactions the more detailed constraint were used for pre-processing conditions. The results are graphically presented in Figure 15.

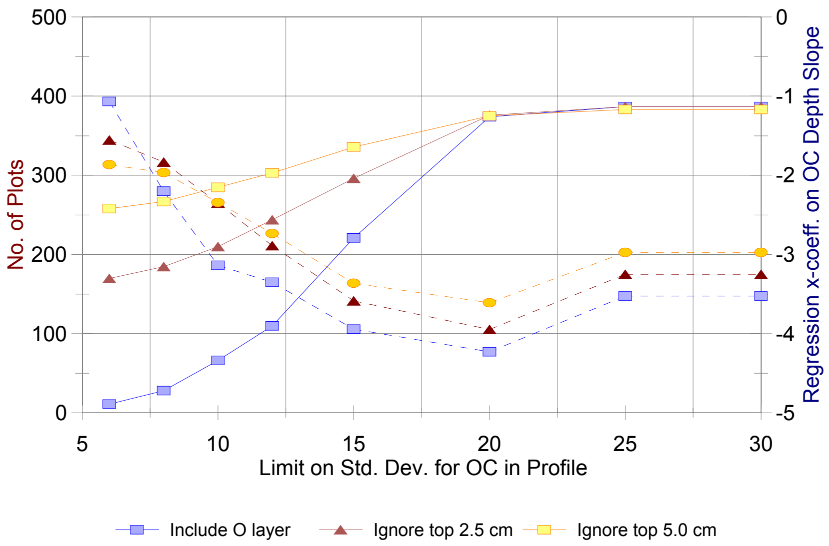


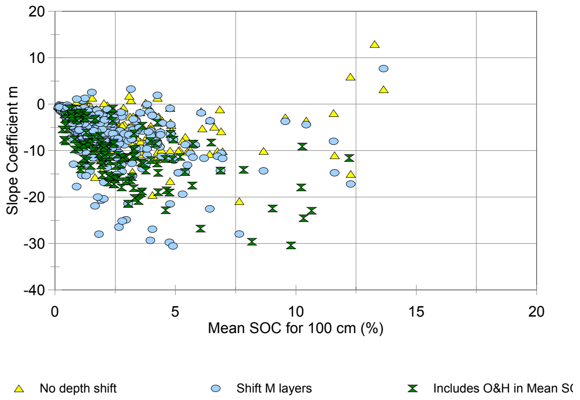
Figure 15: Effect of Various Limits of the Std. Dev. on Profile Number and x-Coefficient of the SOC Content vs. Depth Slope Factor when Including Organic Layers (Level II)

For the three topmost sections excluded from the soil profile (0, 2.5 and 5.0 cm) the number of compliant profiles converges at a SD of approx. 20% to just over 380. As could be expected the number of profiles remaining in the data increases considerably when larger portions of the topmost soil section are removed from the profile.

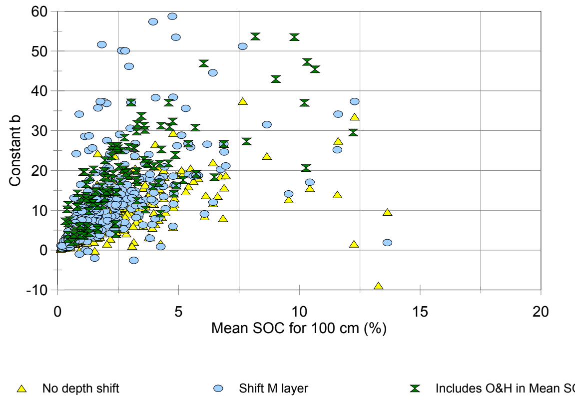
The regression coefficient of the SOC depth slope decreases up to this value to a local minimum. For the standard deviation of the SOC content values >8 the regression coefficient of the OC depth slope remains higher for a lower start of the section within the profile. The rather exceptional behaviour when limiting the standard deviation to <8 was attributed to the low number of conform profiles (11).

Neither development exhibits any sudden jumps which could indicate particular breaks in the composition of profiles with respect to SOC content. The absence of common sudden changes indicates a lack of clustering of the profile composition, which would be more difficult to observe when sampling soil properties by depth layer instead of pedological horizons.

The distribution of the slope coefficient and constant for the logarithmic transformation of soil depth for changes in mean SOC content for the plot profiles is given in Figure 16.



a) Profile SOC Content vs. Coefficient



b) Profile SOC Content vs. Constant

Figure 16: Change in Model Slope Coefficient and Constant with Mean SOC for Complete Soil Section 0-100 cm (Level II)

In the graph the parameters of the linear correlation on the three methods of treating the organic layer are presented. Without taking the organic surface layer into account the general trend of a decreasing slope coefficient with depth changes to an increase in the coefficient for a mean SOC content of approximately 8%. The trends are more accentuated when including the depth of the organic layer, but no the SOC content of the layer. The inversion of the trend in the regression parameters is no discernable when including the depth of the organic layers and the estimated SOC content.

The method of treating the organic layer as a single stratum without further differentiation leads to large variations in SOC content between the organic and the mineral layers. This subsequently excludes profiles with a higher SOC content from the data set used for analysis and precludes an evaluation of the behaviour of SOC content for organic soils. The change in the trend is still notable when removing the limit on layer variation on the data set used.

The findings confirm that the height of the organic layer should be accounted for when evaluating the relationship between SOC content and depth in the soil. Not including the organic layer information reduces the sensitivity of the relationship between SOC content and depth and can lead to spurious results. Conversely, fully using the organic layer information strongly reduces the number of profiles when applying a limit to the variability of SOC content in the profile. This circumstance is particularly prevalent for soil profiles in forests where the presence of a thin organic layer over mineral soils is considerably more widespread than e.g. for profiles taken on arable land. Sampling the organic layer separately and reporting it regardless of the thickness of the layer, at times <1cm, only amplifies the effect. Removing the organic layer when it is below a fixed height increases the number of profiles for a given limit on SOC variability. However, removing the information on the organic component even only partially from the analysis directly affects the slope parameter of the relationship of SOC content with depth. Therefore, this treatment would not appear to be a suitable option when the data are processed with the intention of comparing the results with those obtained from other soil profile datasets.

A possible solution to the problem is to only include the organic layer information in the calculation of the standard deviation of the soil profile until the thickness of the layer indicates the presence of a *histic* or *folic* horizon, i.e. when the organic layer thickness is 10 cm or more from the soil surface (FAO, 1998). This approach has been taken to use the Forest Focus Soil Condition data for Level I and Level II plots.

Organic layers with a lower thickness are merged with the underlying layer until the thickness of the combined layer exceeds 10 cm. Soil properties for the merged layer are the mean of the individual layers weighted by the portion of the layer thicknesses.

3.2.3 Layer Sampling vs. Pedological Horizons

When evaluating the change in SOC content with depth the sampling method applied can be of significant consequence when comparing the results obtained. The reasons for a possible divergence in the coefficients of change can be mainly attributed to the non-linear change in SOC content with depth and using the central point of a layer as the depth to which the mean SOC content of a layer is assigned. The situation is exemplified in Figure 17.

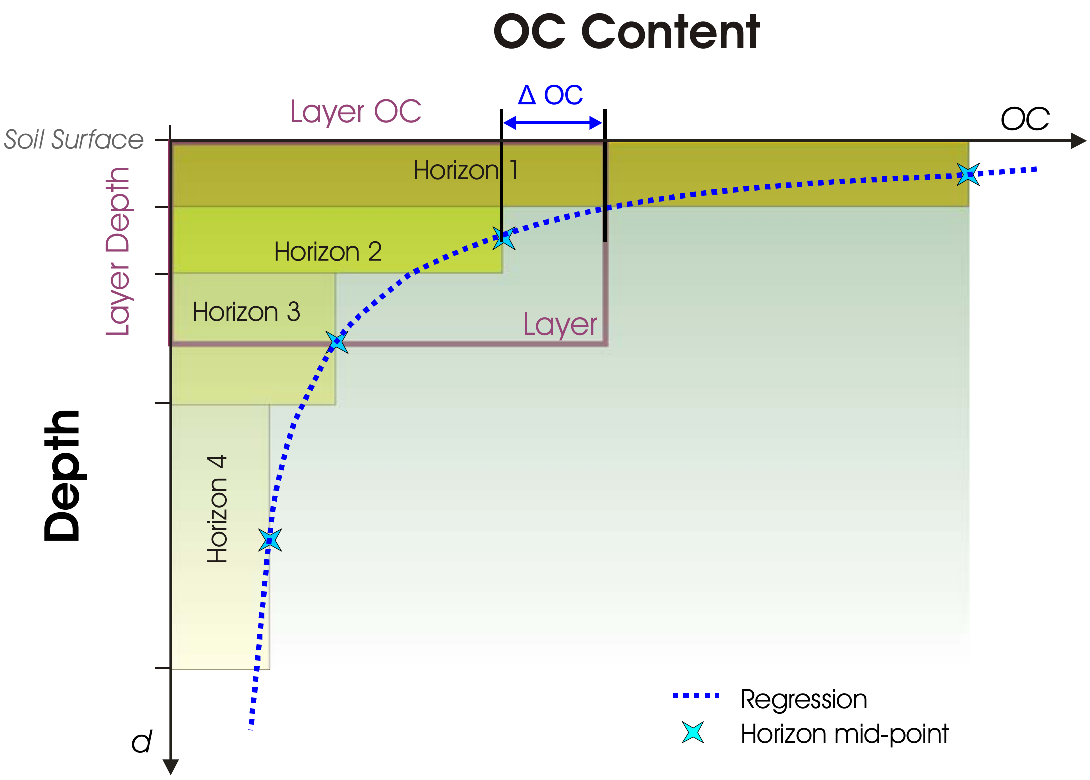


Figure 17: Sampling Soil Properties by Fixed Layers vs. Pedological Horizons

The figure shows several pedological horizons of a soil profile covered by a single depth layer. Proportions of SOC content and depth are drawn to scale. For each horizon and the layer the central depth is indicated. Also indicated is the modelled non-linear decrease in SOC content with depth as defined by the SOC contents of the horizons and their central depths. The SOC content of the layer is the SOC content of the horizons weighted by the thickness of the horizon within the layer calculated as:

$$OC_L = \sum_{i=1}^{n} OC_H^i \times p_H^i$$

where

OC_L: organic carbon content of layer *L*
OC_H: organic carbon content of horizon *H*
p_H: portion of horizon H within layer *L*
i: horizon within layer

When the decrease in SOC with depths is non-linear the mean SOC content of the layer at the central layer depth deviates from the SOC content at that position within the pedological soil profile. Under the condition shown that the layer integrates several pedological horizons the SOC content at the central depth to the layer overestimates the equivalent SOC content at that depth in the profile. The difference in the SOC content (ΔSOC) between the layer and the profile at the depth of the central layer depends on the actual characteristic of the change of SOC content in the profile. To define the change in SOC content with depth for a soil profile the SOC content of the layer should therefore not be assigned to the central depth, but a reduced depth.

For the linear relationship between SOC content and depth using a logarithmic transformation of the depth parameter the difference in depth Δd can be approximated by:

$$\Delta d = d_L - e^{\frac{OC_L - m}{b}}$$

where

m: slope coefficient of relationship SOC content and depth
b: constant of relationship SOC content and depth
d_L: central depth of layer *L*

While the computation of Δd is not demanding the validity of the underlying assumptions very much determines how reasonable it would be to adjust the depth to which the mean SOC content of a layer is assigned. Under-sampling the pedological horizons invariably leads to a levelling of the change in SOC content with depth. Over-sampling a horizon shifts the weight of the layer data in the regression analysis to misrepresent the relationship. Without ancillary information on the change in SOC content with depth the difference in the representative depth of the layer in the profile cannot be reliably determined.

To better understand the effect of sampling layers of fixed depth as compared to samples taken in pedological horizons the fixed layer sampling was simulated using the pedological horizon data of the SPADE/M profiles.

There are some practical limitations to the simulation:

- For once, the SOC content of the layers completely within the upper horizon remains fixed to the SOC content of the horizon. As a result some plots have identical SOC values for all simulated layers of the layer 0-30 cm. For those plots no meaningful relationship of changes in SOC with depth can be determined although a sufficient number of layers are generated by the interpolation methods to allow computing such changes.
- When the layer depth integrated several horizons of the topsoil the computation of a rate of change with depth flattens the relationship.
- When layers are spaced too closely in a profile with horizons of variable depth the repetition of values can introduce an element of bias in the relationship of SOC content with depth.

Interpolating SOC content for layers from pedological horizons precludes some knowledge of the change in SOC content with depth. It is not applicable for corrections of SOC contents, which is a measured property, only to adjust the corresponding depth to one equivalent to a horizon sample.

The number of layers and their depth intervals were chosen according to the data sources used:

a) 4 layers FF: 0-10, 10-20, 20-40, 40-80

b) 5 layers FF: 0-5, 5-10, 10-20, 20-40, 40-80

c) 5 layers 0-10, 10-20, 20-30, 30-60, 60-100

d) 6 layers 0-5, 5-10, 10-20, 20-30, 30-60, 60-100

e) 8 layers 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80, 80-100

f) 9 layers 0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80, 80-100.

For sampling 4 or 5 layers the depth intervals of the layers were aligned to the sample intervals specified for assessing soil conditions under Forest Focus long-term monitoring for effects of atmospheric pollution on the forest environment. There are two options for assessment of the mineral layer from 0 – 10 cm:

- using a single layer and
- dividing it into two units of 5 cm thickness.

The subsoil section is treated as either two layers (30 - 60 cm, 60 - 100 cm) or further subdivided into 5 layers (30 - 40 cm, 40 - 50 cm, 50 - 60 cm, 60 - 80 cm, 80 - 100 cm) to appreciate the effect of reporting for the subsoil.

To evaluate the representation of the layers for pedological horizons the frequency distribution of a central depth of a horizon for the layers was determined for 339 profiles included in the evaluation. The results are shown in Table 6.

Table 6: Distribution of Central Depths of Horizons and Layers in SPADE/M

Depth	**Frequency**	**Layers**					
cm		**9**	**8**	**6**	**5**	**5FF**	**4FF**
0-5	73	73		73		73	
5-10	120	120	193	120	193	120	193
10-20	220	220	220	220	220	220	220
20-30	129	129	129	129	129		
30-40	172	172	172			301	301
40-50	128	128	128				
50-60	137	137	137	437	437		
60-70	98						
70-80	97	195	195			460	460
80-90	76						
90-100	70	146	146	341	341		
TOTAL	**1320**						
Layers	3729	3051	2712	2034	1695	1695	1356

In the database the 339 profiles are defined by a total of 1,320 horizons. To arrive at a number of layers equal to or larger than the number of horizons the soil stratum needs to be subdivided into at least 4 layers, i.e. there are on average approx. 4 horizons defining a profile. A larger number of layers indicates some over-sampling of the profile, but does not exclude that horizon data are averaged.

Results from the combination of the various options of treating the profile data are shown in Table 7. The table presents the slope coefficients of the regression between the pedological horizons and the depth layers for the mean OC content of the section 0 - 100 cm and the slope coefficient of the relationship of changes in OC content with depth.

Table 7: ***Effect of Layer Sampling at Various Intensities on Mean SOC Content and on Relationship of SOC Content with Depth***

	LAYERS					
Topsoil sections	4	3	4	3	3	2
Subsoil sections	5	5	2	2	2	2
Mean SOC content						
Coefficient	1.0021	1.0021	1.0048	1.0048	1.0042	1.0042
r^2	0.9989	0.9989	0.9998	0.9998	0.9924	0.9924
Coefficient of changes in SOC content with depth						
Coefficient	0.7012	0.8052	0.6737	0.7860	0.6487	0.7615
r^2	0.9302	0.9443	0.9078	0.9274	0.8602	0.8808

The various options for simulating layers do not significantly affect the mean SOC content of the soil section. However, the slope coefficients characterizing the relationship between SOC content and depth are strongly affected and generally lower for the layer data than for the horizon data. The differences in slope coefficients tend to decrease with an increase in the number of subsoil layers. Conversely, it appears that the subdivision of the topmost 10 cm into two layers rather decreases the slope coefficient of the regression function, but that it does not affect the strength of the relationship to the same degree.

For the mineral soils in the data set used the coefficient describing the relationship between SOC content and depth would differ by a factor of up to 0.65 when comparing results obtained from layers of fixed depth as opposed to pedological sampling methods. The results of the simulation also suggest that dividing the subsoil stratum into two layers may not provide sufficient detailed to describe the changes in SOC content with depth. Defining two layers describing the uppermost 10 cm instead of one does not improve the coherence of the slope coefficient between the two methods. One explanation is that since only 21.5% of the profiles in the dataset define a distinct horizon above a depth of 5cm the subdivision simply duplicates the SOC content value for two different depths.

In conclusion the sampling method of not differentiating the organic layer and sampling in fixed layers with what amounts to just one sample in the subsoil section very much limits the use of the forest soil dataset to the analysis of the distribution of the SOC content in the profile of mineral soil.

3.2.4 Intensive Monitoring - Level II

The Forest Focus Level II Soil Condition database contains the geographic coordinates for 826 plots from 26 countries. Data on ground samples were taken at 741 plots between 1990 and 2004. For 127 plots the sampling was repeated once, while at 11 plots data from 3 sampling surveys are recorded in the database. For repeated surveys the specifications of the Sub-Manual allow for subsequent surveys to limit the number of mineral layers assessed to just two (0-10 cm, 10-20 cm). Collecting data for other layers has been left an optional activity and corresponding data not always found in the database.

From the nominal number of plots of 826 data from 391 plots could be used for further analysis for the relationship between SOC content with depth. The spatial distribution of those Level II plots is given in Figure 18.

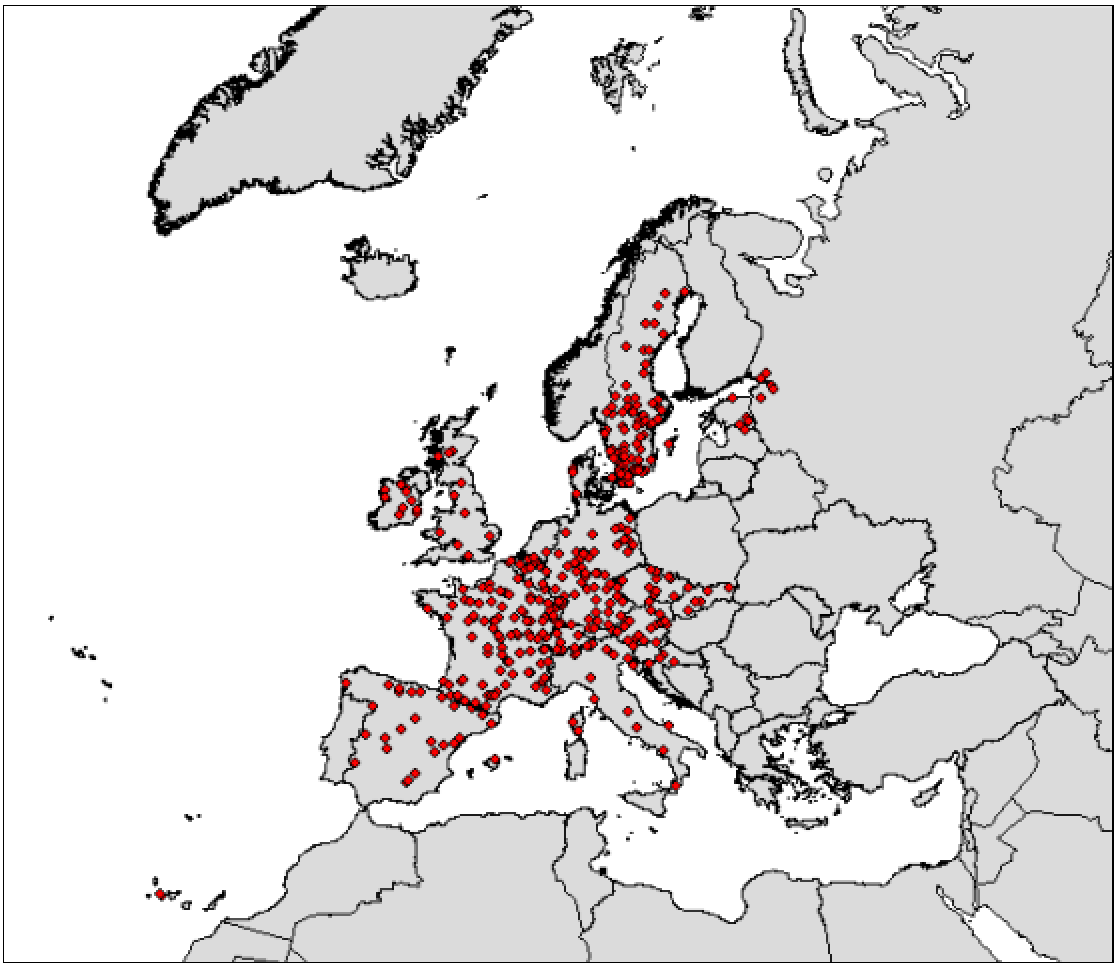


Figure 18: Distribution of Profiles of Forest Focus Level II Soil Profiles with Subsoil Data

One of the main factors reducing the amount of useable plots is the lack of measurements recorded in the database, both for depth layers and parameters. Of the 865 profile data sets for plots with an organic layer (repeated samples included) 330 do not record the organic layer weight. For those data sets the height of the organic layer cannot be computed and therefore the starting depth of the mineral layer cannot be estimated when including the organic layer to position the measurements in the profile. For 174 plots the mineral layers specified did not contain information on SOC content for one or more of the layers. There are also cases of data duplication to record a profile. This situation can occur because data were collected or computed for optional layers from mandatory layers. For example, layers M05 (0-5cm) and M51 (5-10 cm) were supplemented by information of the M01 (0-10 cm) layer. The situation is made more complex when the information for the larger layer does not match the data of the finer layers.

Limiting the SD in the profiles to 10 would have reduced the number of plots suitable for evaluating the relationship of SOC content and depth to just 127. Instead, any organic layer at the top of the profile was merged with a layer at a lower position until the combined layer was >=10 cm in height. This drastically reduced the large variation within the profile frequently caused by an organic layer of very limited thickness.

3.2.4.1 SOC Content on Level II Plots

The distribution of the SOC content with depth of the central layer for 2,856 layers is presented in Figure 19.

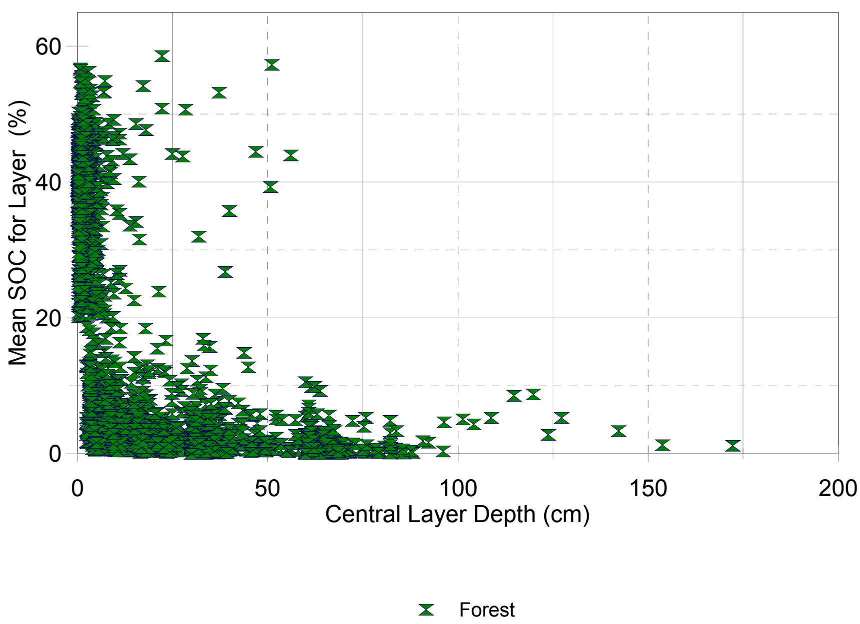
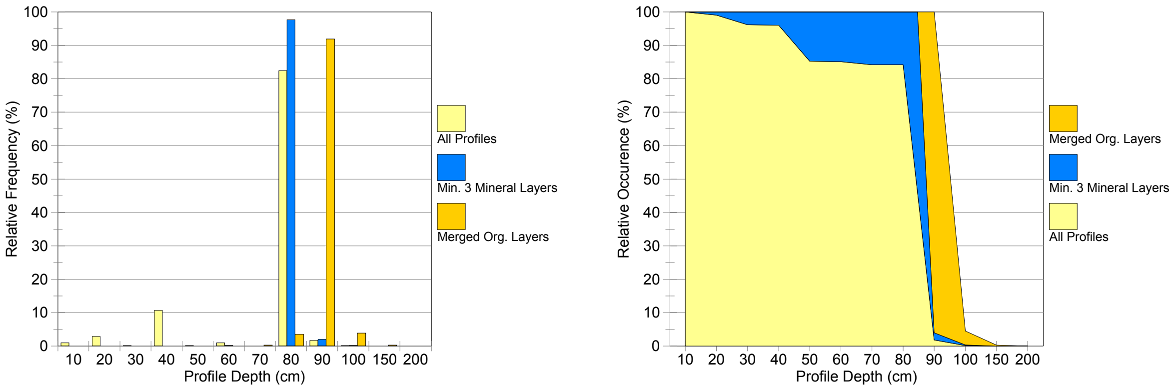


Figure 19: Horizon Depth vs. Soil Organic Carbon for Forest Focus Level II Layers

Similar to the distribution of SOC content with the profile horizons of the SPADE/M data the graph indicates two different behaviours of the content of SOC with layer depth near a SOC content of 20%. Values for depths lower than 80 cm are shown in the graph, because the depth of the mineral layers is given as the estimated depth from the surface, allowing for the height of the organic layer.

The relative frequency of the lowest depth reported for the FF Level II profiles is presented in Figure 20.



a) Profile Depth vs. Relative Frequency *b) Profile Depth vs. Accumulated Relative Frequency*

Figure 20: Frequency Distribution of Profile Depth and Relative Depth Cover

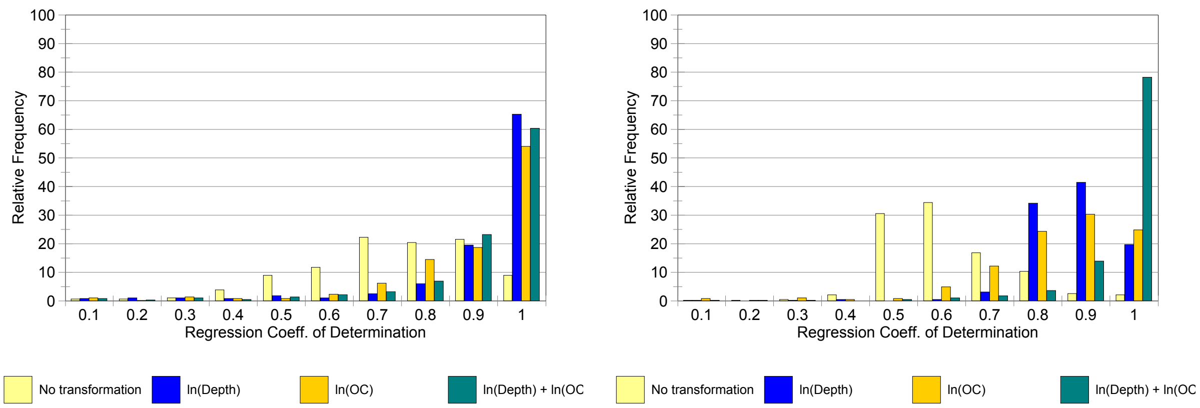
The graph shows the relative distribution of the end of the lowest layer for:

- All Profiles
  all profiles in the dataset, for which a layer depth was reported;
- Min. 3 Mineral Layers
  for profiles for which a regression of SOC content vs. depth could be computed for mineral layers, i.e. with a minimum of 3 mineral layers in the profile and
- Merged Org. Layer
  for profiles where the organic layer was merged until a layer thickness of 10 cm was attained.

The clustering of the end of the lowest layer to be defined by the specifications for sampling (80 cm) is evident irrespective of the treatment of the organic layer. There are some profiles with a lower end below 80 cm, but for which less than 3 layers are recorded and which are therefore excluded form subsequent analysis. The introduction of the organic layers shifts the lower end of the mineral layers mainly to a depth of 80-90 cm.

3.2.4.2 SOC Content and Depth Transformation

The frequency distribution of the coefficient of determination as obtained from 4 combinations of transforming SOC content and/or depth is presented in Figure 21.



a) Mineral Layers, SD<100 *b) Merged Organic Layer, SD<10*

Figure 21: Frequency Distribution of Regression Coefficient of Determination for Logarithmic Transformation of SOC Content and Central Layer Depth for Mineral Layers and for Merged Organic Layers (Forest Focus Level II)

Used in the evaluation of the transformations were only profiles with mineral soils and profiles where the organic layers were merged with mineral layers. No regression analysis could be performed on profiles with only organic layers. The distribution of the fit between SOC content and depth for the mineral layers of 594 Level II profiles (no limit on SD) is comparable to the results obtained from the SPADE/M profiles. The best fit for each profile was achieved when transforming at least one axis. The transformation leads to approx. 60% of the profiles having an r^2 value of >0.9.

The distribution of coefficients of determinations differs considerably when including the organic layer in the profile section evaluated. Presented in the graph is the distribution for 386 profiles with the merged organic layers to a depth of 10 cm, but the distribution when using separate organic layer data are comparable. The treatment resulting in the highest number of r^2 values >0.9 occurs when both, depth and SOC content, are transformed. Any other treatment of SOC content and depth results in a considerably lower score for the correlation coefficient.

The difference in the results depending on the treatment option applied and whether or not including the organic layer data could not be confirmed by data from profiles of the SPADE/M and ISRIC-WISE datasets. The variability could be explained by the practice of generally reporting a distinct organic layer in the Soil Condition dataset as compared to profiles sampled following alternative methods. This leads to an abrupt change in the SOC content within the profile by an order of magnitude rather than a progression with depth. As a consequence, the differences in the correlation between transformations of depth and/or SOC content decrease when setting a limit on the variability of the SOC content in the profile. However, this also drastically reduces the number of profiles available for analysis. The effect is not completely attributable to the sampling method on FF plots. By nature, the structure of soil profiles under forest differs as compared to for example profiles taken on agricultural land. Soils under forest frequently are covered by an organic layer with a distinctly higher OC content than the underlying soil layer, which is mostly absent on arable land.

3.2.4.3 Influence of Mean SOC Content in Profile

The treatment of the data extensively changes the characteristics of the development of SOC content with depth. The relative frequency distribution of the slope coefficients *m* obtained from the regression of the two parameters when not considering the organic layers and when merging the organic layers to a thickness of 10 cm are presented in Figure 22.

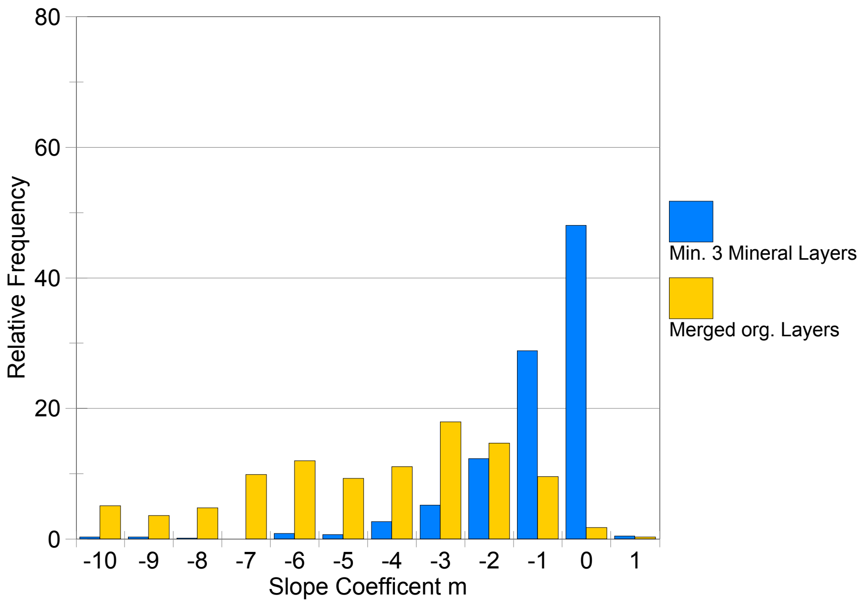
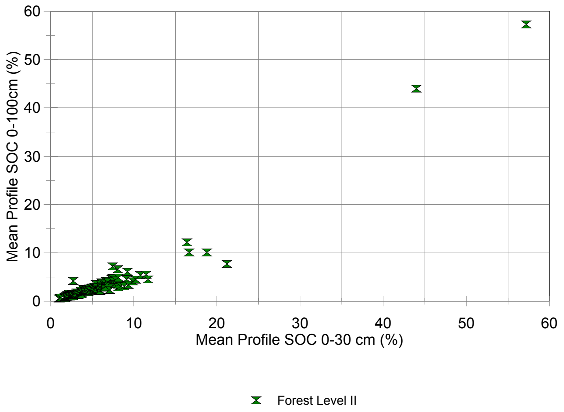


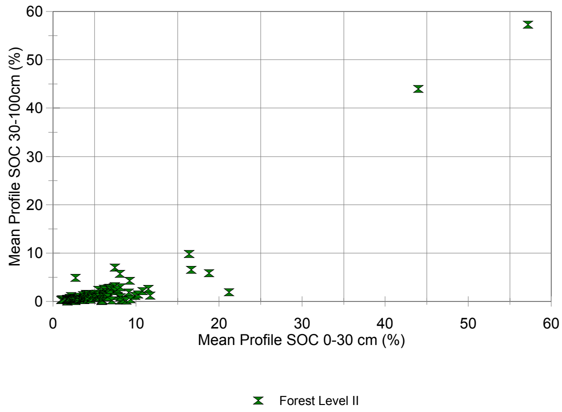
Figure 22: Frequency Distribution of Relative Occurrence of Slope Coefficient m (Level II)

The mineral layers alone show a relatively constant decrease in SOC content with depth where approx. 50% of the profiles fall into the category of 0 to -1 for the slope coefficient. Including the organic layers the most frequent occurrence of slope coefficients to the category are shifted to the range of -3 to -4. The organic layers also generate a fundamentally different distribution of the coefficient with a much larger spread of the coefficients.

When relating the mean SOC content in the topsoil to the SOC content of the subsoil and to the soil segment from 0-100 cm the situation presented in Figure 23 was found.



a) Topsoil vs. 0-100 cm SOC Content



b) Topsoil vs. Subsoil SOC Content

Figure 23: Relationship Between Mean SOC Content in Topsoil and Soil Segment 0-100 cm and Subsoil (Level II)

The relationship between the topsoil SOC content and the segment covering the upper 100 cm of a profile shows a principally linear trend for mineral soils. This trend is much less evident when comparing the SOC content of the topsoil with the subsoil. The lack of a distinct relationship can be explained by the presence of the organic layers in the topsoil, whose effect does not reach the subsoil segment and therefore leads to a less well defined relationship. Using only the mineral layer information very much increases the relationship between topsoil and subsoil SOC content.

The dataset contains only 4 profiles for organic soils and 2 for peat. The geographic clustering of the organic soils makes it unsuitable for defining a meaningful relationship in SOC content between the topsoil and subsoil. The relationship for the mineral soils as described by a linear regression was found as being:

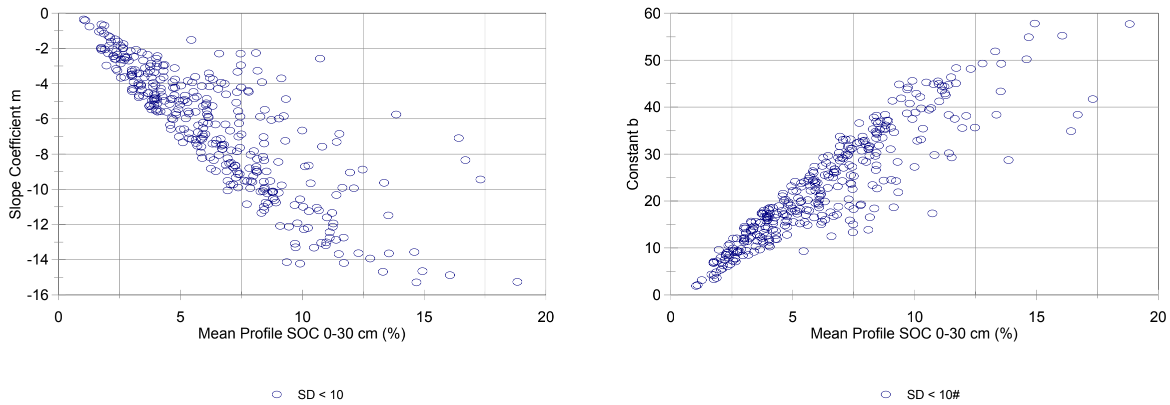
$$SOC_{0\_100}^{\min} = 0.509 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.77, 123 dF)}$$

$$SOC_{SUB}^{\min} = 0.237 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.25, 123 dF)}$$

For the range of SOC content values the mean SOC content to a depth of 100 cm is approximately half the value of the mean SOC for the topmost 30 cm. The coefficient is comparable to the value for the relationship determined for the SPADE/M data (0.52). Using only data from plots under forest the coefficient for the SPADE/M data is 0.47.

Relating the mean SOC content in the 30 cm topsoil to the subsoil results in a coefficient of 0.24. This value compares to a coefficient of 0.27 found for the SPADE/M profiles when relating topsoil to subsoil SOC content. In the interpretation of the results it should be considered that the Level II data only cover the soil to a depth of approx. 80 cm and that according to the general trend the SOC content would slightly decrease to a depth of 100 cm. Both datasets indicate that for forest soils the SOC content in the subsoil is approx. 25% of the SOC content in the topsoil for mineral soils. This contrast quite strongly with the coefficients found for soils under arable land use.

The change in the slope of the relationship between SOC content and depth for the topsoil is given in Figure 24.



a) Topsoil SOC Content vs. Coefficient *b) Topsoil SOC Content vs. Constant*

Figure 24: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Topsoil Applying SD Threshold of 10 (Level II)

For the topsoil the relationship between SOC content and depth is quite distinctly defined for SOC content values up to approximately 12%. For situations with higher topsoil SOC contents the relationship is not quite as evident. The number of plots falling into this category is small (5), which makes it difficult to deduct any conclusive relationship between SOC content in the topsoil and depth specific to profiles with the higher SOC content.

To be consistent with the analysis of SPADE/M data a value of 18% for the SOC content was used to separate profiles in the regression analysis. For plots with less than <18% SOC content in the topsoil the slope and offset values of the relationship characterizing SOC content and depth are:

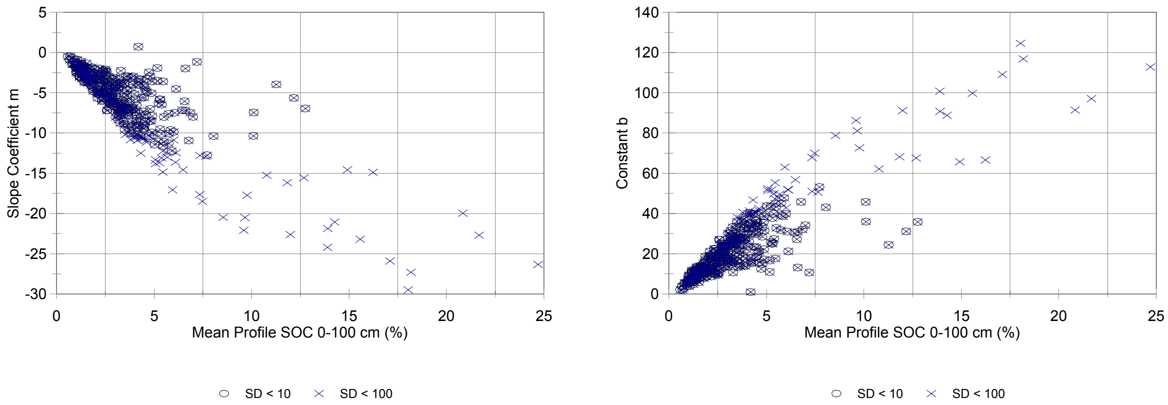
$$m^{\min} = -0.977 \times SOC_{TOP} \text{ (r}^2\text{: 0.66, 347 dF)}$$

$$b^{\min} = 3.553 \times SOC_{TOP} \text{ (r}^2\text{: 0.80, 347 dF)}$$

$$\Rightarrow SOC(d)_{TOP}^{\min} = -0.977 \times SOC_{TOP}^{\min} \times \ln(d) + 3.553 \times SOC_{TOP}^{\min}$$

The y-offset for the regressions was set to 0 since it is assumed that a soil without SOC in the upper layer would also not have any OC at more profound layers.

The relationship between SOC content of the profile segment of 0-100 cm and the regression parameters for SOC content vs. depth is presented in Figure 25.



a) 0-100 cm SOC Content vs. Coefficient *b) 0-100 cm SOC Content vs. Constant*

Figure 25: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Soil Section 0-100 cm Applying SD Threshold of 10 and 100 (Level II)

The relationship shows a well-defined lower edge of the slope coefficient and an increase in variation with SOC content above approx. 10%. The regression parameters are:

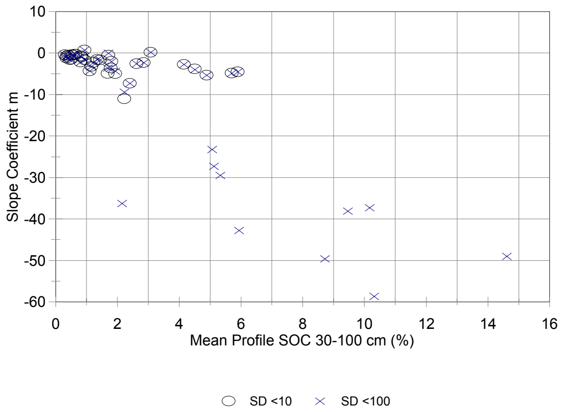
$$m^{\min} = -1.428 \times SOC_{0-100} \text{ (r}^2\text{: 0.20, 333 dF)}$$

$$b^{\min} = 5.855 \times SOC_{0-100} \text{ (r}^2\text{: 0.38, 333 dF)}$$

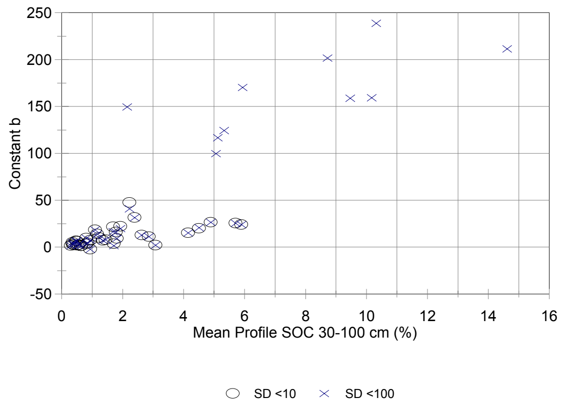
$$\Rightarrow SOC(d)_{0-100}^{\min} = -1.428 \times SOC_{0-100}^{\min} \times \ln(d) + 5.855 \times SOC_{0-100}^{\min}$$

When releasing the condition on the SD from 10 to 100 the coefficient does not change significantly (-1.477), but the coefficient of determination increases from 0.20 to 0.63 (0.38 to 0.74 for the constant).

The relationship between SOC content and the regression parameters for SOC content vs. depth for the subsoil is presented in Figure 26.



a) Subsoil SOC Content vs. Coefficient



b) Subsoil SOC Content vs. Constant

Figure 26: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Subsoil Applying SD Threshold of 10 and 100 (Level II)

The figure shows that limiting the SD of the profiles SOC content to 10 results in a max. mean SOC content of approx. 6%. For subsoil layers with a higher SOC content the SD threshold has to be enlarged to 20 or more (see Table 5). Even when increasing the SD threshold to 100 only 1 profile with a potentially organic subsoil (>12% SOC content) could be included in the analysis dataset.

The effect of the SD threshold for the variability of SOC contents on the number of profiles included in the regression limits the number of profiles to 34. As a result of the variation in the data the change in the parameters of the regression between SOC content and depth has a higher degree of uncertainty attached than results from the analysis of the topsoil or the soil segment to 100 cm.

A linear regression of the profiles with variations in SOC content limited to SD<10 provides the following parameters:

$$m^{\min} = -1.108 \times SOC_{SUB} \text{ (r}^2\text{: 0.14, 33 dF)}$$

$$b^{\min} = 5.523 \times SOC_{SUB} \text{ (r}^2\text{: 0.27, 33 dF)}$$

$$\Rightarrow SOC(d)_{SUB}^{\min} = -1.108 \times SOC_{SUB}^{\min} \times \ln(d) + 5.523 \times SOC_{SUB}^{\min}$$

In a comparative run of the analysis the threshold criterion set for the number of profiles used to compute the regression parameters for each profile was relaxed to 2. It was found that this condition increased the number of profiles to 382, but did not improve the fit of the data.

Widening the condition on the SD from 10 to 100 increased the number of profiles to 44. A linear regression of profiles with a threshold of SD<100 gave the following parameters:

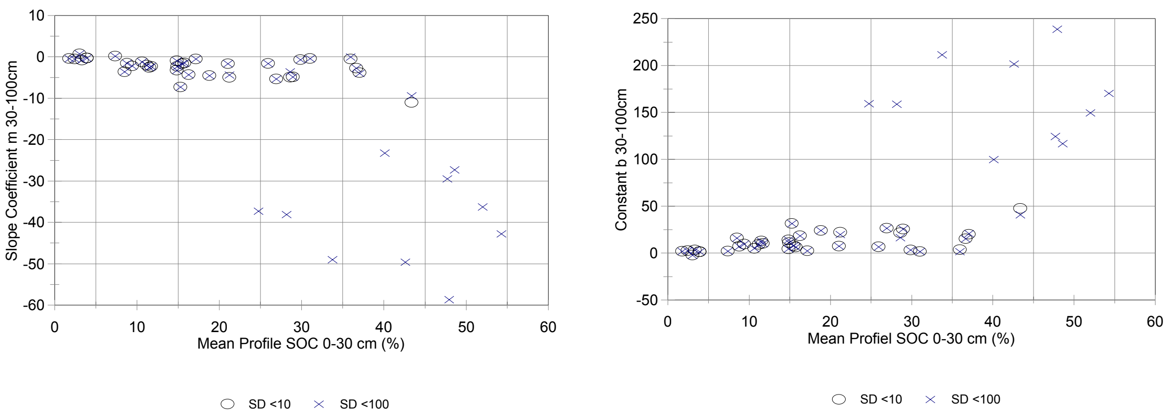
$$m^{\min} = -3.814 \times SOC_{SUB} \text{ (r}^2\text{: 0.69, 43 dF)}$$

$$b^{\min} = 16.151 \times SOC_{SUB} \text{ (r}^2\text{: 0.72, 43 dF)}$$

$$\Rightarrow SOC(d)_{SUB}^{\min} = -3.814 \times SOC_{SUB}^{\min} \times \ln(d) + 16.151 \times SOC_{SUB}^{\min}$$

The significantly lower coefficient was caused by including profiles with a SOC content of 8 to 15% and with comparatively with low values for the slope coefficients. Soil profiles in this part of the spectrum of SOC content values were previously not included.

For the estimation of the subsoil SOC content at any depth between 30-100 cm the slope and constant parameters of the relationship of SOC content and depth for the topsoil would be used. The correlation between the two soil sections is shown in Figure 27.



a) Topsoil SOC vs. Subsoil Coefficient *b) Topsoil SOC vs .Subsoil Constant*

Figure 27: Relationship between Mean SOC Content for Topsoil and Model Slope Coefficient and Constant for Subsoil Applying SD Threshold of 10 and 100 (Level II)

Because of the restricted number of profiles describing the subsoil adequately the correlation between both segments is based on just 34 profiles when limiting the SD of the SOC content values to 10. The regression parameters provide the following values for coefficient and constant:

$$m_{SUB}^{\min} = -1.016 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.23, 33 dF)}$$

$$b_{SUB}^{\min} = 0.628 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.26, 33 dF)}$$

$$\Rightarrow SOC(d)_{SUB}^{\min} = -1.016 \times SOC_{TOP}^{\min} \times \ln(d) + 0.628 \times SOC_{TOP}^{\min}$$

When setting a threshold of 100 for the SD of the SOC content layer data the following relationship is given:

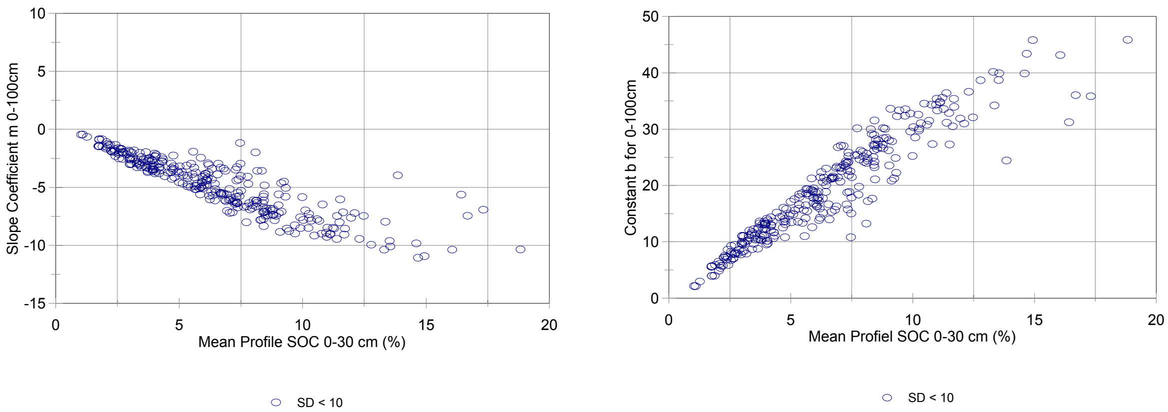
$$m_{SUB}^{\min} = -0.546 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.42, 43 dF)}$$

$$b_{SUB}^{\min} = 2.307 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.43, 43 dF)}$$

$$\Rightarrow SOC(d)_{SUB}^{\min} = -0.546 \times SOC_{TOP}^{\min} \times \ln(d) + 2.307 \times SOC_{TOP}^{\min}$$

The regression parameters for the more restrictive variations in SOC content are mainly comparable to those of relating the subsoil SOC content to the slope and constant for SOC content vs. depth of the subsoil (see Figure 26). They are, however, quite different from the relationship found when widening the limit on the SD for the variations in the SOC content and from the relationship found for SPADE/M data. The relationship of the latter is more comparable to the Level II profiles when not limiting the profiles by the SD of the SOC content.

A comparison of the mean SOC content in the topsoil and the slope and constant of the relationship between SOC content and depth for the soil section of 0-100 cm is presented in Figure 28.



a) Topsoil SOC vs. 0-100 cm Coefficient *b) Topsoil SOC vs .0-100 cm Constant*

Figure 28: Relationship between Mean SOC Content for Topsoil and Model Slope Coefficient and Constant for Soil Section 0-100 cm (Level II)

The relationship appears to be very well defined and supported by the 303 profiles in the data. The parameters derived from a linear regression are:

$$m_{0-100}^{\min} = -0.715 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.76, 302 dF)}$$

$$b_{0-100}^{\min} = 2.898 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.88, 302 dF)}$$

$$\Rightarrow SOC(d)_{0-100}^{\min} = -0.715 \times SOC_{TOP}^{\min} \times \ln(d) + 2.898 \times SOC_{TOP}^{\min}$$

Those values differ to some extent from the corresponding relationship found in the SPADE/M data for soils in forests (coefficient slope: -0.49, constant slope: 2.27). By including the topsoil in both, the independent and the dependent variable, the values attained by the coefficient of determination overestimate the goodness of the fit. Still, this relationship could be more usefully employed than the correlation between the mean SOC content of the topsoil and the regression parameters between SOC content and depth of the subsoil.

3.2.4.4 Influence of Depth of Soil

The depth of the soil layer to an impermeable layer or rock is not extractable from the Soil Condition database to describe the profile. The sampling specifications only cover a layer to a depth of 80 cm. In case soil properties are sampled to a depth less than the layer maximum it is not evident from the data whether the soil does not reach to lower depth or a different division of layer depth has been applied. To provide an overview of layers the frequency distribution of the end of the profile data is presented in Figure 29.

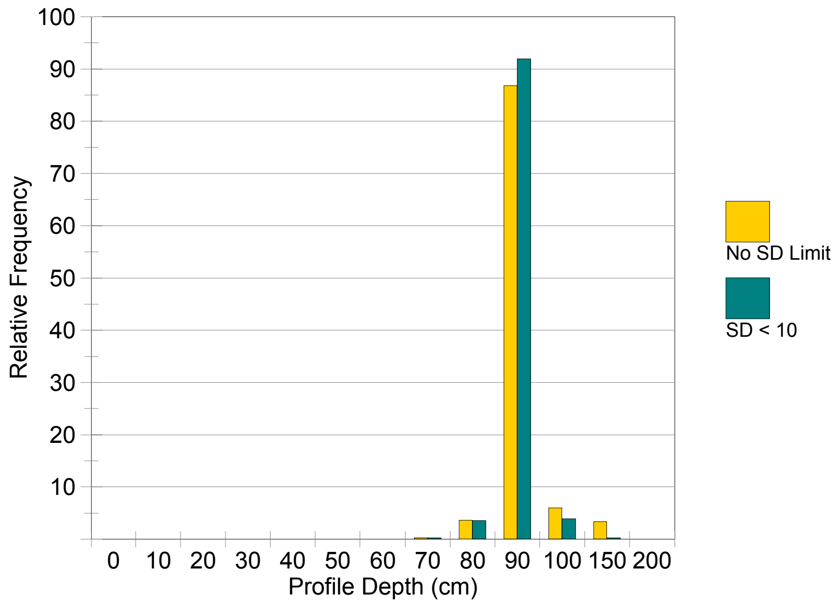


Figure 29: Relative Frequency Distribution of End of Deepest Layer

Distinguished in the options for processing the data were

1. no limit for the SD and
2. a limit of SD<10.

Despite the stipulations in the Sub-Manual on the sampling procedure approx. 85% of the profiles in the corresponding Level II dataset cover the soil to a depth of 80-90 cm.

Changes in the value of the coefficient of the function describing the progression in SOC content with profile depth are graphically presented in Figure 30.

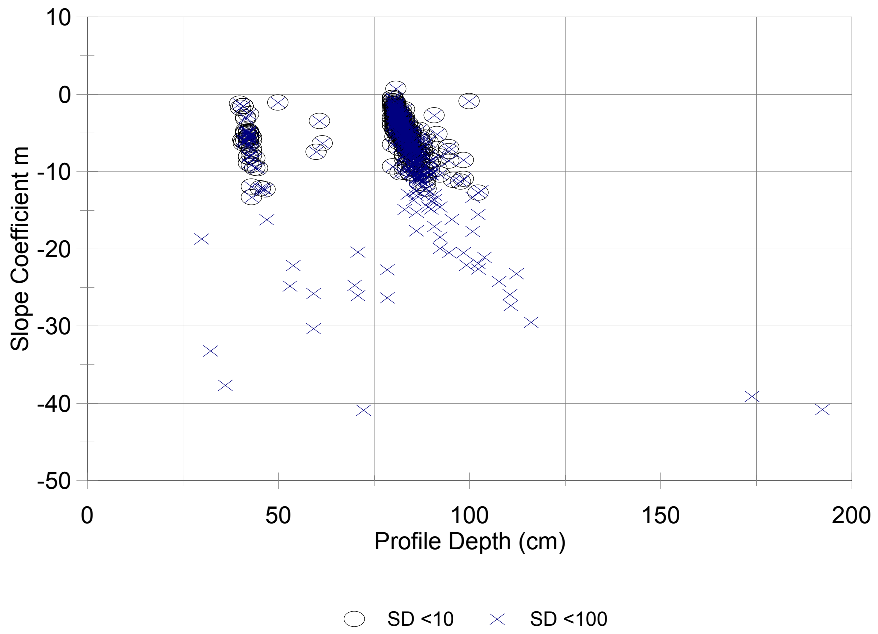
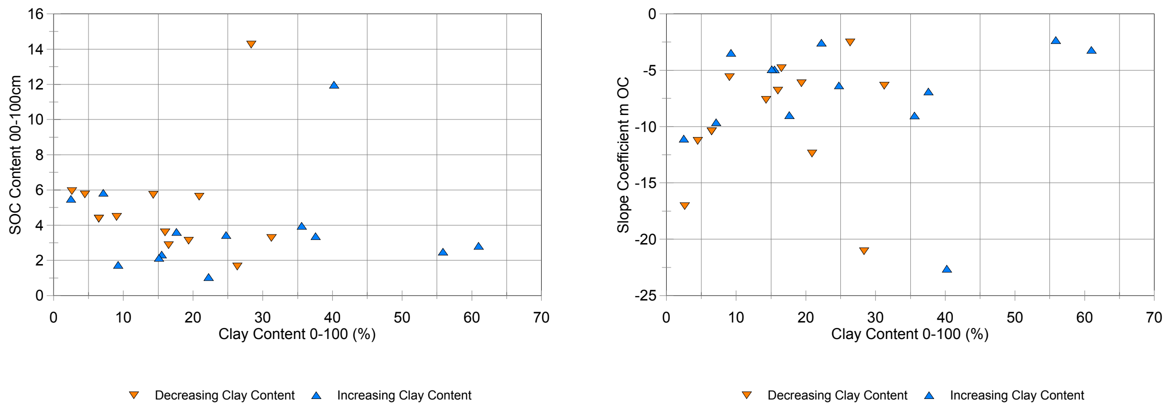


Figure 30: Change in Model Slope Coefficient with Depth of Profile Applying SD Threshold of 10 and 100 (Level II)

By limiting the reporting depth of the soil layers for the Level II plots the prescribed sampling procedure very much restricts any attempts of evaluating changes in the character of the function relating SOC content to depth. Some of the plot data indicate a tendency for a decrease in the slope coefficient with depth, but this reason based on the distribution of the plots in the graph is rather tenuous. In the interpretation of the results it should be kept in mind that the depth of the profile for the Level II plots is also determined by the height attributed to the organic layer. The higher the organic layer the higher will also be the mean SOC content for the plot. With the strong negative relationship between SOC content and the coefficient a comparable trend can be introduced into the data simply by the method of preparing the profile information. With these restrictions on the data no statement on the relationship between the depth of the soil and the development of the parameters used to mathematically describe the changes in SOC content with depth can be pronounced.

3.2.4.5 Influence of Clay Content

A value of the clay content in the subsoil section is recorded for 166 profiles. Yet, the assessment of the relationship between clay and SOC content in the subsoil layer from 30-100 cm is limited by the definition of a single layer ranging from 40 to 80 cm for sampling soil properties and the limited number of observations of the clay content recorded in the dataset. For the analysis of the change of clay content with depth 3 values within the subsoil section are needed, which restricts the number of profiles to 33. Of those just 4 are common with the analysis of changes of SOC in the subsoil. The assessment of the influence of the clay content on SOC content was therefore extended to cover the complete soil section 0-100 cm. In the definition of the parameters for the profiles a threshold of 100 for the SD was applied. This allowed at least to compare changes for those profiles. The relationship is graphically presented in Figure 31.



a) 0-100 Clay vs. 0-100 cm SOC Content *b) 0-100 Clay vs. 0-100 cm SOC Content*

Figure 31: Relationship between Clay and SOC Content and the Slope Coefficient for Soil Section 0-100 cm by Decreasing and Increasing Clay Content with Depth (Level II)

For mineral soils the profiles with sufficient data to compute the change in clay content with depth indicate a decrease in SOC content with increasing clay content. This tendency is independent of the distribution of the clay content within the profile. The slope coefficient for the relationship of SOC content and depth shows a tendency to increase with increasing clay content of the soil from 0-100 cm. Also here the trend seems to be independent from the change in clay content with depth. For organic soil no tendency can be pronounced since only 2 profiles of organic soils have sufficient data.

One should caution against an over-interpretation of the relationship based on the goodness of the fit provided by the regression analysis. The pairs compared are not from independent measurements. When evaluating the change in SOC content to a depth of 100 cm the upper 30 cm are part of this stratum. By limiting the variability of the profile data used in the analysis the continuity of change in the profile is maintained, but so is the auto-correlation of the data. Moreover, when using the relationships identified in the data the function should be applied only to those areas, which correspond to the conditions the data represent. This implies that for soils with significant changes in SOC content to a depth of 100 cm, other than going below or above a mean SOC content of 18%, are not accounted for.

3.2.4.6 SOC Content by Major Soil Category

The mean SOC contents of the Forest Focus Level II profiles for topsoil (0-30 cm) and the subsoil (30-100 cm) by FAO 90 soil category are given in Table 8.

Table 8: SOC Content by Soil Category (Forest Focus Level II)

Soil FAO90	Soil Organic Carbon Content		No. of Profiles
	Topsoil	Subsoil	
	%	%	
Arenosols	17.1	1.5	4
Calcisols	3.0	0.9	1
Cambisols	13.9	1.4	8
Fluvisols	3.9	0.6	1
Gleysols	2.4	0.6	1
Planosols	23.0	0.6	2
Podzols	19.0	2.7	6
All	**15.2**	**1.6**	**23**

The table contains data form 23 profiles, which cover 7 soil categories. For those profiles the mean subsoil SOC content is 10.5% of the topsoil SOC content. When interpreting this figure the particular limitations in sampling Forest Focus soil data need to be considered. The SOC content of the topsoil is largely liable to cover higher values than the soil categories of the profiles suggest. The lack of differentiation in the organic layer and in particular the lack of data on the height of the layer very much limit the comparability of the Forest Focus soil data with data from other soil profile surveys.

3.2.5 Systematic Monitoring Plots - Level I

The Level I soil database of Forest Focus contains information on 5,144 plots. For an analysis of soil properties in the subsoil segment the number of plots is largely reduced due to a lack of suitable data.

- For 335 plots a single layer is recorded and for 791 the properties of 2 layers are included. Those 1,126 plots could not be used in the analysis of the relationship between SOC content and layer depth because the description of changes in SOC content with depth needs at least 3 depth values.

- Level I data mainly describe the topsoil layer to a depth of 20 cm. As a consequence a further reduction in the number of suitable profiles is caused by a lack of data for mineral layers below a depth of 30 cm.

For the analysis of changes in SOC to a depth of 100 cm a description of the SOC content to the lower limit should be recorded in the database than specified by the Sub-Manual. Because the deepest mineral layer specified in the Forest Focus field guide for sampling soil profiles was 40-80 cm for a profile to be included in the analysis the minimum coverage of the soil section 0-100 cm was set to 75%. In the database only 113 plots record soil properties with adequate coverage. The spatial distribution of those Level I profiles is depicted in Figure 32.

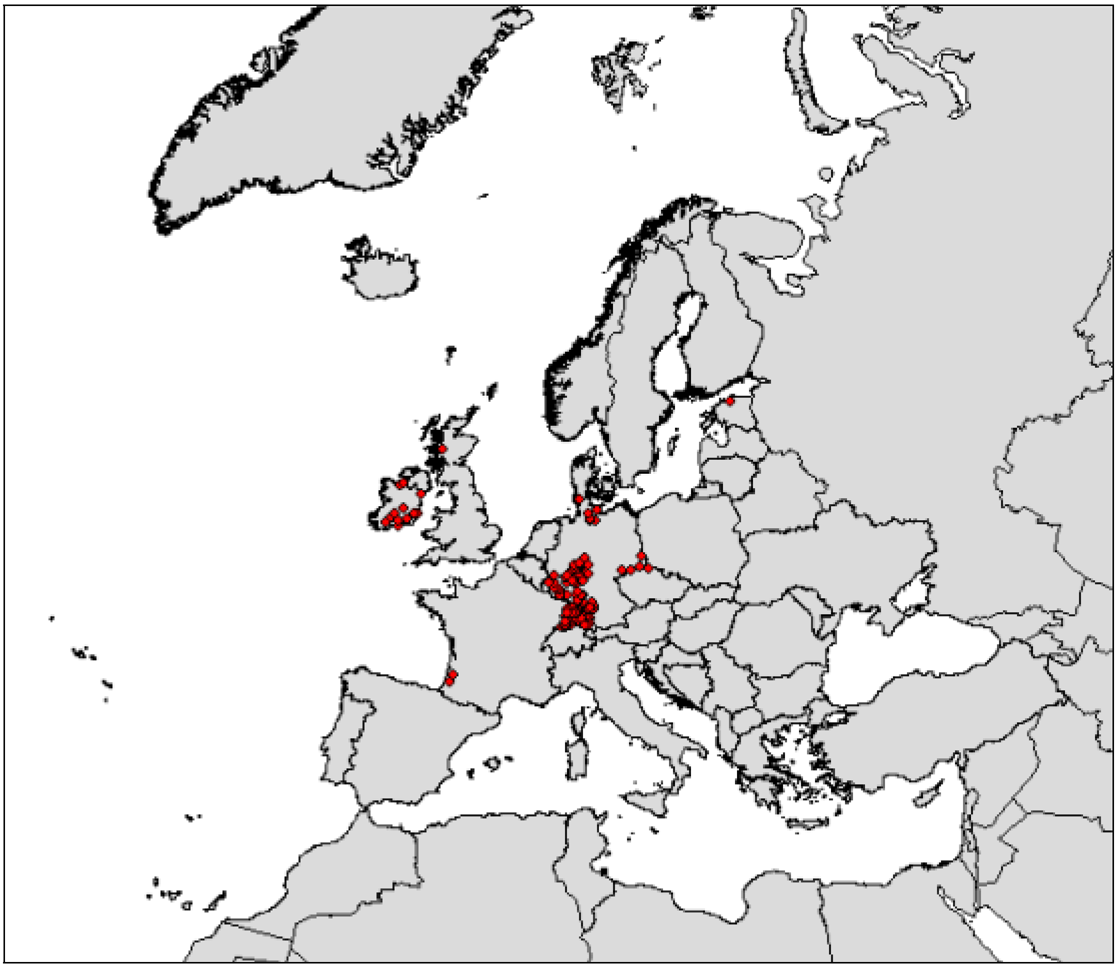


Figure 32: Distribution of Profiles of Level I Soil Profiles with Subsoil Data

Data to a depth of 100 cm are available for just 47 plots. The lack of information on soil properties for the subsoil very much limits the use of the database for the purpose of the investigation. Irregularities in the description of the depth layers were noted in 240 cases. They were almost exclusively caused by missing layers in the profile. Other inconsistencies were the duplicate coverage of depth layers (22 cases). While the nominal year of the survey is 1995 the dates given for the analysis of the data range from 1985 (97 cases) to 1998 (1 case).

3.2.5.1 SOC Content in Layers

The distribution of SOC content with layer depth in the dataset is given in Figure 33.

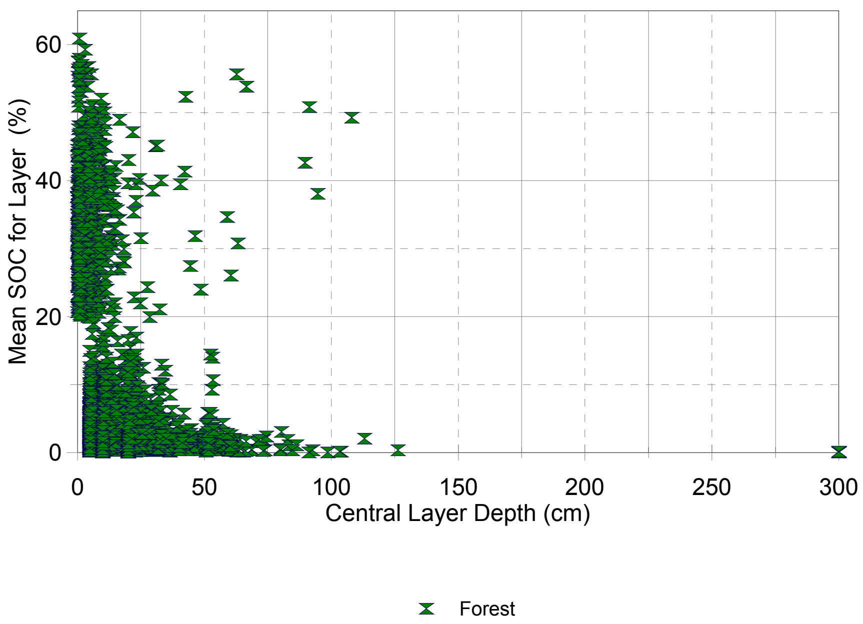
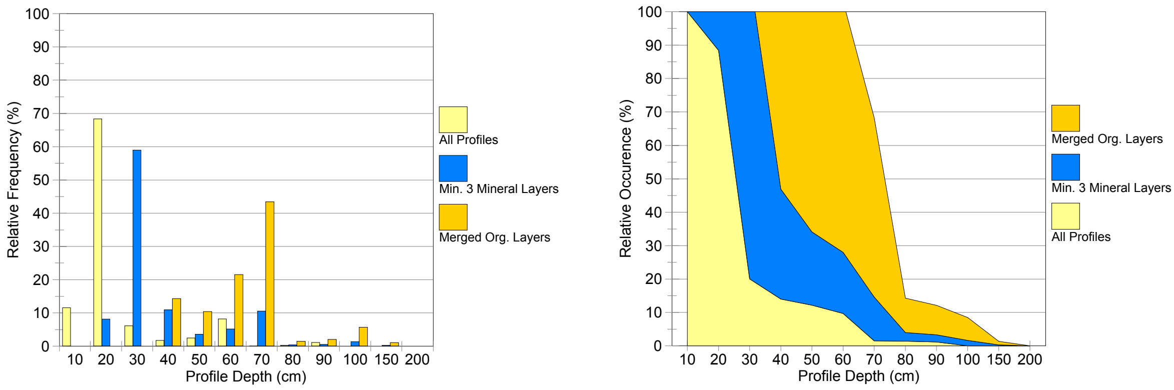


Figure 33: Horizon Depth vs. Soil Organic Carbon for Forest Focus Level I Layers

The distribution of the 13,723 layers used in the graph shows the general decrease in SOC content with increasing depth for mean SOC content values below approximately 20%. For layers sampled with a SOC content above 20% a second peak of an increasing layer depth centres around 40% of SOC content.

The soil data sampled on Forest Focus Level I plots mainly covers the topmost 20 cm. Data from lower depths are only included for a small number of plots (see Figure 32). The relative frequency of the lowest depth for which data are reported in the dataset is given in Figure 34.



a) Relative Frequency by Depth *b) Accumulated Relative Frequency*

Figure 34: Frequency Distribution of Profile Depth and Relative Depth Cover

For the presentation of the frequency of the depth, to which data for a soil profile is reported, three different treatments of the data were distinguished:

- **All profiles**
  Data were grouped into the frequency bins as they were recorded in the dataset. Because, with few exceptions, the layer depth is recorded only for mineral layers this treatment can be interpreted as indicating the depth to which data for the mineral layer are reported within a profile.

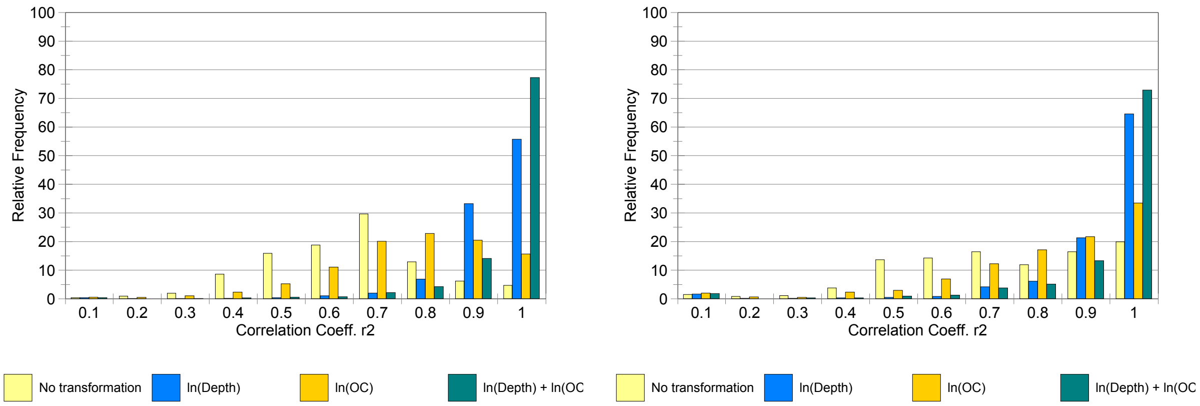
- **Min. 3 mineral layers**
  This treatment shows the distribution of the depth to which data for the mineral layers are reported for the profiles with data for at least 3 mineral layers. The availability of data for at least 3 layers is a requirement of the regression analysis of SOC continent changes with depth.

- **Merged org. layer**
  Shown is the frequency of the occurrence of the lowest layer within a profile when including an estimate of the height of the organic layer in the profile and merging any organic layers until a height of 10 cm was attained. As a further processing condition the SD of the layer SOC contents of a profile was limited to 10.

Overall, the number of profiles which can be used to evaluate the change in SOC content with depth trends is only a portion of the number of profiles in the dataset. The graph clearly shows that for 80% of the profiles in the dataset the information on the mineral layer is limited to a depth of 20 cm. When restricting the profiles to those with at least three mineral layers 80% of the observations are reported to a depth of less than 40 cm. By including in the profile an estimated height of the organic layer approx. 45% of the profiles then cover the soil to a depth of 80 cm. The treatment of the layer data also affects the number of profiles compliant with the criteria set for the analysis. While 4,770 profiles contain SOC content data for one or more mineral layers 3,123 contain data on 3 or more mineral layers. The third option of treating the profile further reduces the number of data plots to 748 profiles.

3.2.5.2 SOC Content and Depth Transformation

The influence of the logarithmic transformation of depth and / or SOC content on the slope and constant parameters of the linear regression between SOC content and depth for FF Level I profiles is presented in Figure 35.



a) Mineral Layers, SD<100 *b) Merged Organic Layer, SD<10*

Figure 35: Frequency Distribution of Regression Coefficient for Logarithmic Transformation of SOC Content and Central Layer Depth for all Layers and for Merged Organic Layers (Forest Focus Level I)

Based on the distribution of the coefficient of determination (r^2) the best fit for individual profiles is achieved when transforming both axes, i.e. depth and SOC content, followed by a transformation of only SOC content. The tendency is less prevalent when limiting the analysis to profiles with a SD <10 for the layer SOC content. For the occurrence of values of >0.8 for the r^2 the performance of the single axis transformation is practically equal to the transformation of both axes.

3.2.5.3 Influence of Mean SOC Content in Profile

The treatment options of the organic layer not only shift the mineral layers in the soil profile but also affect the parameters of the relationship between SOC content and depth, in particular when including the SOC content of the organic layer in the computations. The distribution of the relative frequency of the regression coefficients and constants for the mineral fraction of profiles with at least 3 mineral layers and when estimating a height for the organic layer and merging layers to a minimum height of 10 cm is presented in Figure 36.

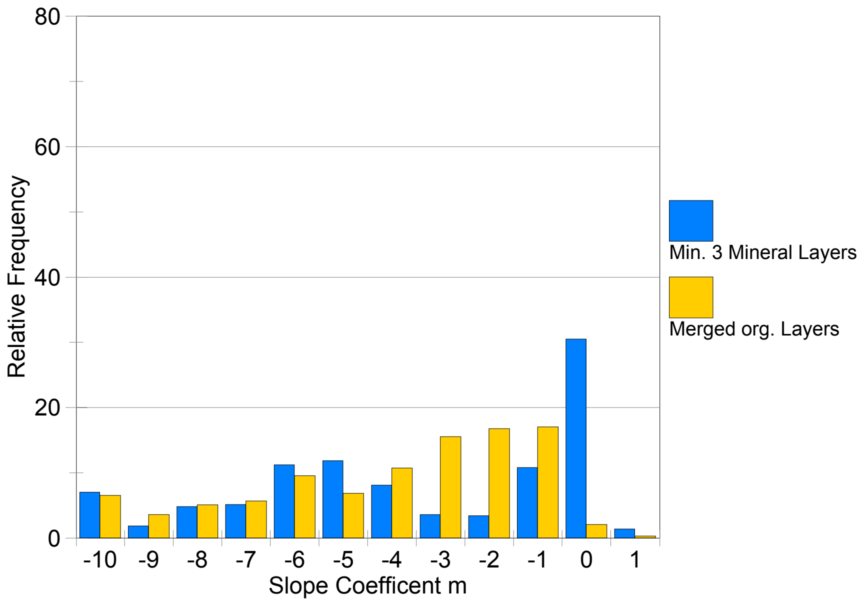
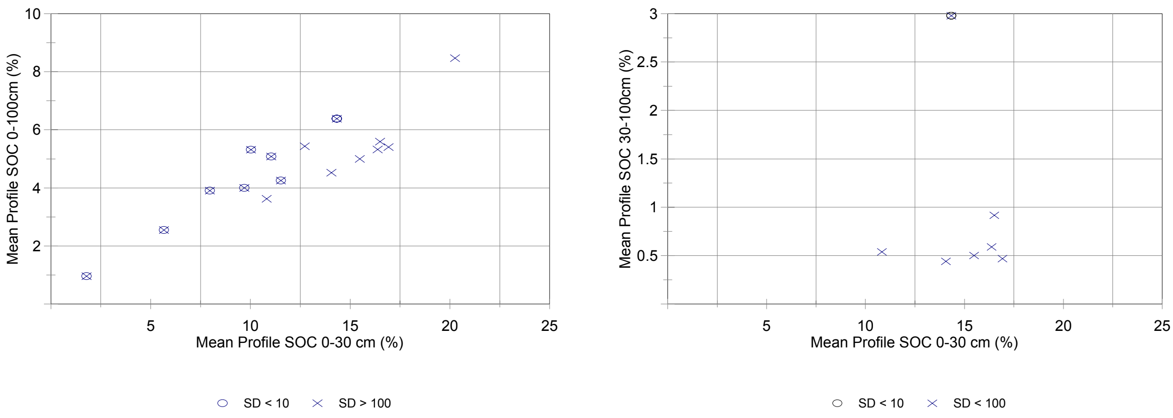


Figure 36: Frequency Distribution of Relative Occurrence of Regression Slope Coefficient m (Forest Focus Level I)

The graph illustrates the shift of slope coefficients to lower values when including the information on the organic layers in the regression analysis of SOC content and depth. For profiles with 3 or more mineral layers approx. 1/3 of the profiles have slope coefficients between -1 and 0, while the occurrence of lower values for the slope coefficients is more evenly distributed between the two treatments. The general trend is comparable to data from the Level II profiles, although there is a marked difference in the distribution of lower slope coefficient for profiles with 3 or more mineral layers. For Level II profiles there is hardly a profile with a slope coefficient below -6 whereas there is still a notable number of profiles with coefficients as low as -10 for Level I profiles. Since there is less variability between profiles in the SOC content at lower levels than closer to the surface. One reason for the difference could be the rather incomplete description of soil profiles for Level I plots, where frequently information on SOC content in the lower parts is absent.

The relationship between the mean SCO content in the topsoil and the soil segment to a depth of 100 cm is presented in Figure 37 (for merged organic horizons).



a) Topsoil vs. 0-100 cm SOC Content *b) Topsoil vs. Subsoil SOC Content*

Figure 37: Relationship between Mean SOC Content in Topsoil and Soil Segment 0-100 cm and Subsoil (Level I)

The values of the mean SOC content for the profile segments were computed by including merged organic layers to a minimum height of 10 cm. The number of suitable profiles was just 8 when restricting the SD < 10. The number rose to 16 when removing the restriction (SD < 100). When comparing mean SOC contents between the topsoil and the subsoil the number of suitable profiles was just 1 for a SD threshold of 10 and 7 when using a threshold of 100. The remaining profiles were all in a narrow range of SOC contents in the topsoil (11-17%). This small number of profiles and the narrow range of mean SOC contents covered precludes obtaining any reasonable results from a regression analysis of the mean SOC content between topsoil and subsoil.

A linear regression between the mean SOC contents of the topsoil and the soil segment 0-100 cm gave the following parameters:

$$SOC_{0\_100}^{\min} = 0.380 \times SOC_{TOP}^{\min} \quad (r^2\text{: 0.76, 15 dF})$$

For the 8 profiles of positively mineral soils (<12%) the slope coefficient was found to be 0.426. Both values are noticeably below the slope coefficient found for Level II profiles (0.509). While the slope coefficients of the regressions between the mean SOC contents of the topsoil with the soil segment 0-100 cm do probably not differ for mineral soils and all soils (95% confidence level) the observed difference between Level I and Level II profile data is significant (95% confidence level). To some degree the lower slope coefficient in the Level I data is caused by including profiles with a SD >= 10 in the analysis, which show a tendency for a lower slope coefficient, although not significantly so. Another hypothesis is that the soil types of the profiles included in the analysis influences the relationship. Approx. 50% of the Level I profiles are classified as *Cambisoil*, mainly *humic* or *gleyic*. In the Level II data those soils show a slightly lower-than-average slope coefficient. However, there is insufficient evidence to substantiate any of the hypotheses.

In the absence of sufficient data to define the relationship between the mean SOC content in the topsoil and the subsoil the slope coefficient can be estimated from the relationship between the topsoil and the profile segment 0-100 cm by:

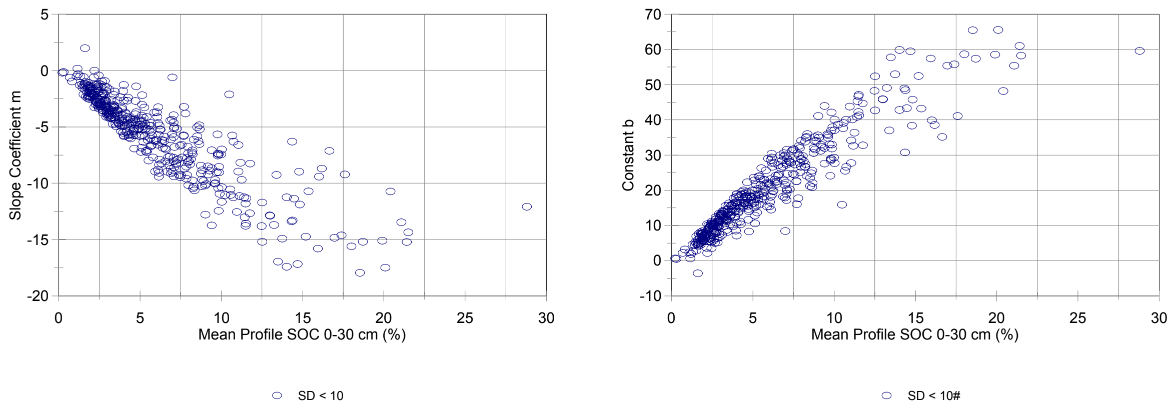
$$m_{TOPxSUB} = \frac{m_{TOPx0\_100} - 0.3}{0.7}$$

where

m_{TOPx0_100}: regression slope coefficient of topsoil vs. 0-100 cm segment
$m_{TOPxSUB}$: regression slope coefficient of topsoil vs. subsoil

For the 16 Level I profiles this would amount to a subsoil SOC content of approx. 16% of the topsoil SOC content. This contrasts with a value of 24% of the subsoil SOC content as compared to the topsoil SOC content for Level II profiles.

The relationship between the mean SOC content in the topsoil and the slope coefficient obtained from the regression between the SOC content and depth is presented in Figure 38.



a) Topsoil SOC Content vs. Coefficient *b) Topsoil SOC Content vs. Constant*

Figure 38: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Topsoil applying SD Threshold of 10 (Level I)

For the linear regression used the development of the coefficient and the constant show a decrease in the relationship for profiles up to a mean topsoil SOC content of approx. 15% or more. This tendency is comparable to the situation found for profiles of the Level II and SPADE/M datasets.

For profiles with a SOC content of <18% the parameters of a linear relationship are:

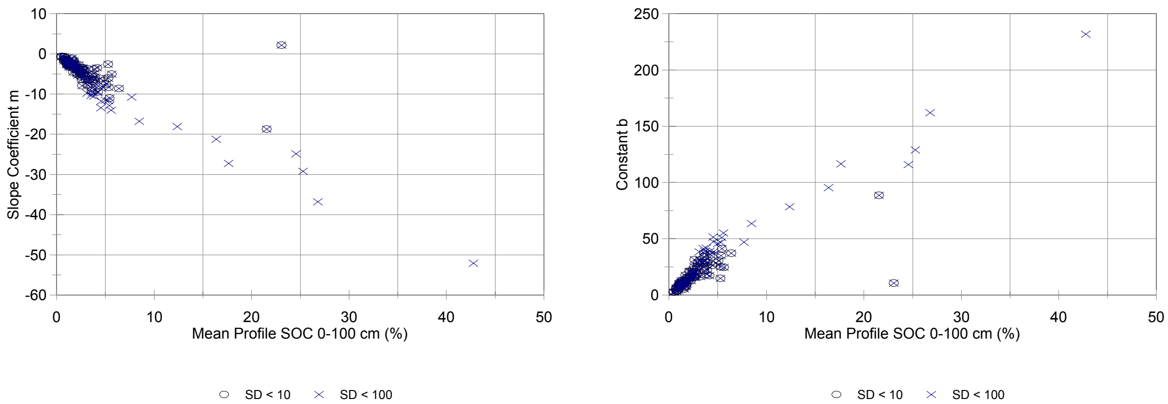
$$m^{\min} = -0.931 \times SOC_{TOP} \text{ (r}^2\text{: 0.76, 428 dF)}$$

$$b^{\min} = 3.408 \times SOC_{TOP} \text{ (r}^2\text{: 0.87, 428 dF)}$$

$$\Rightarrow SOC(d)_{TOP}^{\min} = -0.931 \times SOC_{TOP}^{\min} \times \ln(d) + 3.408 \times SOC_{TOP}^{\min}$$

The values for the coefficient and constant are comparable to those found for Level II data and any differences are not significant at a 95% confidence level.

The change in the parameters of the linear relationship of SOC content and depth for the profile segment 0-100 cm is graphically presented in Figure 39.



a) 0-100 cm SOC Content vs. Coefficient *b) 0-100 cm SOC Content vs. Constant*

Figure 39: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Soil Section 0-100 cm applying SD Threshold of 10 and 100 (Level I)

Restricting the analysis to profiles with a SD of the layer SOC content <10 limits the analysis to profiles with a mean SOC content of less than 6%. By increasing the threshold to 100, basically removing the criterion, profiles with a mean SOC content up to 43% could be included. For one profile of a *terric Histosol* the SOC content increased with depth. This situation was not found atypical for a *Histosol*, and was also observed in SPADE/M profiles, although more generally for profiles with higher SOC contents.

For soils with a mean SOC content of <18% the following relationship was established:

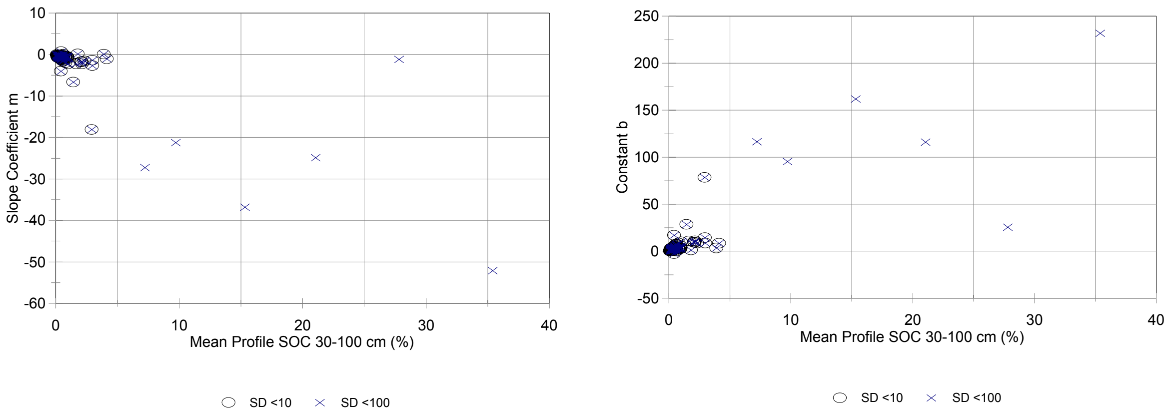
$$m^{\min} = -1.654 \times SOC_{TOP} \text{ (r}^2\text{: 0.80, 106 dF)}$$

$$b^{\min} = 7.044 \times SOC_{TOP} \text{ (r}^2\text{: 0.85, 106 dF)}$$

$$\Rightarrow SOC(d)_{0-100}^{\min} = -1.654 \times SOC_{TOP}^{\min} \times \ln(d) + 7.044 \times SOC_{TOP}^{\min}$$

The slope coefficient is lower for Level I profiles than for those of the Level II dataset, but still comparable. Both differ significantly from the coefficient found for the SPADE/M profiles, where a value of -0.676 was determined for soils under forest.

The relation ship between the mean SOC content in the subsoil and the parameters of the linear function used to describe the change in SOC with depth using a threshold for the SD of 10 and 100 are presented in Figure 40.



a) Subsoil SOC Content vs. Coefficient *b) Subsoil SOC Content vs. Constant*

Figure 40: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Subsoil applying SD Threshold of 10 and 100 (Level I)

When restricting the SD to 10 only profiles with a mean SOC content in the subsoil of <5% are included in the analysis. For those profiles the slope and constant hardly change with the mean SOC content of the subsoil. The parameters are:

$$m^{\min} = -1.161 \times SOC_{SUB} \text{ (r}^2\text{: 0.16, 88 dF)}$$

$$b^{\min} = 5.874 \times SOC_{SUB} \text{ (r}^2\text{: 0.23, 88 dF)}$$

$$\Rightarrow SOC(d)_{SUB}^{\min} = -1.161 \times SOC_{SUB}^{\min} \times \ln(d) + 5.874 \times SOC_{SUB}^{\min}$$

The regression coefficient of the 89 profiles is largely determined by just 2 profiles with a marked decrease in the slope of the SOC content : depth relationship while the remaining 87 profiles did not show a discernable trend.

For an analysis without effective limit on the variation of SOC content (SD < 100) 6 additional profiles were included with a mean SOC content ranging from 7% to 35%. Those additional profiles do not exhibit any relationship between the slope and constant of the SOC content vs. depth data and the mean SOC content of the subsoil.

For completeness the regression parameters were also computed for profiles with a SD threshold of < 100 which were as follows:

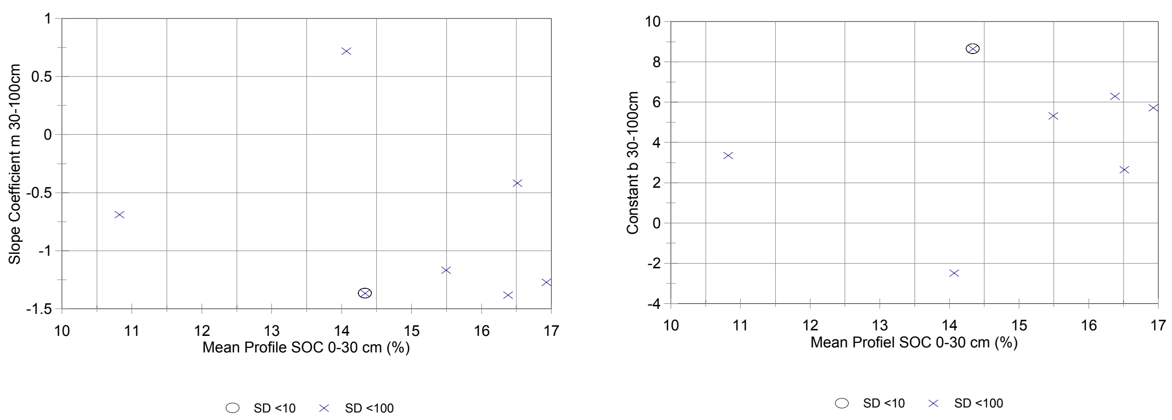
$$m^{\min} = -1.178 \times SOC_{SUB} \text{ (r}^2\text{: 0.61, 94 dF)}$$

$$b^{\min} = 5.495 \times SOC_{SUB} \text{ (r}^2\text{: 0.67, 94 dF)}$$

$$\Rightarrow SOC(d)_{SUB}^{\min} = -1.178 \times SOC_{SUB}^{\min} \times \ln(d) + 5.495 \times SOC_{SUB}^{\min}$$

The parameters are comparable to those of the profiles with a limit in the SD of <10. As has been demonstrated before a marked difference in the changes of SOC content may exist between mineral and organic soils, which suggests processing them separately when extrapolating SOC content from the topsoil to the subsoil. Hence, the parameters for the integrated profile data given above should be treated with caution.

When relating the mean SOC content of the topsoil to the slope and constant from the relationship of the profile SOC content vs. depth only 1 suitable profile could be found. Removing the limit on the variation of the SOC content within a profile resulted in 7 profiles. The resulting situation is presented in Figure 41.

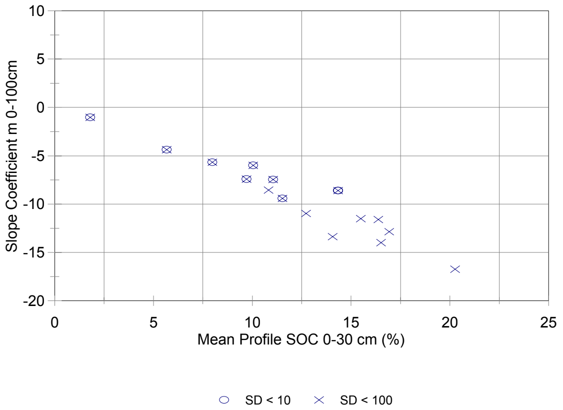


a) Topsoil SOC Content vs. Subsoil Coefficient *b) Topsoil SOC Content vs. Subsoil Constant*

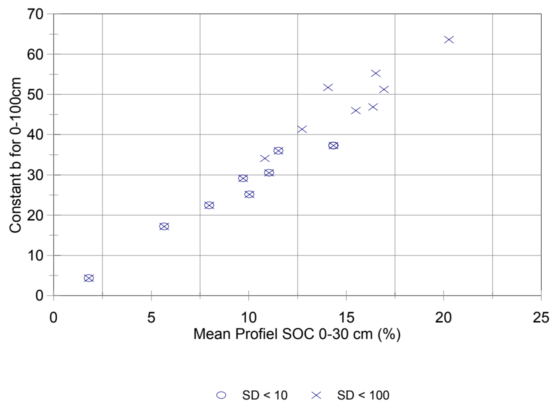
Figure 41: Relationship between Mean SOC Content for Topsoil and Model Slope Coefficient and Constant for Soil Section 0-100 cm applying SD Threshold of 10 and 100 (Level I)

The number of profiles with sufficient data to analyse changes in SCO content with depth and the limited distribution of the SOC contents precludes computing meaningful regression parameters for profiles.

Relating the mean SOC content of the topsoil to the coefficient and constant from the relationship of the profile SOC content vs. the soil segment 0-100 cm resulted in 8 profiles for a SD threshold of < 10 and 16 for a threshold of < 100. The relationship is graphically presented in Figure 42.



a) Topsoil SOC Content vs. 0-100 cm Coefficient



b) Topsoil SOC Content vs. 0-100 cm Constant

Figure 42: Relationship between Mean SOC Content for Topsoil and Model Slope Coefficient and Constant for Subsoil applying SD Threshold of 10 and 100 (Level I)

There would not appear to be a significant difference in the relationship found between profiles with a variation in SOC content limited to SD<10 and those without such a limit. Also, the one profile with an organic topsoil did not reveal a relationship any different from the one found for mineral topsoil profiles.

The regression parameters for the linear relationship for profiles with a SD threshold of < 100 are:

$$m_{0-100}^{\min} = -0.762 \times SOC_{TOP} \quad (\mathrm{r}^2\text{: } 0.88,\ 14\ \mathrm{dF})$$

$$b^{\min} = 3.043 \times SOC_{TOP} \quad (\mathrm{r}^2\text{: } 0.93,\ 14\ \mathrm{dF})$$

$$\Rightarrow SOC(d)_{0-100}^{\min} = -0.762 \times SOC_{TOP}^{\min} \times \ln(d) + 3.043 \times SOC_{TOP}^{\min}$$

The relationship would seem highly significant for the profiles used in the analysis. In the interpretation of the results one should consider that the data are auto-correlated and that only 1 profile with a mean SOC content of 5% is included. The assessment of the relationship of topsoil and subsoil indicates mean SOC content and the slope coefficient of profile SOC content vs. depth were found to be largely unrelated in the data analysed.

As a consequence, the values provided by the regression analysis for the coefficient of correlation underestimate the proportion of variability in when applied more generally across the whole range of SOC contents of mineral soils.

3.2.5.4 Influence of Depth of Soil

The guide to sampling soil condition data at Level I plots and Level II plots only detail the layers at which the conditions should be assessed. Not specified are noting the depth of the organic layer, describing the whole soil profile or indicate the depth to rock, the presence of an impermeable layer or obstacles to the development of roots. With respect to evaluating the effect of the depth of the soil layer on the development of SOC content with depth the information provided by the data is very much restricted.

The relative frequency of the lowest depth to which profile data are recorded in the Level I dataset is graphically presented in Figure 43.

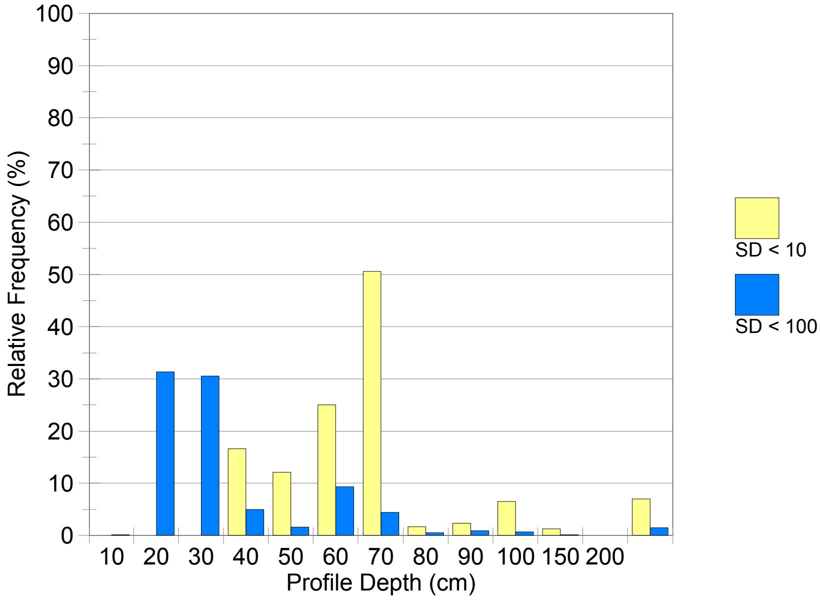
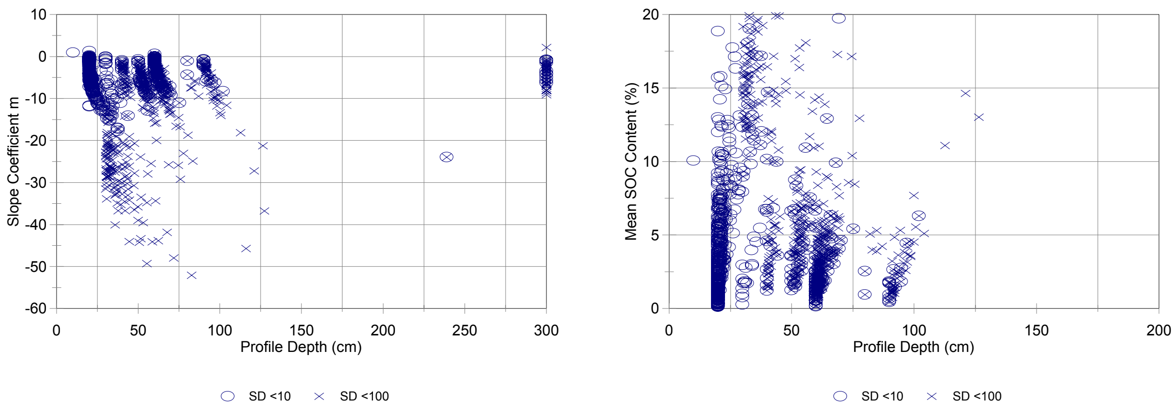


Figure 43: Relative Frequency Distribution of End of Deepest Layer in Profile (Level I)

The distribution shows that most Level I profiles report soil conditions to a depth of 30 cm (SD < 100), provided the height of the organic layer is included. When restricting the profiles to those with a SD < 10 for the variation in the layer SOC content of a profile approx. 50% of the profiles with sufficient data for a regression analysis contain data to a depth of 70 cm, at the cost of the number of total number of profiles available for analysis. The distribution of profile data depth differs from the situation depicted in

Figure 34 in particular for profiles without restriction on the variation in the layer SOC content because for the regression analysis a minimum of 3 layers are specified. By merging thin layers to a single layer with a thickness of at least 10 cm the number of layers in a profile available for analysis is reduced, which results in the change in the distribution of profile depths.

Subsequent to the specifications for sampling soil profile data the relationship between parameters of the SOC content vs. depth regression and the depth of the soil cannot be described in detail. From the data it is not evident whether the deepest layer recorded can be taken as an indicator for the soil depth. Rather, in most cases it can be assumed that the lowest extent of the deepest layer reported for a profile does not represent the depth of the soil. Nonetheless, the relationship between the lowest extent of the last layer of a profile was plotted against the slope coefficient of the relationship between the profile layer SOC content and depth. The result is presented in Figure 44.



a) Profile Depth vs. Coefficient *b) Profile Depth vs. Constant*

Figure 44: Change in Model Slope Coefficient with Depth of Profile applying SD Threshold of 10 and 100 (Level I)

The relationship between the depth of the profile and the slope coefficient of the function describing the changes in SOC content with depth indicate a decrease in the coefficient with increasing profile depth. The trend is very much influenced by the treatment of including the organic layer in the profile. The difference in SOC content between the organic and the mineral layer lowers the slope coefficient for the relationship between SOC content and depth. This tendency is pronounced with an increased thickness of the organic layer, which in turn also leads to a lower limit of the profile. From the data a particular relationship between soil depth and the progression of SCO content with depth cannot be pronounced.

3.2.5.5 Influence of Clay Content

In contrast to Level II the Level I data set does not contain information on measured clay content. As stated by the sampling specifications soil texture for Level I plots is recorded according to the USDA-FAO classification scheme for soil texture (coarse, medium, medium fine, fine and very fine). Yet, the information recorded in the data set uses 5 classes for soil texture. The FAO classification scheme distinguishes 12 classes for texture, which are not found in the dataset. No values could be found in the data set for the estimates of clay content (in %) stipulated in the sampling specifications. It should be noted that the only specifications available were those starting with 2002. The specifications on which the sampling of the Level I data set are based could not be retrieved and may be presumed to differ in those respects from latter versions. As a consequence, the influence of clay content on the distribution of SOC in the soil profile could not be evaluated for Level I profiles.

3.2.5.6 SOC Content by Major Soil Category

A summary of topsoil and subsoil mean SOC contents for Forest Focus Level I profiles aggregated by FAO90 level 1 soil classes is given in Table 9.

Table 9: SOC Content by Soil Category (Forest Focus Level I)

FAO90 Soil	Forest		
	Topsoil	Subsoil	No. of Profiles
Anthrosols	16.9	0.5	1
Cambisols	14.6	0.7	3
Gleysols	15.5	0.5	1
Podzols	1432	1.7	2
All	**14.9**	**0.9**	**7**

The results are shown for reasons of completeness of the analysis with the findings from the other datasets used in the study. There are only 7 profiles for which a meaningful SOC content for both soil layers could be determined in the dataset. The profiles are assigned to 4 soil classes according to the FAO980 classification scheme. For these profiles the SOC content of the subsoil averages on 6.2% of the SOC content of the topsoil. As with Forest Focus Level II data the considerable difference is largely attributable to the practice specified for sampling and reporting the organic layer and influenced by the method applied to establish a profile for the plot data.

3.3 ISRIC-WISE

The World Inventory of Soil Emission Potentials (WISE) soil database version 1.1 of the International Soil Reference and Information Centre (ISRIC) contains 4,382 profiles with global coverage (Batjes, 2002). In the area of interest 551 soil profiles of the database are situated. Their spatial distribution is illustrated in Figure 45.

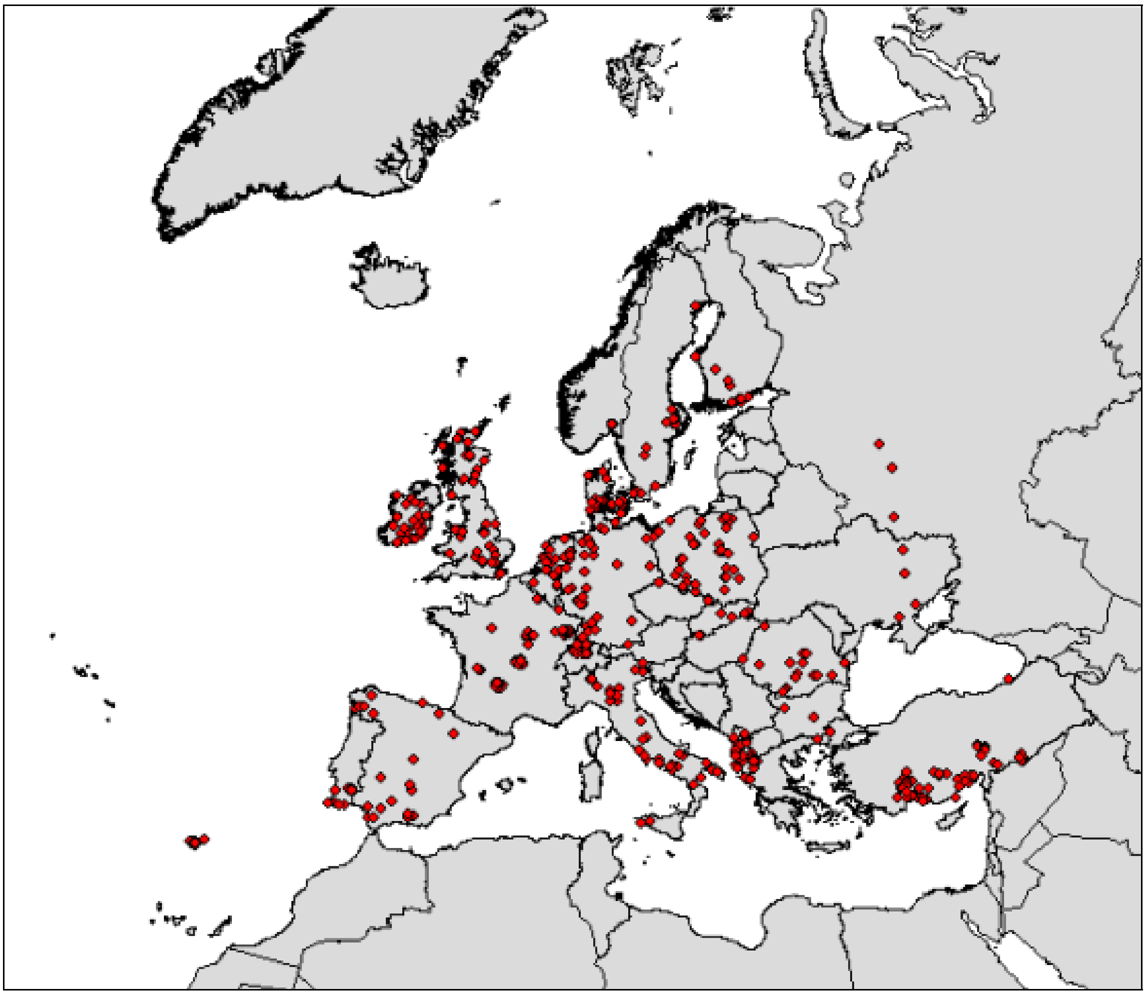


Figure 45: Distribution of Profiles Used from ISRIC-WISE Database

For 539 profiles data for SOC content are recorded in the database. One profile (ES015) contained a value of 96.11% for the SOC content in horizons 2. This value is obviously erroneous and the profile was removed from the data set used for analysis. The dates of sampling of the profiles indicate a sampling period from 1957 to 1995. For 88 profiles the information on the date is insufficient for identifying the sampling date. The soil classification used in the evaluation stated as FAO90 and not directly comparable to the SPADE/M information, where soils are classified according to the FAO85 scheme.

The profiles of the ISRIC-WISE data set belong to 83 different soil classes. Of those, 23 classes are assigned to one profile while for 36 soil types the frequency of occurring less than 3. For 20 soil classes the frequency of occurrence is 10 or more profiles. The most common soil classes are *Dystric Cambisol* (34 profiles, 6.2%), *Eutric Cambisol* (31 profiles, 5.6%) and *Haplic Luvisol* (31 profiles, 5.6%).

The land use information is coded according to a classification using 3 levels of detail. The table field contains codes for 42 classes with a mixture of levels of the coding scheme. The land use information was reclassified to the 4 classes used in the evaluation. In most cases the re-coding was straightforward. Only the assignment of the FAO/ISRIC classes to the evaluation class “shrub” was ineffective. The class could be unambiguously assigned to just 2 codes (AT3: Non-irrigated shrub cultivation; AT4: Irrigated shrub cultivation). In 13 cases where a correspondence could not be established the profile land use was set to the class “Other / Not classified”.

3.3.1 SOC in Plot Horizons

The data set uses the start of the mineral soil layer as the origin for recording horizon depth. The height of any organic surface horizon overlying the mineral layer is recorded with a negative entry for horizon depth. To be compatible with other data sets used in the evaluation the topmost profile, organic or mineral, is set to represent the profile surface, i.e. a depth of 0. For profiles with organic surface layers (negative depth) the depths figures were adjusted to record the topmost profile horizon starting at 0 cm.

The distribution of the mean SOC content of 2,228 profile horizons by the central depth of the horizon is presented in Figure 3.

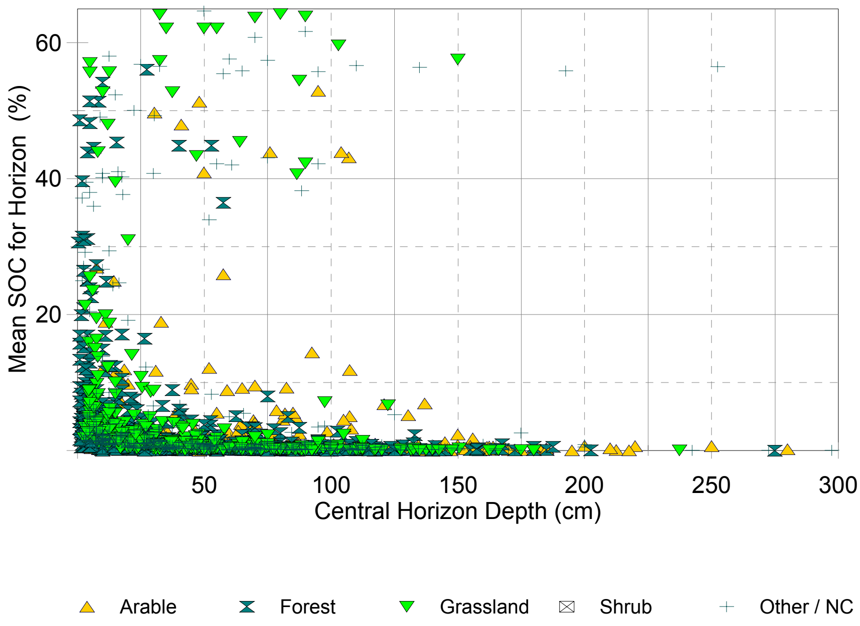


Figure 46: Horizon Depth vs. Soil Organic Carbon (ISRIC-WISE)

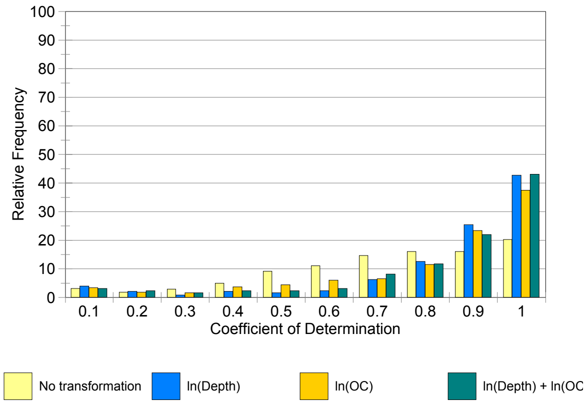
The distribution of the horizon SOC content shows the familiar distinction between mineral and organic horizons:

- For horizons with a SOC content below approx. 20% the SOC content generally decreases with depth.
- For horizons with a SOC content above approx. 20% the SOC content shows a tendency to increase with depth.

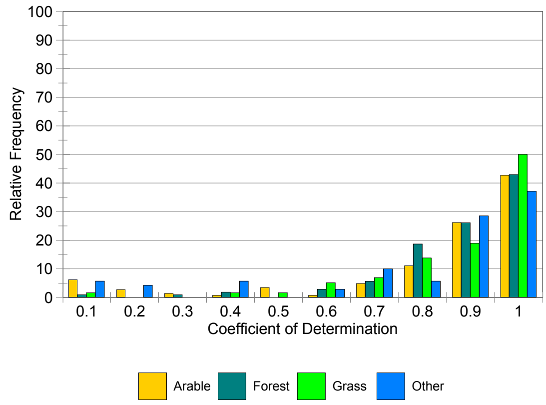
The graph also indicates that for deeper organic soils grassland and arable land uses are prevalent while the profiles under forest are on shallower soils.

3.3.2 SOC Content and Depth Transformation

The relationship between SOC content and depth for each profile was analysed for the 4 options of transforming the variables. For the soil section 0-100 cm, a minimum coverage of 75% of the section and a limit on the SD<10 of the SOC content the distribution of the coefficient of determination (r^2) was established for each profile. The result together with the relative distribution of the transformed depth parameter is presented in Figure 47.



a) Transformation Options

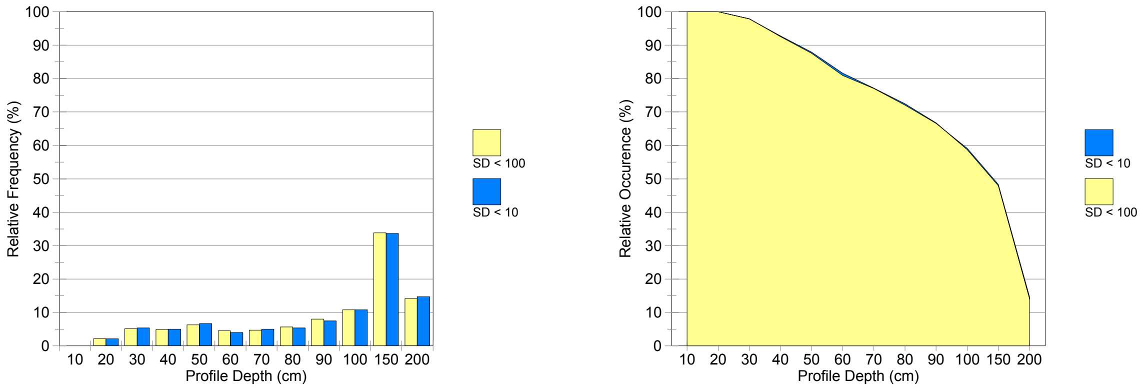


b) Land Use Classes for Transformed Depth

Figure 47: Frequency Distribution of Combinations of Logarithmic SOC and Central Horizon Depth Transformation and Transformation of Depth by Land Use (ISRIC-WISE)

For 40% of the profiles a value >0.9 is obtained for the coefficient of determination when logarithmically transforming the depth variable or both variables. The logarithmic transformation of just the SOC content variable puts 39% of the profiles in this range. For the depth transformation 50% of the soil profiles under grass show a r^2 value of >0.9. The lowest score was found for profiles assigned to "other" land uses with 37% are in this range when describing the change in SOC content with depth.

The frequency distribution of the lowest horizon reported for a profile as well as the accumulated distribution are presented in Figure 48.



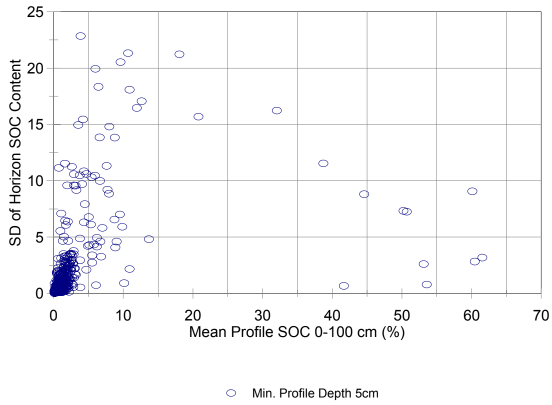
a) Lowest Horizon by SD of SOC Content *b) Accumulated Relative Frequency*

Figure 48: Relative Occurrence of Profile Depth (ISRIC-WISE)

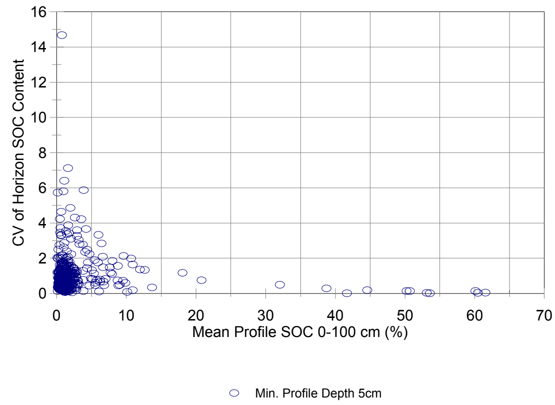
The graph shows a clear peak in the distribution for profile depths ranging between from 100 – 150 cm. Approx. one third of all profiles report horizon data to that depth. The accumulated distribution indicates that nearly 50% of all profiles reach to a depth of 150 cm. The graph distinguishes between profiles with a limit of the SD < 10 and all profiles. The relative frequency distribution did not show any significant difference in the occurrence of profile depth between the profiles with a limited variability in SOC content and those without restriction.

The variability in the SOC content between the horizons forming a profile for the soil section 0-100 cm can be expressed by the SD or the Coefficient of Variation (CV), the latter for a normalization by the mean SOC content. The relationships plotted against the mean profile SOC content are presented in Figure 49.

The distribution of the SD shows a sharp increase with the profile SOC content for soils with a mean SOC content of approx. 15-20%. For organic soils the SD generally decreases with SOC content. This development for organic soils is influenced by the presence of an upper limit to SOC content. The relative variation in SOC content is highest for profiles with a low SOC content. It decreases to <1 for profiles with a mean SOC content of 12%. In the distribution of the variation the ISRIC-WISE data set is very comparable to the results obtained for the SPADE/M profiles.



a) 0-100 cm SOC Content vs. SD



b) 0-100 cm SOC Content vs. CV

Figure 49: Relationship between Standard Deviation (SD) and Coefficient of Variation (CV) and Profile SOC Content with Varying Cover of Profile Depth (ISRIC-WISE)

3.3.3 Influence of Land Cover

The relationship between land cover type and variability of the profile was investigated by varying the data cover of the soil segment 0-100 cm from including the topsoil section to 75% of the total profile section. For the topsoil no limit on the variability of the SOC content was set, which is consistent with objective of providing an estimate for the subsoil SOC content from topsoil information. The limit on the variability of SOC content for the whole segment 0-100 cm reduces the presence of profiles with mixed mineral and organic horizons in the sample. Mixed profiles have discontinuous developments of SOC content with depth and could be identified by the assigned soil type. The results of the analysis on changes in the number of profiles when using 30% and 75% coverage of the 0-100 cm segment with data on horizons in a profile and SOC content variability are given in Table 10.

Table 10: Distribution of Soil Profiles by Land Cover Class under Two Treatments for Soil Segment 0-100 cm

Land Cover	**Treatment Conditions**		**Change**
	Cover: >30% SD: no limit	**Cover: >75% SD: <10**	**%**
Arable	160 (35.7%)	141 (39.5%)	-11.9
Forest	131 (29.2%)	96 (26.9%)	-26.7
Grassland	74 (16.5%)	55 (15.4%)	-25.7
Shrub	0 (0.0%)	0 (0.0%)	-
Other / NC	83 (18.5)	65 (18.2)	-21.7
TOTAL	**448**	**357**	**-20.3**

Of the 551 profiles used 448 completely cover the topsoil. Approx. 1/3 of the profiles are located on arable land, 30% under forest and 1/6 on grassland. The distribution of more homogenous profiles to a depth of at least 75cm mainly affects those under forest and on grassland with a reduction of approx. 25%. Profiles on arable land would appear to be deeper and less variable in within-profile SOC content than profiles sampled on other land use types.

The distribution of the depths by land cover type for 537 profiles is presented in Figure 50.

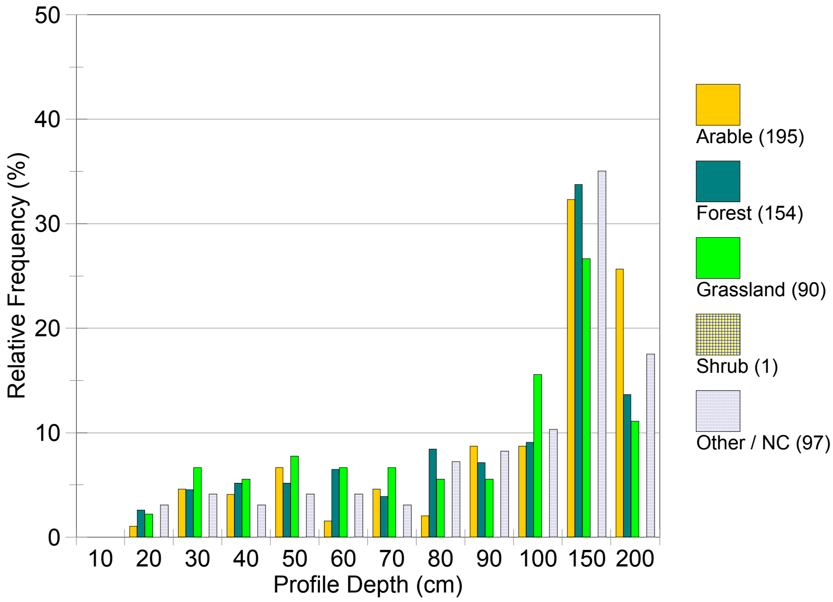


Figure 50: Frequency Distribution of Land Cover Types by Profile Depth (ISRIC-WISE)

The graph shows the previously mentioned prevalence of profiles on arable land for deeper soils. In particular, for soils with a depth > 200 cm arable land use dominates. By contrast, profiles from grassland tend to be more widespread on shallower soils and is the most widely found land use for profiles with a depth below 80 cm.

The occurrence by land use type of the regression coefficient derived from the relationship between SOC content and depth for the soil segment 0-100 cm was computed to evaluate the distribution of the coefficient. The resulting relative frequency aggregated by bins is depicted in Figure 51.

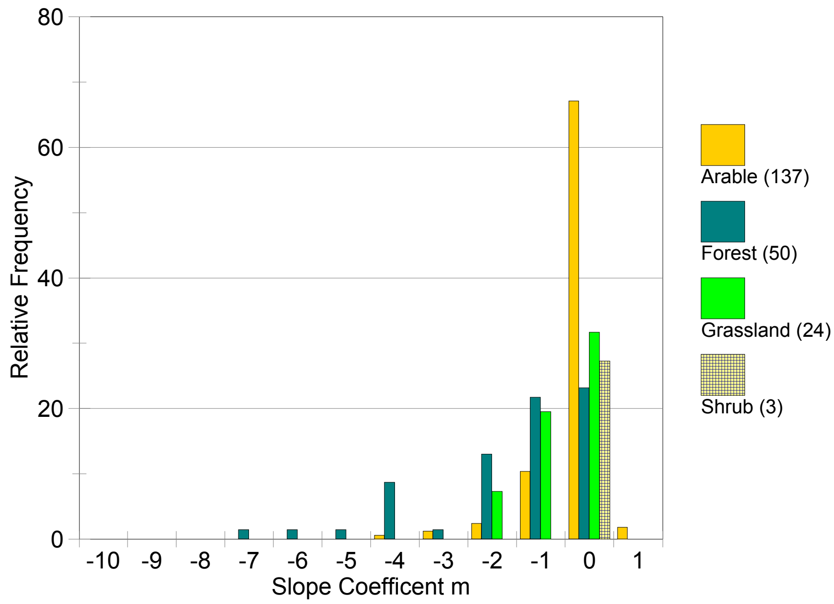
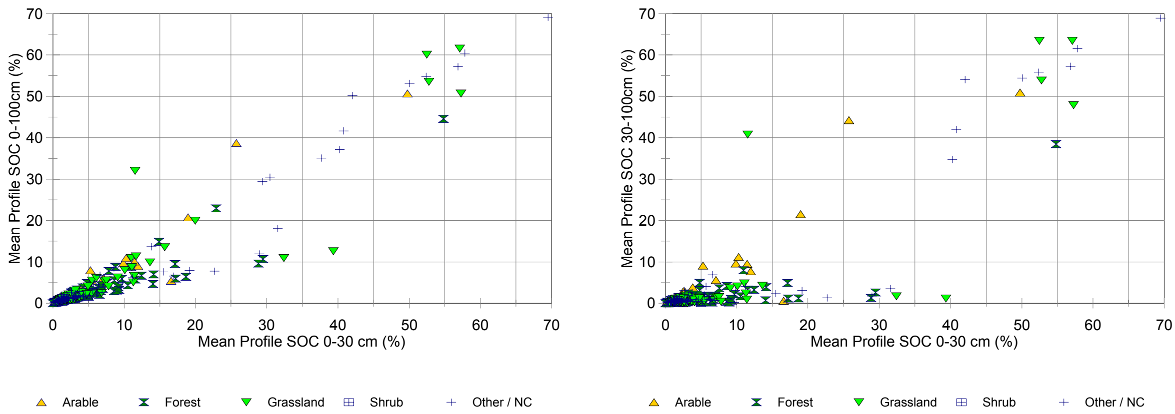


Figure 51: Frequency Distribution of Relative Occurrence of Slope Coefficient m by Land Cover Type (ISRIC-WISE)

The graph shows a predominance of arable soils for a gradual decrease of SOC content with horizon depth. This tendency is reflected by the finding that over 65% of all profiles have a slope coefficient between -1 and 0. For profiles under forest the decline in SOC content with depth tends to be steeper, while the change for profiles on grassland takes an intermediate position.

3.3.4 Influence of Mean SOC Content in Soil Section

The mean SOC content in the topsoil was compared to corresponding values in the complete segment 0-100 cm and just the subsoil. The data pairs for the profiles are presented in Figure 52.



a) Topsoil vs. 0-100 cm SOC Content *b) Topsoil vs. Subsoil SOC Content*

Figure 52: Relationship between Mean SOC Content of Topsoil and Subsoil and Combined Soil Segment (ISRIC-WISE)

The relationship between the mean SOC content of the topsoil and the segment 0-100 cm indicates divergent trends for SOC contents above approx. 15%. The profiles on the lower data belong to the soil types *Gleyic Podzol* (*PZg*) and *Dystric Gleysol* (*GLd*) on grassland and non-specific land use types. These soil types indicate the presence of a discontinuity in soil horizon properties or the presence of an organic horizon overlaying mineral soil. As a consequence, there is very limited or no relationship in SOC content between the topsoil and the subsoil. This situation can be observed when plotting the mean SOC content of the topsoil against the subsoil. For profiles with a topsoil SOC content of above approx. 12% the subsoil SOC content remains practically unchanged. For the 11 profiles of the *Gleyic Podzol* 10 profiles show a very distinct decrease in SOC content between the topsoil and the subsoil. None of these profiles are on arable land. For the 15 profiles classified as *Dystric Gleysol* only the 2 profiles with a mean SOC content of 20% in the topsoil show a comparable development. This situation indicates a more complex relationship between topsoil and subsoil SOC content for the *Dystric Gleysol* then for the *Gleyic Podzol*.

The parameters for a linear relationship between the SOC content in the topsoil and the soil segment 0-100 cm was found to be:

$$SOC_{0-100} = 0.887 \times SOC_{TOP} \text{ (r}^2\text{: 0.90, 534 dF)}$$

No *PZg* profiles: $$SOC_{0-100} = 0.923 \times SOC_{TOP} \text{ (r}^2\text{: 0.92, 523 dF)}$$

Limiting the profiles to mineral soils (SOC content < 18) the relationships were found to be:

$$SOC_{0-100}^{\min} = 0.658 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.65, 504 dF)}$$

No *PZg* profiles: $SOC_{0-100}^{\min} = 0.685 \times SOC_{TOP}^{\min}$ (r^2: 0.67, 498 dF)

For organic soils (SOC content >=18%) the relationships were:

$$SOC_{0-100}^{org} = 1.219 \times SOC_{TOP}^{org} - 13.0 \text{ (} r^2 \text{: 0.78, 28 dF)}$$

No *PZg* profiles: $SOC_{0-100}^{org} = 1.173 \times SOC_{0-100}^{org} - 9.7$ (r^2: 0.80, 23 dF)

For the entirety of profiles the relationship between the topsoil and the soil segment 0-100 cm SOC content is close to 1 when not including profiles from *Gleyic Podzol*. This would indicate that there is practically no change in the SOC content from the topsoil to the subsoil. In a simplistic approximation this would connote that more than twice the amount of SOC is stored in the subsoil than in the topsoil.

When separating the profiles into mineral and organic a more complex relationship was found. For profiles with a SOC content of <18% in the topsoil the SOC content of the soil segment 0-100 cm is approx. 2/3 of the topsoil value. Based on the number of profiles the deviating trend for *Gleyic Podzol* does not significantly change the relationship.

For organic soils a notably different relationship emerges. There appears to be a general increase in SOC content with depths. Those increases concern profiles on arable land, but also forest and grassland on peat. All profiles where the mean SOC content for the segment 0-100 cm qualifies them as organic are classified as *Histosols* (*Hs*), either *terric* (*HSf*) or *fibric* (*HSf*). The profile data for *Histosols* also demonstrates that one should not rely merely on the soil class in the assignment of mineral or organic soil types in a dataset. One of the profiles classified as *Histosols* had a mean SOC content of 3% for the segment 0-100 cm while another had a mean SOC content of 3.1% for the subsoil, which is inconsistent with the definition of the soil class. Despite the non-conform classifications the latter was included in the analysis of the regression analysis for organic soils, because the topsoil SOC content was > 18% (19.2%).

In the assessment of the regression the y-offset was computed for organic soils rather than set to 0 as for mineral soils. Even when forcing the y-offset to 0 the slope coefficient of 0.96 remains significantly different from the coefficient found for mineral soil profiles. Thus, based on the results of the regression analysis, the change in SOC content with depth is very likely to be different between mineral and organic soils. However, in the interpretation of the results it should be considered that the slope coefficient of the SOC content relationship for organic soils is very much influenced by just 2 profiles, one on grassland and one on arable land.

Relating the SOC content of the topsoil to the subsoil demonstrates the difference in the change in SOC content with the amount of SOC in the soil. Without the duplication of the topsoil in the supposedly independent data set the divergent relationships are more apparent. There is practically no relationship between the topsoil and subsoil SOC content for the *Gleyic Podzol* in the profile data.

The regression analysis of the relationship between topsoil and subsoil SOC content produced the following results:

$$SOC_{SUB} = 0.809 \times SOC_{TOP} \text{ (r}^2\text{: 0.76, 472 dF)}$$

No *PZg* profiles: $$SOC_{SUB} = 0.885 \times SOC_{TOP} \text{ (r}^2\text{: 0.83, 461 dF)}$$

Limiting the profiles to mineral soils (SOC content < 18%) the relationships were found to be:

$$SOC_{SUB}^{\min} = 0.355 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.19, 447 dF)}$$

No *PZg* profiles: $$SOC_{SUB}^{\min} = 0.391 \times SOC_{TOP}^{\min} \text{ (r}^2\text{: 0.22, 441 dF)}$$

For organic soils (SOC content >=18%) the relationships were:

$$SOC_{SUB}^{org} = 1.461 \times SOC_{TOP}^{org} - 27.0 \text{ (r}^2\text{: 0.70, 23 dF)}$$

No *PZg* profiles: $$SOC_{SUB}^{org} = 1.215 \times SOC_{SUB}^{org} - 11.8 \text{ (r}^2\text{: 0.66, 17 dF)}$$

For mineral soils the relationship in SOC content between topsoil and subsoil hardly exists. The mean SOC content for the topsoil of all profiles with a topsoil SOC content of <18% is 2.8%. By contrast, The mean SOC content for the subsoil of all profiles with a topsoil SOC content of <18% is 1.0%. Hence, while there is a pronounced decrease in SOC content from the topsoil to the subsoil this is not immediately evident from the regression analysis. The change in SOC content with depth is more prevalent for soils with a mean SOC content of >18% in the topsoil.

For mineral soils the regression coefficient relating SOC content of the topsoil to the soil segment 0-100 cm and the subsoil was computed for the major land use types. The results are given in Table 11.

Table 11: Parameters of Linear Regression between SOC Content of Topsoil and Soil Segment 0-100 cm and Subsoil (ISRIC-WISE)

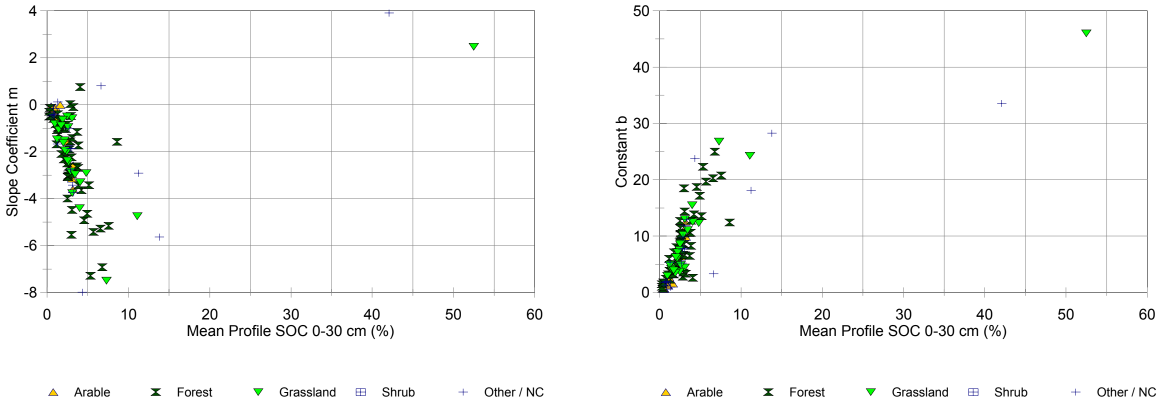
Regression Analysis	Slope Coeff.	Coefficient of Determination r^2	Lower Limit (95%)	Upper Limit (95%)
		TOP vs. 0-100		
Arable <18	0.729	0.78	0.690	0.769
Forest <18	0.576	0.77	0.541	0.611
Grass < 18*	0.707	0.87	0.663	0.750
Other / NC	0.662	0.79	0.606	0.717
		TOP vs. SUB		
Arable <18	0.573	0.53	0.513	0.634
Forest <18	0.247	0.43	0.215	0.280
Grass < 18*	0.246	0.49	0.211	0.282
Other / NC	0.322	0.31	0.259	0.384

* Profile No. 2836 (soil type *HSs*) not included.

The results of the regression analysis show a general decrease in the variability of the data for individual land use types as compared to the results obtained from all profiles. This could be taken as an indication for a distinct relationship between the topsoil and subsoil SOC contents of one or more land use types.

When comparing the relationship between the topsoil and the soil segment 0-100 cm the mean SOC content profiles under forest show a correlation coefficient which is distinctly different from those found for other land use types. However, when comparing the relationship between the topsoil and the subsoil mean SOC content profiles on arable land a distinctly different development emerges, while the relationship for profiles under forest and on grassland are quite similar.

The influence of the level of SOC on the relationship between topsoil and subsoil SOC content was evaluated by assessing the rate of change in SOC content with depth. The results of plotting the mean SOC content in the topsoil versus the coefficient and constant derived from the regression of SOC content with depth are presented in Figure 53.



a) Topsoil SOC Content vs. Coefficient *b) Topsoil SOC Content vs. Constant*

Figure 53: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Topsoil by Land Cover Type (ISRIC-WISE)

The graph indicates a decrease in the regression coefficient with increasing SOC content in the topsoil. From this general trend 2 profiles with mineral soils deviated by showing an increase in SOC content with depth and 4 profiles show a comparable rate in the SOC content : depth coefficient, but with a distinct offset. Further investigation of the data of these profiles could not shed any light as to the reasons for the off-set from the general trend for those profiles.

The regression analysis of the mean topsoil SOC content with coefficients and constants obtained from relating the horizon topsoil SOC content to the central horizon depth gave the following parameters for mineral profiles:

$$m_{TOP} = -0.630 \times SOC_{TOP} \;\; (\mathrm{r}^2\text{: 0.35, 106 dF})$$

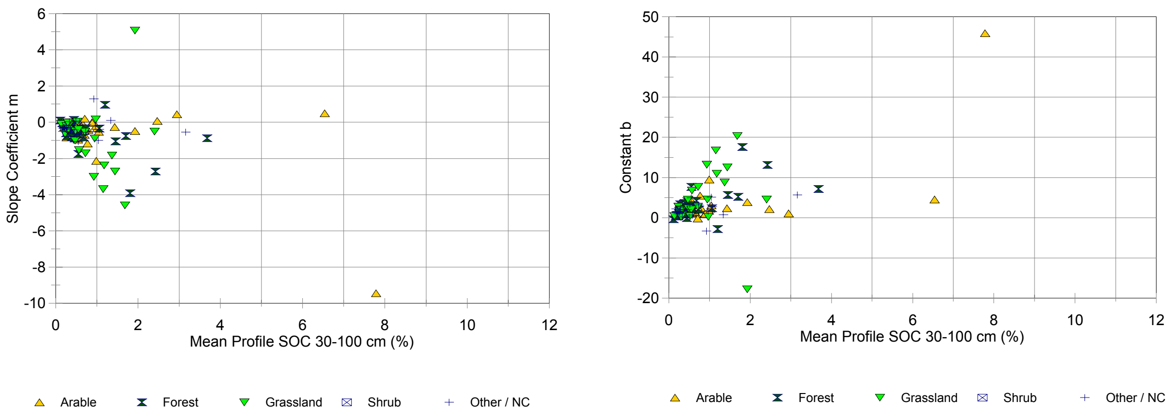
$$m_{TOP}^{arable} = -0.760 \times SOC_{TOP} \;\; (\mathrm{r}^2\text{: 0.73, 13 dF})$$

$$m_{TOP}^{forest} = -0.735 \times SOC_{TOP} \;\; (\mathrm{r}^2\text{: 0.42, 55 dF})$$

$$m_{TOP}^{grassland} = -0.678 \times SOC_{TOP} \;\; (\mathrm{r}^2\text{: 0.54, 21 dF})$$

The 2 profiles in the data set with organic profiles were not further analyzed. They were found to significantly differ in their characteristics from the distribution of SOC content in mineral soils, and it was not expected that the characteristics of the relationship could be defined from just 2 profiles.

For the relationship between the mean SOC content in the subsoil and the coefficients and constants from the regression of subsoil SOC content and depth the data pairs are presented in Figure 54.



a) Subsoil SOC Content vs. Coefficient *b) Subsoil SOC Content vs. Constant*

Figure 54: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Subsoil by Land Cover Type (ISRIC-WISE)

The relationship of the subsoil SOC content with the regression coefficients and constants of the SOC content changes with depth indicates a less defined change for the subsoil than for the topsoil. In contrast to the topsoil data the subsoil dataset only contains results for profiles with a mean SOC content <8%. Almost 20% of the subsoil profiles show no change in SOC content with depth or even a slight increase. One profile classified as a *Eutric Flivisol* shows a marked increase in subsoil SOC content with depth. The magnitude of the increased was caused by a relatively low SOC content of a horizon stretching from 18-45 cm and a subsequent increase for deeper horizons. The profile data does not provide an explanation for the uncharacteristic behaviour of the SOC content development in the profile. Because the trend displayed by the profile was found to be anomalous the data were not included in the regression analysis. The results of the change in regression coefficient relating SOC content to depth in the subsoil are:

$$m_{SUB} = -0.646 \times SOC_{SUB} \text{ (r}^2\text{: 0.25, 126 dF)}$$

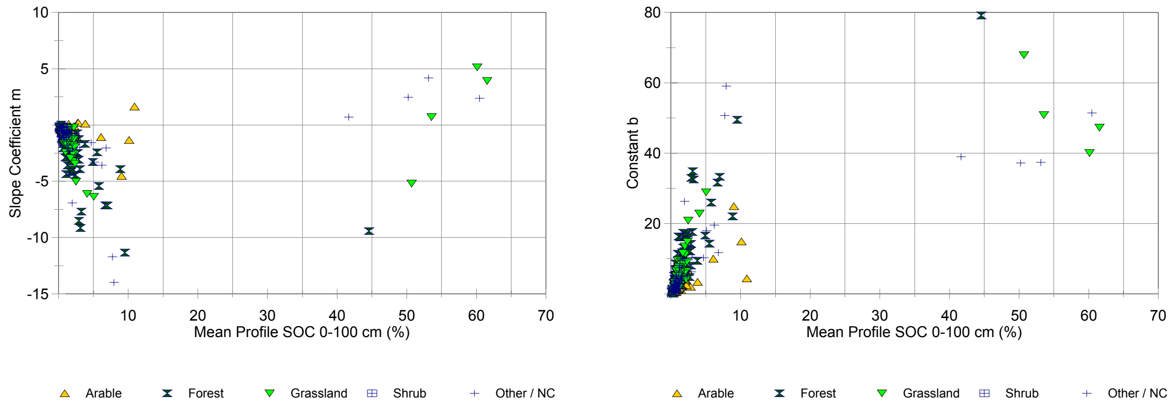
$$m_{SUB}^{arable} = -0.074 \times SOC_{SUB} \text{ (r}^2\text{: -0.68, 41 dF)}$$

$$m_{SUB}^{forest} = -0.686 \times SOC_{SUB} \text{ (r}^2\text{: 0.21, 36 dF)}$$

$$m_{SUB}^{grassland} = -1.410 \times SOC_{SUB} \text{ (r}^2\text{: 0.32, 24 dF)}$$

The changes in the regression coefficient are notably different between the land use types. For profiles on arable land an increase in the regression coefficient of SOC content vs. depth dominates in the subsoil. For profiles on grassland the decrease in the slope coefficient persists also in the subsoil. To a lesser degree this decrease is also notable for profiles under forest.

The results of relating the mean SOC content in the soil segment 0-100 cm and the coefficients and constants from the regression of SOC content and depth for the segment are presented in Figure 55.



a) 0-100 cm SOC Content vs. Coefficient *b) 0-100 cm SOC Content vs. Constant*

Figure 55: Relationship between Mean SOC Content and Model Slope Coefficient and Constant for Soil Section 0-100 cm by Land Cover Type (ISRIC-WISE)

The graph shows the distinctly different relationship between the change in the regression coefficient between mineral and organic soils. A regression analysis between the mean SOC content of the segment 0-100 cm and the coefficient of the relationship between SOC content and depth provided the following results:

$$m_{0-100} = -0.850 \times SOC_{0-100} \text{ (r}^2\text{: 0.46, 346 dF)}$$

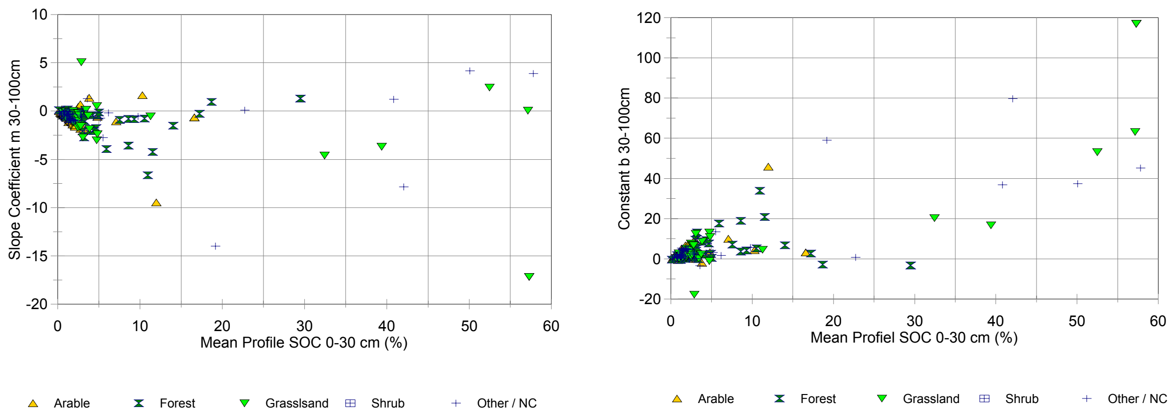
$$m_{0-100}^{arable} = -0.347 \times SOC_{0-100} \text{ (r}^2\text{: -0.13, 139 dF)}$$

$$m_{0-100}^{forest} = -1.040 \times SOC_{0-100} \text{ (r}^2\text{: 0.51, 94 dF)}$$

$$m_{0-100}^{grassland} = -1.179 \times SOC_{0-100} \text{ (r}^2\text{: 0.71, 50 dF)}$$

The general tendency of a distinctly different relationship for profiles on arable land as compared to those under forest or on grassland found for the subsoil, but not the topsoil, is also present in the structure of the soil segment 0-100 cm. This indicates that changes in SOC content with depth are more comparable for soils under forest and grassland than either with development of soils on arable land.

In order to estimate the SOC content at a certain depth in the subsoil the mean SOC content in the topsoil is associated with the regression parameters describing the relationship between SOC content and depth in the subsoil. The available data pairs from the profiles are presented in Figure 56.



a) Topsoil SOC Content vs. Subsoil Coefficient *b) Topsoil SOC Content vs. Subsoil Constant*

Figure 56: Relationship between Mean SOC Content for Topsoil and Model Slope Coefficient and Constant for Subsoil by Land Cover Type (ISRIC-WISE)

Following the low level of correlation between the topsoil and the subsoil mean SOC content the relationship between the mean SOC content of the topsoil and the slope coefficient of the SOC content vs. depth association in the subsoil was as expected rather weak. The development of SOC content with depth for one profile on grassland (No. 1695) was found to be outside the common trend, with a strong increase in SOC content with depth for an organic soil. Because of the particularity of the profile it was excluded from the formulation of parameters representing a general relationship. The regression analysis of data from profiles with a mean SOC content < 18% in the topsoil resulted in slope and constants of:

$$m_{SUB} = -0.208 \times SOC_{TOP} \ (\text{r}^2\text{: 0.14, 238 dF})$$

$$m_{SUB}^{arable} = -0.232 \times SOC_{SUB} \ (\text{r}^2\text{: -0.10, 111 dF})$$

$$m_{SUB}^{forest} = -0.202 \times SOC_{SUB} \ (\text{r}^2\text{: 0.24, 54 dF})$$

$$m_{SUB}^{grassland} = -0.218 \times SOC_{SUB} \ (\text{r}^2\text{: -0.02, 50 dF})$$

Those findings lead to the following general formulation of the relationship between topsoil mean SOC content and the regression coefficient of the relationship between SOC content and depth for the subsoil:

$$\Rightarrow SOC(d)_{SUB}^{\min} = -0.208 \times SOC_{TOP}^{\min} \times \ln(d) + 1.157 \times SOC_{TOP}^{\min}$$

For profiles with higher SOC content a tendency for the slope coefficient to increase is suggested by the data. However, for data from one plot with peat on grassland (No. 1698) displays a notable rate of SOC content decreasing with subsoil depth. The profile horizon data do not indicate any particular inconsistency in the values reported. With the few profiles for organic soils this single profile very much dominates the results of a regression analysis. While accepting the profile data as real and useful when appreciating the variation in soil conditions including the profile in the formulation of general trends was considered unsupportive. Excluding the profile data from the analysis results in a slight increase (m = +0.07) in the regression coefficient of SOC content vs. depth with increasing SOC content in the subsoil for organic soils and peat.

For profiles of individual land use types and for the collection of all profiles available for the analysis the correlation between the mean SOC content of the topsoil and the subsoil slope coefficient of the change of the SOC content with depth in the subsoil thus determined the level of dependability is rather low. Alternatively, the relationship can also be approximated from the correlation between the mean SOC content of the topsoil and the soil segment 0-100 cm. The computation was developed from the following approach:

$$SOC(d)_{SUB} = m_{SUB} \times \ln(d) + b_{SUB}$$

The general function for the subsoil coefficient can be related to the mean SOC content of the subsoil by a linear function as:

$$m_{SUB}^{\min} = n_1^{\min} \times SOC_{SUB}$$

In an approximation the mean SOC content of the subsoil can be linked to the mean SOC content of the topsoil and the soil segment 0-100 cm by proportionally weighing the sections:

$$SOC_{SUB} = \frac{SOC_{0-100} - 0.3 \times SOC_{TOP}}{0.7}$$

The mean SOC content of the segment 0-100 cm is correlated to the mean topsoil SOC content by:

$$SOC_{0-100}^{\min} = n_2^{\min} \times SOC_{TOP}^{\min}$$

By substitution the slope coefficient for the SOC content at a given depth in the subsoil estimated from the mean topsoil SOC content becomes:

$$m_{SUB}^{\min} = n_1^{\min} \times \frac{n_2^{\min} \times SOC_{TOP}^{\min} - 0.3 \times SOC_{TOP}^{\min}}{0.7} = n_1^{\min} \times \frac{n_2^{\min} - 0.3}{0.7} \times SOC_{TOP}^{\min}$$

Correspondingly, the function constant for the subsoil can be estimated from topsoil and segment 0-100 cm data. For mineral soils the relationship between the topsoil SOC content and the coefficient defining changes in SOC content with depth in the subsoil thus becomes:

$$\Rightarrow SOC(d)_{SUB}^{\min} = -0.232 \times \ln(d) \times SOC_{TOP}^{\min} + 1.410 \times SOC_{TOP}^{\min}$$

For organic soils the subsoil slope coefficient n_1^{org} varies considerably between the 7 profiles in the data subset. Instead of using the method detailed above for organic soils the coefficient was estimated from 14 profiles available for characterizing the relationship of the topsoil mean SOC content and the subsoil slope coefficient. The corresponding values were averaged by soil type to achieve a more compact data set for the analysis. Subsoil slope coefficient and constant were estimated by:

$$m_{SUB}^{org} = n_1^{org} \times SOC_{TOP}^{org} + c_1^{org} \text{ and } b_{SUB}^{org} = n_2^{org} \times SOC_{TOP}^{org} + c_2^{org}$$

The function for the subsoil SOC content at a given depth *d* is then:

$$SOC(d)_{SUB}^{org} = \left(n_1^{org} \times SOC_{TOP}^{org} + c_1^{org}\right) \times \ln(d) + n_2^{org} \times SOC_{TOP}^{org} + c_2^{org}$$

Using the values derived from the analysis the subsoil SOC content could be estimated based on the mean topsoil SOC content as:

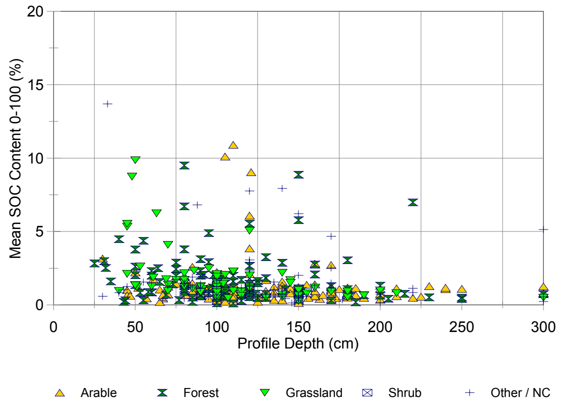
$$SOC(d)_{SUB}^{org} = \left(0.075 \times SOC_{TOP}^{org} - 2.4\right) \times \ln(d) + 0.898 \times SOC_{TOP}^{org} + 5.2$$

Care should be applied in the interpretation of the function parameters. The function results in a slight increase in SOC content with depth for topsoil SOC contents > 20%. This trend corresponds to the correlation of topsoil to segment 0-100 cm mean SOC content. Nonetheless, the function parameters are based on the data from just 9 profiles with organic topsoil and subsoil. When applying the SOC content threshold only to the topsoil data from 5 additional profiles are included, all of which indicate a change from an organic topsoil horizon to a mineral subsoil. Yet, the function is not applicable to those profiles. Under conditions where the subsoil SOC content is to be estimated the knowledge of a mineral subsoil can only be derived from the soil type and this information should be taken into account in addition to the mean topsoil SOC content.

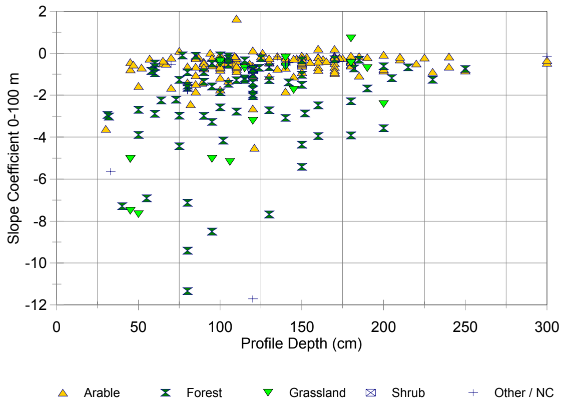
It should further be considered that while the method is mathematically apt and may be considered an alternative to the regression analysis in cases where subsoil data are scarce it does in no way improve the reliability of the relationship between topsoil and subsoil SOC content.

3.3.5 Influence of Depth of Soil

The amount of OC in a soil segment may be affected by the depth of the soil above the rock layer. Profile depth would influence the correlation between mean SOC content and depth. In the absence of data on the depth of the soil stratum the lowest horizon depth of a profile is used as a substitute. To evaluate the relationship the profile depth is related to the mean SOC content of the soil segment 0-100 cm and the slope coefficient of the SOC content vs. depth correlation. The results for the collection of all profiles are presented in Figure 57.



a) Profile Depth vs. 0-100 cm SOC Content



b) Profile Depth vs. 0-100 cm Coefficient

Figure 57: Maximum Profile Depths vs. Mean SOC Content for Soil Segment 0-100 cm and Change in Model Slope Coefficient with Depth of Profile (ISRIC-WISE)

The data indicate a decrease in the variability of the mean SOC content and slope coefficient with the depth of the soil stratum. The graph may hide more consistent correlations for individual soil types. With the total number of 449 profile pairs available for the evaluation data for 13 soil types were included with data from 10 or more profiles. For those soil types the relationship between soil depth and the mean SOC content and the slope coefficient of the SOC content : depth correlation of the soil segment 0-100 cm were assessed individually.

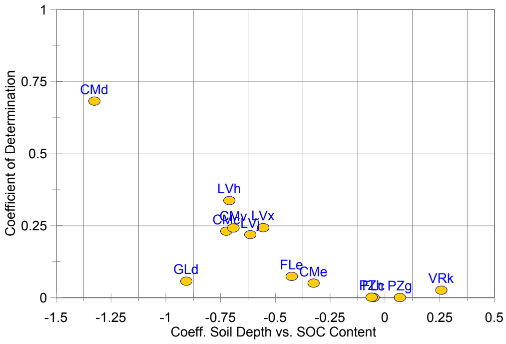


Figure 58: Regressions Coefficient of Linear Function between Soil Depth and Mean SOC Content for Soil Segment 0-100 cm vs. Coefficient of Determination of Correlation (ISRIC-WISE)

Table 12: Parameters of Linear Regression between Soil Depth and Mean SOC Content for Soil Segment 0-100 cm vs. Coefficient of Determination of Correlation (ISRIC-WISE)

Soil	No. of Profiles	Slope Coeff	Coeff. of Deter.	Coeff. Min (95%)	Coeff. Max. (95%)
CMc	10	0.723	0.23	-1.799	0.352
CMd	33	1.325	0.68	-1.655	-0.994
CMe	21	0.325	0.05	-1.055	0.437
CMv	10	0.690	0.24	-1.685	0.304
FLc	16	0.052	0.00	-0.980	0.877
FLe	18	0.425	0.07	-1.216	0.366
GLd	12	0.906	0.06	-3.486	1.673
LVh	26	0.709	0.34	-1.127	-0.291
LVj	13	0.614	0.22	-1.381	0.154
LVx	19	0.555	0.24	-1.056	-0.055
PZg	10	0.069	0.00	-1.992	2.130
PZh	23	0.060	0.00	-0.629	0.509
VRk	16	0.258	0.03	-0.628	1.144

As the graph illustrates the regression coefficient is negative for 11 out of the 13 profiles analyzed. The graph also shows the generally low level of predictability of the SOC content from soil depth and indicates a low level of significance that the slope coefficient will be different from 0. It simply indicates that the lower the regression coefficient of the relationship between the coefficient of the SOC content-to-depth function and the SOC content the less likely it is that no relationship exists.

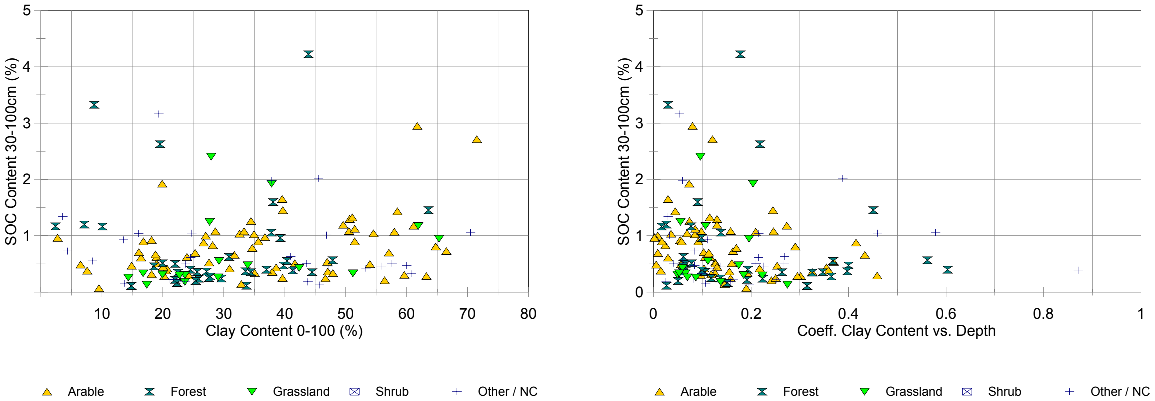
The lower and upper values of the regression coefficient of the correlation between the soil depth and the mean segment SOC content, both transformed by a natural logarithm, for the 13 soil types are given in Table 12. At a confidence level of 95% only the profiles of *Dystric Cambisol* (*CMd*) and *Chromic Luvisol* (*LVx*) could be considered to provide sufficient evidence for predicting SOC content from soil depth.

The evaluation of the influence of soil depth on the mean SOC content in a soil segment suggested that there may be a decrease in mean SOC content in the soil segment 0-100 cm for some soil types more than for others. The correlations is probably non-linear, although with the data available it was not possible to establish a definite relationship and its characteristics. The impact of soil depth on the distribution of OC in the profile seems to be more expressed when the soil stratum is deeper than 100 cm which suggest that even when estimating the distribution of OC from the topsoil information on soil depth beyond 100 cm could be of use.

3.3.6 Influence of Clay Content

An increase in clay content in deeper parts of the soil is linked to an increase in SOC content in those parts. This relationship should be separated from an increase on SOC quantity with clay content in deeper soils, because with an increase in clay content also the bulk density increases.

For the collection of profiles with an increase in clay content with depth the relationship between the mean SOC the clay content and the mean subsoil SOC content and the slope coefficient of the subsoil SOC content vs. depth function are presented in Figure 59.



a) 0-100 cm Clay vs. Subsoil SOC Content *b) Profile Depth vs. 0-100 cm Coefficient*

Figure 59: Relationship between Clay Content and Subsoil SOC Content and the Coefficient of the Relationship Clay Content vs. Depth and the Subsoil SOC Content for Profiles with an Increase in Clay Content with Depth (ISRIC-WISE)

The graphs distinguish in the data from the 148 profiles between land use types. Alternatively, profiles could be grouped by soil type, but the number of profiles of a particular soil type was commonly low and reached 10 profiles only for one soil type (*LVh*, *Halplic Luvisol*). For those profiles the SOC content in the subsoil actually decreases with increasing clay content.

While no particular correlation or trend could be identified between clay content and SOC content in the subsoil for profiles where the clay content increases with depth the data show a strong decrease in the variability of the subsoil SOC content with increasing coefficient for the change in clay content with depth.

For profiles with a decrease in clay content with depth the relationships are not quite inversed. There is no discernable relationship between clay content and SOC content in the profiles. There is further no notable change in the variability of the subsoil SOC content and the coefficient of the change in clay content with depth for those profiles. Contrary to profiles with an increase in clay content with depth for profiles with a decrease in clay content with depth the mean SOC content in the subsoil seems to increase with a higher mean clay content in the profile. This suggests that the influence of the clay content in the subsoil on OC depends on the distribution of clay within the profile.

The findings suggest that the relationship between SOC and clay content are more complex and governed by factors other than just the clay content in the subsoil. For some soil types opposing trends were found in the relationship depending on whether clay content increases with depth or decreases. For a more comprehensive analysis the number of profiles for a given soil type would have to be substantially larger than what was available from the data set.

3.3.7 SOC Content by Major Soil Category

The mean SOC content in the topsoil and subsoil sections by FAO90 Level 1 soil category are given in Table 13.

From the dataset covering Europe the topsoil and subsoil SOC contents of 471 profiles could be compared for 25 main soil categories. The most frequently encountered soil categories are *Cambisols* (96 profiles), *Luvisols* (84 profiles), *Fluvisols* (41 profiles), *Podzols* (40 profiles) and *Gleysols* (38 profiles). There would appear to be a notable preference of some soil categories to be associated with specific land uses. For example, *Vertisols* are mainly covered by arable land use (85%), while *Podzols* are predominantly found under forest cover in the profiles of the dataset.

Overall, the subsoil SOC content amounts to 55% of the SOC content of the topsoil. The averaged value varies markedly with land use: for arable profiles it is 73%, for forest 27% and for grassland 61%. The relative portion SOC content in the subsoil is 36% when both soil layers are of mineral type. For organic topsoils and subsoils the portion increases to 105%, i.e. an increase in SOC content in the subsoil layer over the topsoil. All aggregated figures are weighted by the number of profiles in the survey, not the distribution of the soils across Europe. The figures should therefore not be interpreted as being universally representative values but rather be taken as a guidance for various soil types.

Table 13: SOC Content by Soil Category (ISRIC-WISE)

SOIL FAO90	ARABLE			FOREST			GRASS			OTHER / NC			ALL		
	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles	Topsoil	Subsoil	No. of Profiles
Acrisols							1.3	0.2	1	4.3	0.5	1	2.8	0.4	2
Alisols	1.7	0.8	2				1.6	0.2	2	1.5	0.6	1	1.6	0.5	5
Andosols	8.1	7.2	4	8.9	4.5	7				6.2	2.4	3	**8.1**	**4.8**	14
Arenosols	0.5	0.2	1	0.4	0.2	1				1.3	0.2	1	0.7	0.2	3
Anthrosols				2.1	1.6	2							2.1	1.6	2
Chernozems	**2.0**	**0.9**	13	2.7	0.4	2				2.6	1.6	4	**2.2**	**1.0**	19
Calcisols	0.9	0.4	4				7.3	1.4	1	0.7	0.5	7	**1.3**	**0.5**	12
Cambisols	**1.6**	**0.7**	34	**2.8**	**0.7**	34	**3.3**	**0.9**	19	1.9	0.5	9	**2.4**	**0.7**	96
Fluvisols	**1.6**	**1.2**	21	2.2	0.9	5	**2.3**	**0.7**	10	3.0	2.0	5	**2.0**	**1.2**	41
Gleysols	3.3	0.5	9	4.1	0.7	5	**7.6**	**1.1**	13	**5.1**	**0.6**	11	**5.4**	**0.8**	38
Gypsisols										1.3	0.5	1	1.3	0.5	1
Histosols	31.5	38.9	3	54.8	38.5	1	46.3	53.9	5	40.2	40.6	8	**41.3**	**44.1**	17
Kastanozems	1.2	0.7	5				1.7	0.8	1				1.3	0.7	6
Leptosols	1.5	0.9	2	10.6	3.0	3	8.1	2.8	2				7.3	2.3	7
Luvisols	**0.9**	**0.5**	34	**1.9**	**0.5**	32	1.7	0.4	9	1.6	0.6	9	**1.5**	**0.5**	84
Lixisols							2.5	0.6	1				2.5	0.6	1
Podzoluvisols	1.0	0.3	2	2.8	0.2	1	1.9	0.1	2	1.4	0.2	1	1.7	0.2	6
Phaeozems	**2.6**	**1.6**	17	2.1	0.7	6	2.0	1.1	2	1.6	0.7	3	**2.3**	**1.3**	28
Planosols				2.4	0.4	8				3.6	0.7	3	**2.7**	**0.5**	11
Plinthosols				0.7	0.1	1							0.7	0.1	1
Podzols	2.9	0.6	2	**9.6**	**0.9**	21	10.4	1.4	7	**12.7**	**1.8**	10	**10.2**	**1.2**	40
Regosols				0.5	0.2	5				0.3	0.1	1	0.5	0.2	6
Solonchaks	0.5	0.7	1							0.8	0.3	2	0.7	0.4	3
Solonetz										1.2	0.5	2	1.2	0.5	2
Vertisols	**1.4**	**1.1**	22				1.0	0.3	1	1.2	0.9	3	**1.4**	**1.1**	26
All	**2.3**	**1.7**	**176**	**4.4**	**1.2**	**134**	**7.2**	**4.4**	**76**	**7.3**	**4.7**	**85**	**4.6**	**2.5**	**471**

bold: defined by 10 or more profiles

3.4 UK Soil Database for CO_2 Inventory

The national soil database used to model soil carbon fluxes and land use for the national carbon dioxide inventory for the UK (Thomson *et al.*, 2008; Bradley *et al.*, 2005) was made available for evaluation proposes by the Centre for Ecology and Hydrology, Edinburgh..

The soil properties were stored in an aggregated form of two depth layer:

- layer 0 – 30 cm (topsoil);
- layer 30 – 100 cm (subsoil).

The data for the sections are based on soil profile properties. The soil properties for each of the layers are organic carbon (content and quantity), sand, silt and clay content and bulk density. The soil data are provided separately for the following land use types:

- “Arable”: cultivated land (mainly arable and ley (short term) grassland);
- “Grass”: managed permanent grassland;
- “Forest”: woodland (deciduous and coniferous trees);
- “Semi”: semi-natural vegetation and grassland that receives no management.

No specific land use class was defined for urban areas. For continuous urban areas the SOC content was set to 0t C ha^{-1} and for suburban areas a value of 0.5 of the SOC content of the same soil series under pasture (land use type “Grass”) was used. To model soil carbon fluxed under different land uses the soil database had to cover the multitude of possible combinations of soil type under land cover with information on topsoil and subsoil. Where there was no information available from measured profiles estimates values were entered from suitable measured data based on expert judgement or as in the case of SOC content , derived from a conversion table with grassland set as the reference. Mostly this would have come from similar soil series sampled in the same geographic area. The coverage of soil data by measured profiles greatly varies between England & Wales, Northern Ireland and Scotland. As most measured data in Northern Ireland was from a narrow range of soil series under pasture there was much more substitution form other sources, often with profile data from England & Wales. As a consequence, the ratio of topsoil to subsoil OC content contains an element of data redundancy because in cases where only a few suitable soil cores were available the ratio of parameter values between the topsoil and the subsoil for this soil series would appear in several places in the database for similar series (Milne, 2009). No information on which parameters were derived from measured profiles and which were from actual measurements was available to separate the data in the analysis.

The data are stored in form of a single table, including all land use types, depth sections and soil properties. Separate tables are provided for England & Wales, Northern Ireland

and Scotland. For this study the tabulated data were transferred to a normalized data model without modifying the data values and processed using a database management system instead.

Due to the aggregation of data according to soil categories geographic coordinates were not available, which would have allowed mapping the soil property data at a specific location. Information on how to integrate without ambiguity the data of the classification schemes used in the three regions could not be established and hence the tables were treated separately.

The number of soil types in the tables varies depending on the region:

- England & Wales: 433; 410 soil series names + 23 descriptive names
- Northern Ireland: 476 series codes; 1 named "ALL"
- Scotland: 540 sequential codes; no soil series names

Not all records contain data on every soil properties for each of the land use types. This can be a characteristic of the soil type, e.g. no texture data for peat, although in other cases the absence of data is not immediately obvious.

To reduce the influence of data redundancy data which were unmistakably calculated from other soil properties were excluded from the analysis. For some cases calculated values were apparent in the spreadsheet tables by formulas which were entered in the table fields. The spreadsheet for England & Wales contained 18,419 data entries, of which 2,563 were evidently calculated from other data by a standard equation (spreadsheet formula in field). As a consequence, no topsoil data are available for the land use "Wood" for England & Wales, because such data were calculated largely from data of the land use "Semi" by applying a constant factor. For England & Wales the SOC content of "Wood" profiles was calculated by applying a factor of 1.8 to the SOC content value of the "Semi" land use. In other cases the link between data fields was less evident. For Northern Ireland identical values for SOC content were found for "Wood" and "Semi" for most soil categories. Since soil profiles for Northern Ireland were taken almost exclusively on grassland most values of SOC content for forests and semi-natural are surrogate data. The SOC content for those profiles is computed as 1.33*SOC content of permanent grassland (DEFRA, 2003), but the spreadsheet did not contain live formulas linking the fields. Subsequently, those data entries were included in the analysis.

A illustration of the records with data for organic carbon content for topsoil and subsoil after removing data calculated by formulas in the three spreadsheet tables is presented in Figure 60.

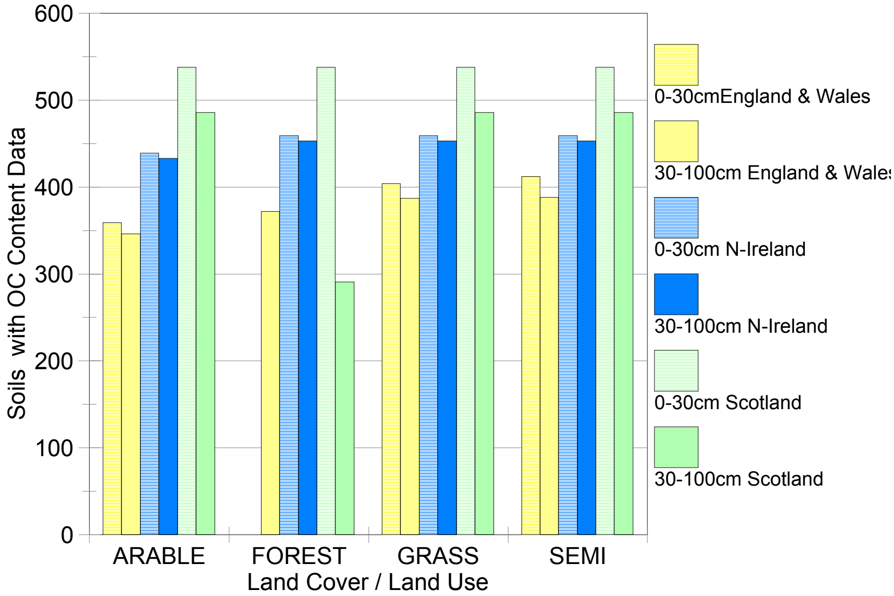


Figure 60: Table Records with Data for Soil Organic Carbon Content by Land cover Type and Region (UK)

The graph shows that the number of records with data for SOC content varies between land use types for England & Wales, while it remains quite stable in the data for Northern Ireland and Scotland. All regions show more data for the topsoil layer than for the subsoil with the biggest difference found for the Scottish data. The amount of data with values for SOC content vary significantly for forest in the subsoil for Scotland from 486 for other land cover types to 291.

The lack of formulas in the spreadsheets files or the amount of field entries does not as such signify that data from independent observations are recorded. One indicator for independence of observations is a high degree of unique entries for a combination of parameters. An overview over the number of soil classes with data for SOC content by land use type and unique combinations of SOC, clay, silt, sand content and bulk density is presented in Table 14.

Table 14: Soil Class Data in Tables

Region	Soil Category	Soil Classes with Data for SOC Content						
		Arable	Forest	Grass	Semi	Total	All	Unique*
England & Wales	433	359	0**	404	412	1175	2668	2022
		346	372	387	388	1493		
Northern Ireland	476	439	459	459	459	1816	3608	787
		433	453	453	453	1792		
Scotland	540	538	538	538	538	2152	3901	2791
		486	291	486	486	1749		

* Unique combination of SOC, clay, silt, sand content and bulk density
** Does not include any data calculated by formula in spreadsheet data

The table shows by region and land use type the number of soil categories with data for SOC content. It also indicates the total number of data for SOC content for the topsoil and subsoil of all land use types. The total number of soil categories ranges from 433 for England & Wales to 540 for Scotland. The distribution of data between land cover types is generally stable for data for Northern Ireland and Scotland, but more variable for England & Wales. Noticeable is the absence of measured data for soils under forest for England & Wales. All data recorded in the tables were found to be the result of applying a conversion factor from data for other land uses.

The ratio of all data over unique combinations is 0.76 for England & Wales, 0.72 for Scotland and 0.22 for Northern Ireland. While some repetition of soil properties between land cover types and depth layer could be expected the degree of data duplication for Northern Ireland is unusual. Some combinations are repeated up to 60 times in the data. In particular for organic soils there is relatively little differentiation between land cover types and soil layer. For soils with a lower SOC content no differentiation is recorded, predominantly for soils under forest and semi-natural land.

3.4.1 SOC Data in Profile Layers

The database does not contain the measurements taken for pedological horizons of the profiles but the weighted means of a soil property distributed within the fixed-depth topsoil and subsoil layers (DEFRA, 2003). Therefore, the distribution of SOC content by depth can only cover the distribution of the mean SOC content of the various soil categories for either of the two soil sections. The relative frequency distribution by land use type and region is given in Figure 61.

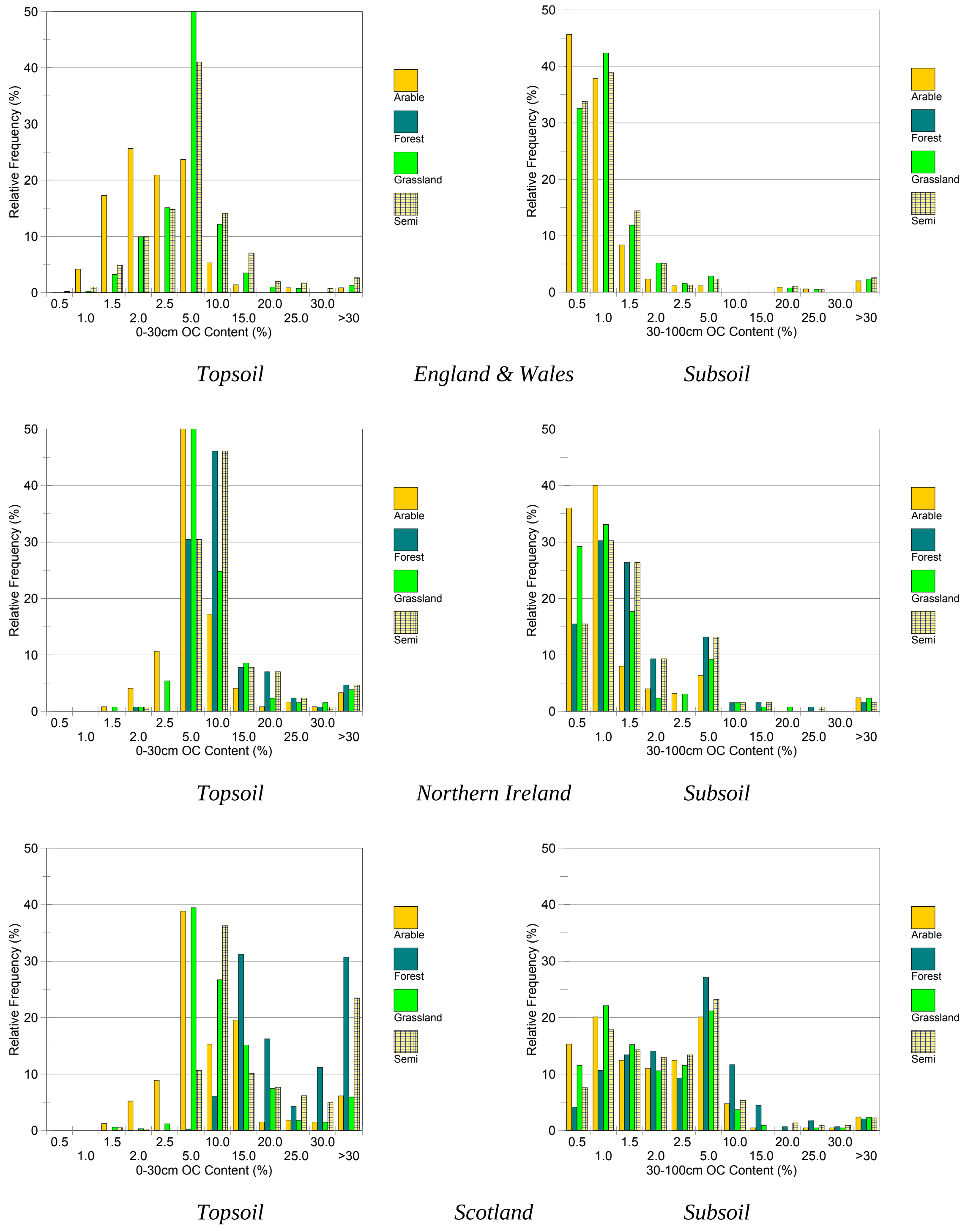


Figure 61: Relative Frequency of Mean SOC Content for Topsoil and Subsoil by Land Cover Type and Region

The graphs show a generally lower SOC content in the subsoil than the topsoil for the soil series. There are notable differences in the distribution of SOC content between the regions. For England & Wales the arable land is predominantly found on soils with lower SOC content in both, topsoil and subsoil. Grassland is mainly concentrated on soils with medium topsoil SOC content, while semi-natural areas tend to be located on soils with medium to high SOC content in the topsoil, but lower contents in the subsoil.

Soils in Northern Ireland show less variation in the topsoil SOC content than those of England & Wales. Arable land is concentrated on soils with a topsoil SOC content of approx. 5-10%, as are areas of grassland. By contrast, subsoil SOC contents are more variable in the soil data of Northern Ireland than for England & Wales. Forests and semi-natural areas, having the same soil properties, are prominent on soils with higher topsoil and subsoil SOC content.

The soils of Scotland show less of a distinction between the relative occurrence of arable land and grassland by SOC content. Forests dominate land use on soils with a topsoil SOC content between 10-30%. Land cover types up to subsoil SOC contents of approx. 10% are relatively evenly distributed with a preference for soils with a low SOC content to be used as arable land.

3.4.2 SOC Content and Depth Coefficient

With just two mean values for the topsoil and subsoil the characteristics of the distribution of SOC content with depth cannot be established. Instead, a coefficient based on the ratio of the subsoil over the topsoil mean SOC content can be used as a general indicator. Analogous to a linear function the relationship can be expressed as $SOC_{SU} = m * SOC_{TOP}$. This coefficient was computed for the four land cover classes and separately for the regional datasets. The results are graphically presented in Figure 62.

The graphs depict on the left-hand side the relative frequency of the subsoil to topsoil coefficient by values merged into bins ranging from 0 to 1 (1: subsoil has the same SOC content as topsoil). The right-hand side depicts the raw ration values (not rounded, but computed to 16 digits) and their relative frequency of occurrence.

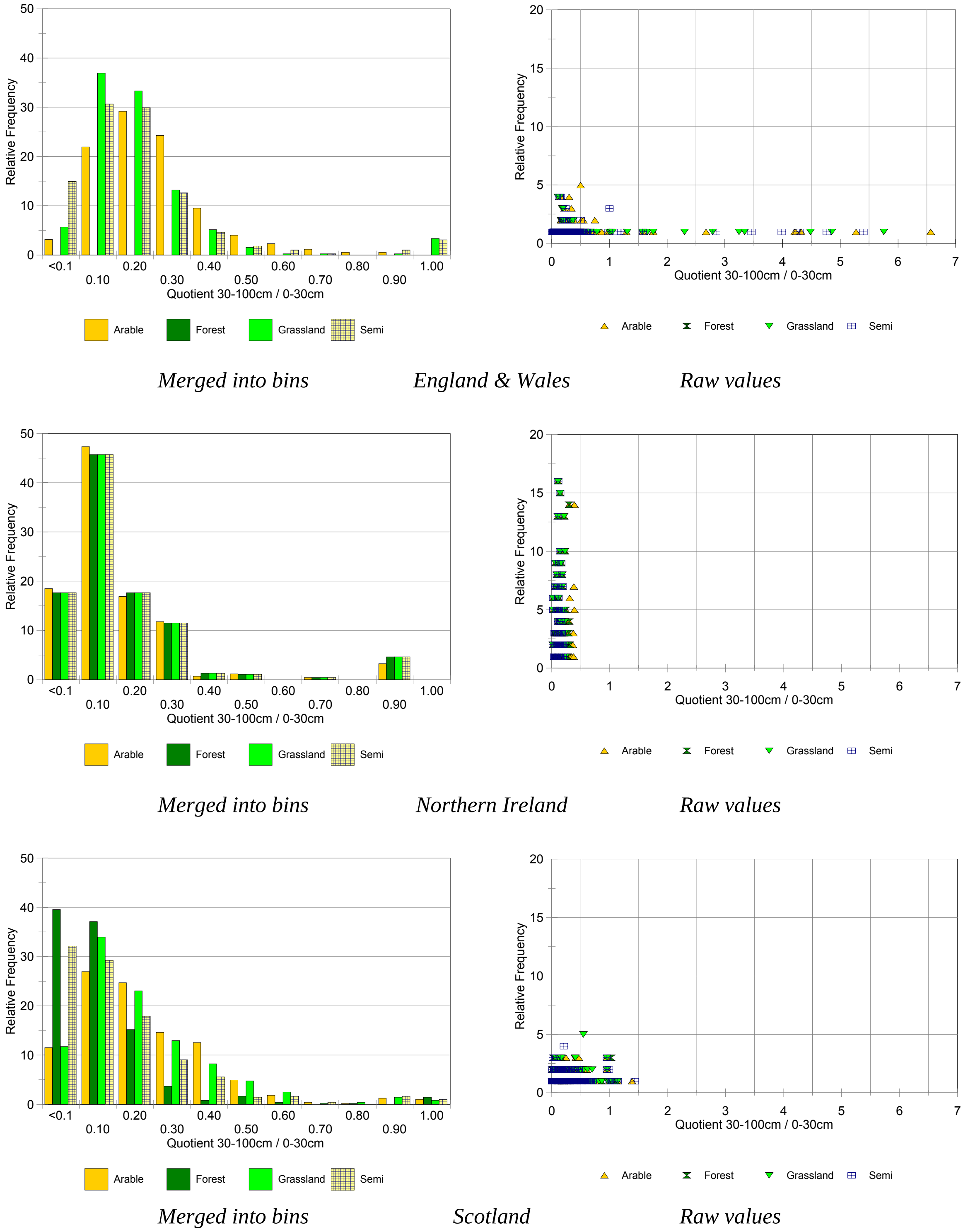


Figure 62: Coefficient of Subsoil over Topsoil SOC Content

For the relative frequency distribution merged into bins the graph suggests some similarity in the behaviour of the SOC content data for mineral soils of England & Wales and Scotland, and a remarkably different distribution of the data reported for Northern Ireland. For the raw values of the coefficients all datasets demonstrate distinct characteristics in the distribution of the values. The data for England & Wales have a low repeat rate of ratio values and a comparatively small value range. In the interpretation of the frequency value the removal of the major part of forest data should be considered, although the range of the ratio values would not have changed from applying a fixed conversion factor for SOC content. The span of values is narrower for the dataset for Northern Ireland than for England & Wales, while the occurrence of identical ratio values is comparatively elevated. The data for Scotland show an intermediate range of values and a frequency of the occurrence of individual coefficient values comparable to the data from England & Wales. Notable here is the high occurrence of profiles with a very low quotient for profiles under forest and semi-natural vegetation.

3.4.3 Influence of Land Cover

From the data for England & Wales and Scotland presented in Figure 62 one may infer that soils under arable land differ less in SOC content between the topsoil and subsoil than those under other land use types, in particular grassland. On soils with a substantial difference in SOC content between topsoil and subsoil (coefficient < 1) the dominant land use is forest and semi-natural. The relative occurrence of the non-merged coefficients displays the largely different distribution of SOC content between the topsoil and the subsoil for the datasets from the three regions. A relatively high repeat frequency of the same ration values are shown for data from Northern Ireland. The repeat frequency of ratio values is generally below 10 for England & Wales and Scotland. The Scottish data is characterized by a large range of low SOC content topsoil associated with high SOC content in the subsoil.

The distribution of the coefficient computed from the mean SOC content for topsoil and subsoil by land use and separated by mineral or organic topsoil is given in Table 15.

Table 15: Distribution of Mean SOC Content Ratio by Land Cover

Land Cover	England & Wales		Northern Ireland		Scotland	
	Mineral Topsoil	Organic Topsoil	Mineral Topsoil	Organic Topsoil	Mineral Topsoil	Organic Topsoil
Arable	4.18	17.14	7.61	4.43	5.21	18.52
Forest			7.32	9.61	9.53	11.28
Grassland	5.10	13.76	7.44	9.11	5.44	12.00
Semi	5.47	20.38	7.32	9.61	5.67	20.51
ALL	**4.92**	**18.80**	**7.43**	**9.01**	**5.73**	**11.67**

A low level of distinction between land use and soil category for the dataset for Northern Ireland is evident, also when separating the SOC content coefficient into mineral and organic topsoils. The compactness in the data for Northern Ireland contrasts with the discrimination of coefficients for land use and topsoil category apparent in the datasets for England & Wales and Scotland. Despite the differences in the profiles for these regions the distribution of the coefficient by land use is unexpectedly similar. This correspondence is not present when comparing the mean coefficient of all land use types, because the forest data for England & Wales are excluded. The otherwise divergent characteristics of the data from England & Wales and Scotland may be taken to indicate that the coefficients found could be used to estimate the subsoil SOC content from the topsoil value. One should caution against such a supposition, not least because the coefficients presented in the table are means computed from the distribution of soil types and do not necessarily follow the distribution of land use in the regions.

3.4.4 Influence of Mean SOC Content in Soil Layer

The degree to which the SOC content of the subsoil layer may be estimated from the SOC content in the topsoil can be evaluated from a comparison of the values reported for the two soil sections. The relationships are graphically presented in Figure 63.

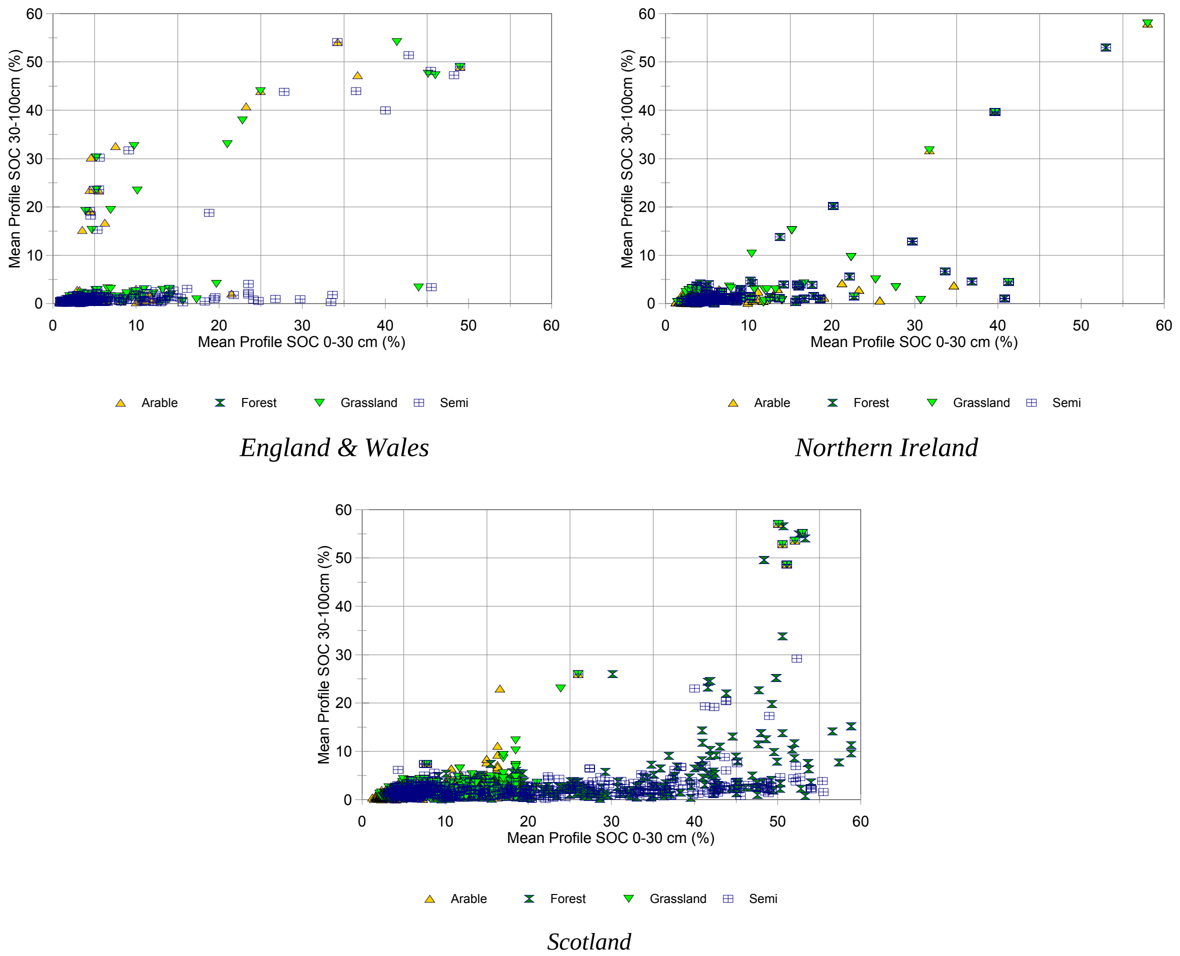


Figure 63: Relationship between Mean SOC Content of Topsoil and Subsoil (UK)

The relationships between topsoil and subsoil SOC content illustrated in the graph show distinctly different situations in the data between the regions:

- *England & Wales*

  The data of England & Wales does not indicate a general relationship between the SOC content of the topsoil to the subsoil for topsoils with a SOC content < 6%. Conversely, for soils with an organic subsoil the SOC content of the subsoil increases with increasing topsoil SOC content. The data for the subsoil SOC content present a complete gap without records between 4.1 and 15.3%. No comparable gap exists for topsoil SOC contents and it is not apparent what causes this absence of coverage. Besides, other soil profile data contain subsoil SOC contents in this range, such as the SPADE/M or the ISRIC/WISE datasets.

- *Northern Ireland*

  A trend comparable to the one for England & Wales is found for the data for Northern Ireland. However, the constant slope coefficient for an organic subsoil indicates that for some soils a fixed relationship of 1:1 was defined in the data between the topsoil and subsoil SOC content. For all 57 cases of a soil with a subsoil SOC content >13% the ratio is 1.0. There are other clusters of regularly occurring ratio values, such as 96 cases of 6.89, 72 cases of 2.56, 64 cases of 8.95, or 40 cases of 4.43. The number of cases with a relatively high frequency of occurrence have in common that the frequency of occurrence is divisible by 4. This may indicate that a constant factor was applied to relate topsoil to subsoil SOC content rather indiscriminately of the land use type.

- *Scotland*

  The SOC content coefficients for Scotland differ notably from the results obtained for the other two regions in particular for organic soils. There would appear to be a relationship in SOC content between the topsoil and the subsoil SOC content for soils with an organic subsoil. Where peat occurs in the topsoil (SOC content >30%) no relationship with the subsoil SOC content could be identified. Although not evident from the graph also the Scottish data contains some ratio values of topsoil to subsoil SOC content with a high occurrence. There were 76 cases of 4.74%, 68 cases of 2.62% and 58 cases of 4.27%. No factual reason could be found explaining the similarity in the behaviour.

For reasons of comparability with other datasets the mean SOC content of the soil segment 0-100 cm was estimated from the topsoil and subsoil data (weighted mean). The parameters for a linear relationship between the SOC content in the topsoil and the soil segment 0-100 cm for the data of England & Wales was found to be:

$$SOC_{0-100} = 0.773 \times SOC_{TOP} \quad (r^2\text{: 0.68, 1,120 dF})$$

Despite a coefficient of determination of 0.68 it should be noted that integrating all soils into a single pool is not supported by the data. There is a distinctly different relationship in SOC content of the topsoil to the subsoil between mineral and organic soils in the dataset. This is visually apparent when comparing the topsoil to the subsoil SOC content (see Figure 63).

The data indicate that the SOC content of the subsoil allows estimating the topsoil SOC content to a larger degree than in the opposite direction, with regional differences. This association may provide a reasonable correlation between the topsoil and subsoil SOC content, but a low level of dependence of the subsoil SOC content from the topsoil.

In the regression analysis a distinction was made not only between mineral and organic soils, but also between the topsoil and the subsoil. Limiting the profiles to mineral soils in the topsoil the relationships for the data for England & Wales were found to be:

a) topsoil SOC content < 12%

$$SOC_{SUB}^{\min} = 0.399 \times SOC_{TOP}^{TOP<12} \text{ (r}^2\text{: 0.07, 1,052 dF)}$$

b) subsoil SOC content < 12%

$$SOC_{SUB}^{\min} = 0.131 \times SOC_{TOP}^{SUB<12} \text{ (r}^2\text{: -0.23, 1,078 dF)*}$$

c) topsoil and subsoil SOC content < 12%

$$SOC_{SUB}^{\min} = 0.205 \times SOC_{TOP}^{TOP+SUB<12} \text{ (r}^2\text{: 0.13, 1,031 dF)}$$

For largely organic soil sections the relationships were:

a) topsoil SOC content > 12%

$$SOC_{SUB}^{org} = 1.280 \times SOC_{TOP}^{TOP>12} - 15.6 \text{ (r}^2\text{: 0.56, 66 dF)}$$

b) subsoil SOC content > 12%

$$SOC_{SUB}^{org} = 0.684 \times SOC_{TOP}^{SUB>12} + 19.7 \text{ (r}^2\text{: 0.80, 40 dF)}$$

c) topsoil and subsoil SOC content > 12%

$$SOC_{SUB}^{org} = 0.507 \times SOC_{TOP}^{TOP+SUB>12} + 26.6 \text{ (r}^2\text{: 0.43, 19 dF)}$$

* Adjusted coefficient of determination quoted for y-intercept=0, which can be negative.

The distribution of the SOC content between topsoil and subsoil and results from the regression analysis suggest that deriving the SOC content of the subsoil from the topsoil alone would lead to unreliable estimates. When limiting the topsoil to mineral soils subsoils with organic material are included in the data and influence the relationship. Even when limiting topsoil and subsoil to mineral material the topsoil SOC content could not adequately explain the variation in the subsoil.

For soils with an organic subsoil the situation is different when profiles with mineral topsoils are also removed. For those soils the SOC content in the subsoil generally increases with the topsoil SOC content. There remains some distinction for soils with a topsoil SOC content either side of approx. 15% SOC content.

A detailed evaluation of the relationship between topsoil and subsoil SOC content for data from Northern Ireland was not performed. The extent of the pre-defined relationships in particular for organic soils could only find the factors used to associate the two soil sections (m = 1.0).

For the Scottish data the absence of a mineral topsoil over an organic subsoil in the dataset was notable. Such profiles were reported for England & Wales and Northern Ireland. Instead, the soil data for Scotland contain a substantial number of profiles with organic or peat in the topsoil over a mineral subsoil. This group of soils is hardly present in the data for England & Wales or for Northern Ireland.

For the mainly mineral soil components in the topsoil of the Scottish data the regression parameters were computed as:

a) topsoil SOC content < 12%

$$SOC_{SUB}^{\min} = 0.234 \times SOC_{TOP}^{TOP<12} \text{ (r}^2\text{: 0.12, 1,095 dF)}$$

b) subsoil SOC content < 12%

$$SOC_{SUB}^{\min} = 0.114 \times SOC_{TOP}^{SUB<12} \text{ (r}^2\text{: 0.03, 1,886 dF)}$$

c) topsoil and subsoil SOC content < 12%

$$SOC_{SUB}^{\min} = 0.234 \times SOC_{TOP}^{TOP+SUB<12} \text{ (r}^2\text{: 0.12, 1,095 dF)}$$

For largely organic soils the parameters were:

a) topsoil SOC content > 12%

$$SOC_{SUB}^{org} = 0.355 \times SOC_{TOP}^{TOP>12} - 3.8 \text{ (r}^2\text{: 0.23, 842 dF)}$$

b) subsoil SOC content > 12%

$$SOC_{SUB}^{org} = 0.820 \times SOC_{TOP}^{SUB>12} - 2.2 \text{ (r}^2\text{: 0.21, 57 dF)}$$

c) topsoil and subsoil SOC content > 12%

$$SOC_{SUB}^{org} = 0.820 \times SOC_{TOP}^{TOP+SUB>12} - 2.2 \text{ (r}^2\text{: 0.21, 57 dF)}$$

One result of the analysis is that in the profiles of the Scottish data the topsoil is always organic when the subsoil is organic. Other than this only the absence of a clear relationship could be pronounced.

A summary of the regression parameters for the regional datasets and separated by land use is given in Table 11.

Table 16: Parameters of Linear Regression between SOC Content of Topsoil and Subsoil for Mineral Soils(UK)

Regression Analysis	Slope Coeff.	Coeff. Determination r^{2*}	Lower Limit (95%)	Upper Limit (95%)
		England & Wales		
Arable	0.515	0.09	0.399	0.631
Forest				
Grass	0.398	0.10	0.318	0.478
Semi	0.342	0.05	0.259	0.425
		Northern Ireland		
Arable	0.146	-0.23	0.135	0.157
Forest	0.182	-0.01	0.169	0.194
Grass	0.178	0.07	0.164	0.193
Semi	0.182	-0.01	0.169	0.194
		Scotland		
Arable	0.252	0.28	0.236	0.268
Forest	0.181	-0.16	0.159	0.204
Grass	0.258	0.15	0.240	0.275
Semi	0.231	-0.06	0.211	0.251

* Adjusted r^2 quoted, which can be negative.

The coefficient of correlation between topsoil and subsoil SOC content did not reveal any tangible evidence of a relationship between the two soil sections. This lack of a connection is not caused by a small number of outlying points but by a general dispersion of the data.

Results of analysing the correlation between SOC content and depth in the SPADE/M and ISCRIC-WISE profile datasets have shown a tendency for a more pronounced decrease in SOC content with higher topsoil SOC content for a mineral subsoil. This development was investigated using the UK soil dataset based on the relationship between the topsoil SOC content and the ration of topsoil to subsoil SOC content. The results are graphically presented in Figure 64.

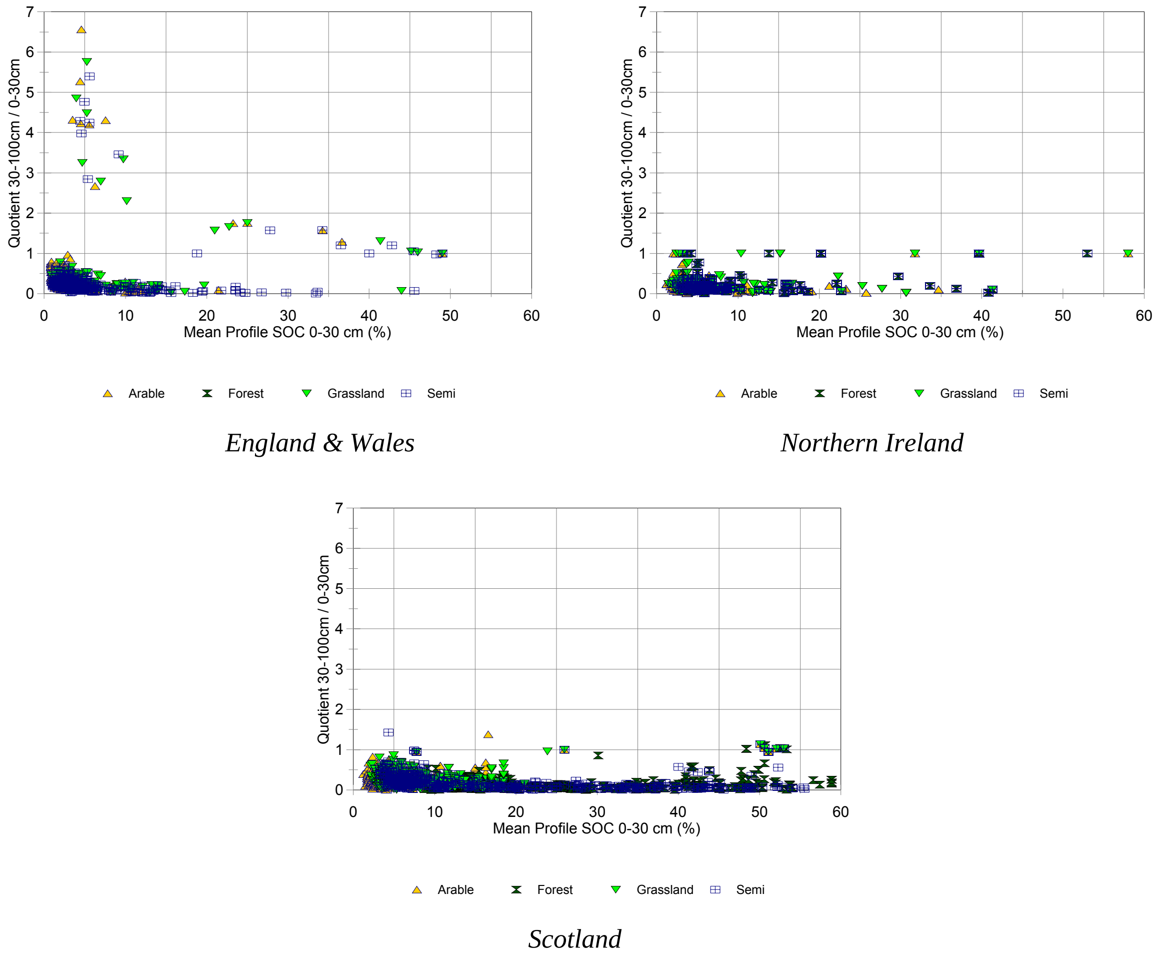


Figure 64: Relationship between Mean SOC Content and Coefficient for SOC Content (UK)

From the graph no relationship between the topsoil SOC content and the coefficient of the SOC content between layers could be deducted. Distinguishing between mineral and organic soil sections did not provide any additional information on an association linked to a particular land use type. The graph shows that for peat in England & Wales and Northern Ireland a comparatively uniform distribution of SOC content between the topsoil and the subsoil is recorded for the various soil types. For the soils in Scotland the presence of peat in the topsoil by itself does not allow formulating any assumption on the subsoil SOC content.

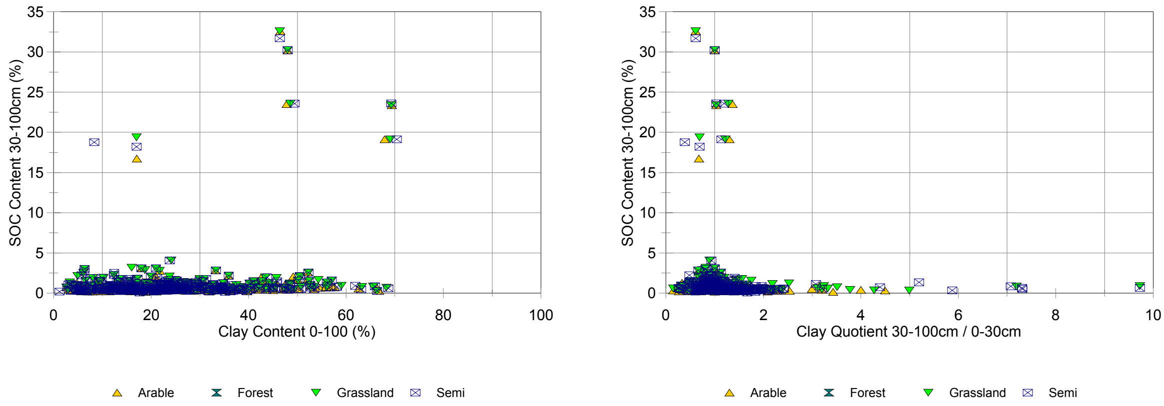
3.4.5 Influence of Depth of Soil

Changes in SOC content with depth can only be evaluated based on the mean values assigned to the topsoil and subsoil with fixed and uniform depth limits. The dataset available for the study did not contain information on typical profile depths for any soil type, although this parameter is specified in the accompanying document (DEFRA, 2003). It was therefore not possible to evaluate a relationship between the soil depth and the topsoil SOC content.

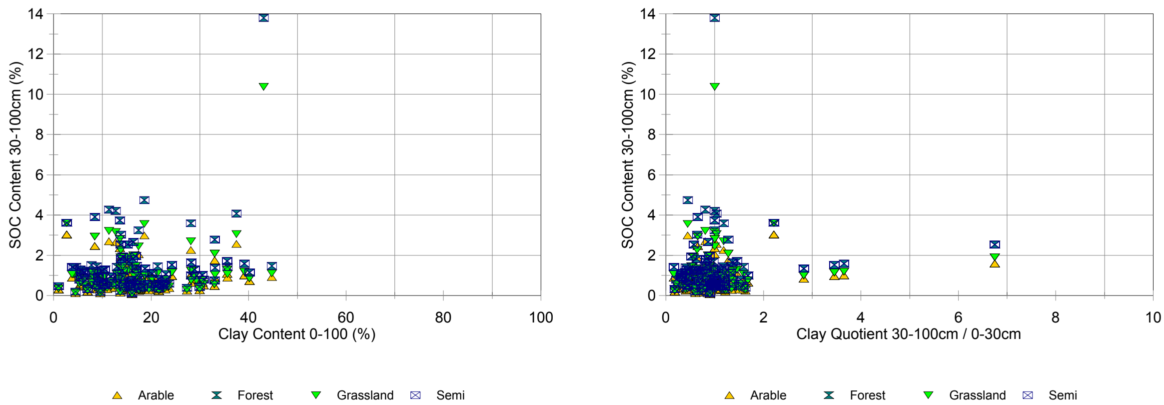
3.4.6 Influence Clay Content

An increase in clay content in deeper parts of the soil is linked to an increase in SOC content with depth. For the UK data the clay content in the soil segment 0-100 cm was estimated and compared to the subsoil SOC content. Furthermore, the change in clay content between the topsoil and the subsoil was related to the subsoil SOC content. The resulting data pairs are presented in Figure 65.

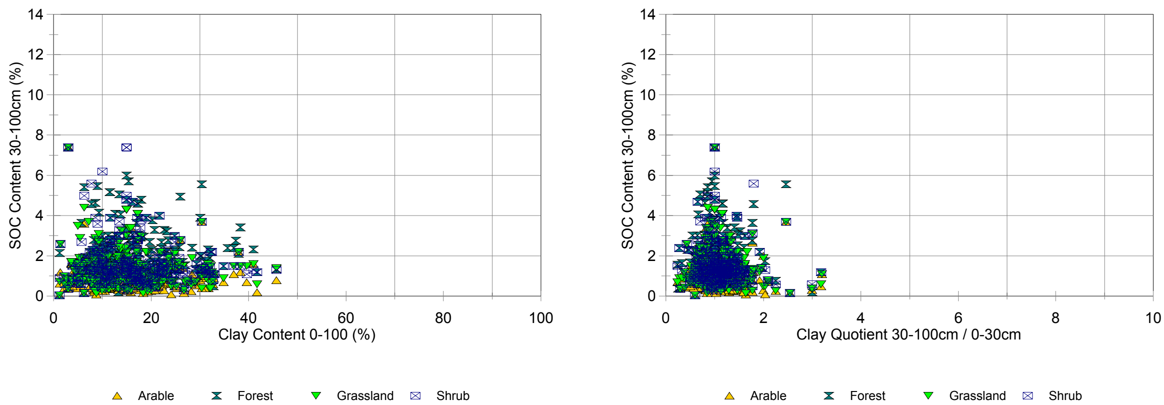
The relationships shown in the graph do not indicate any particular association between an increase in the presence of clay in the subsoil and the SOC content. The variation of the subsoil SOC content peaks around a coefficient of 1 and decreases with distance from a uniform SOC content between topsoil and subsoil layers. This behaviour is most notable in the graph for the soil data form Scotland, but also prevalent in the data from England & Wales and Northern Ireland.



England & Wales



Northern Ireland



Scotland

Figure 65: Relationship between Clay Content and Subsoil SOC Content and the Ratio of Topsoil to Subsoil Clay Content (UK)

4 SUMMARY AND CONCLUSIONS

The study investigated the vertical distribution of OC in sampled soil data from several independent databases with large-scale coverage. The vertical distribution of soil characteristic was assessed on the ground using different methods of delineating profile sections to which the data relate. Data from the SPADE/M and ISRIC-WISE datasets characterize the profiles as pedological horizons, thus describing sections with more or less homogeneous characteristics, while the data from the Forest Focus survey and the UK CO_2 Inventory use layers of fixed depth, which should describe the topsoil or subsoil layers used in this study more readily. The Forest Focus data posed a particular problem to the analysis by reporting the organic layer data without sufficient detail on the distribution of SOC content within the layer or the layer depth. A summary of the factors found to influence the function parameters when modelling the distribution of SOC content in the subsoil from the topsoil and any general conclusions which could be drawn from the evaluation are given below.

- **Profile Sampling Method**

  The rate of change of SOC content with depth was found to depend on the method used to sample the profile:

  - ***Profile Sampling by Pedological Horizons***

    Arranging the profiles by soil category the mean SOC contents in the topsoil and the subsoil for the surveys sampling pedological horizons are presented in Figure 66.

    The mean SOC contents for the SPADE/M profiles use the FAO85 classification while the ISRIC-WISE profiles are described following the classification scheme of FAO 90, which may explain some divergence between the data. For soils with mineral profiles the SOC content in the subsoil is approx. 33% of the SOC content of the topsoil. By contrast, for organic soils the SOC content in the subsoil is approx. 10% higher in the subsoil than the topsoil.

    For the study area the mean SOC contents and the relative value of the subsoil SOC content with respect to the topsoil value are more variable than the values given for SOC quantities at the global scale (see Figure 1). In the data used the relative SOC content in the subsoil ranges between 15 to 80% of the SOC content in the topsoil. For the major soil categories the variation is not related to the topsoil SOC content, as indicated by the figures from Batjes, 1996 on SOC quantity. This disparity could be due to the distribution of bulk density in the profile and the general decrease of bulk density with increasing g SOC content.

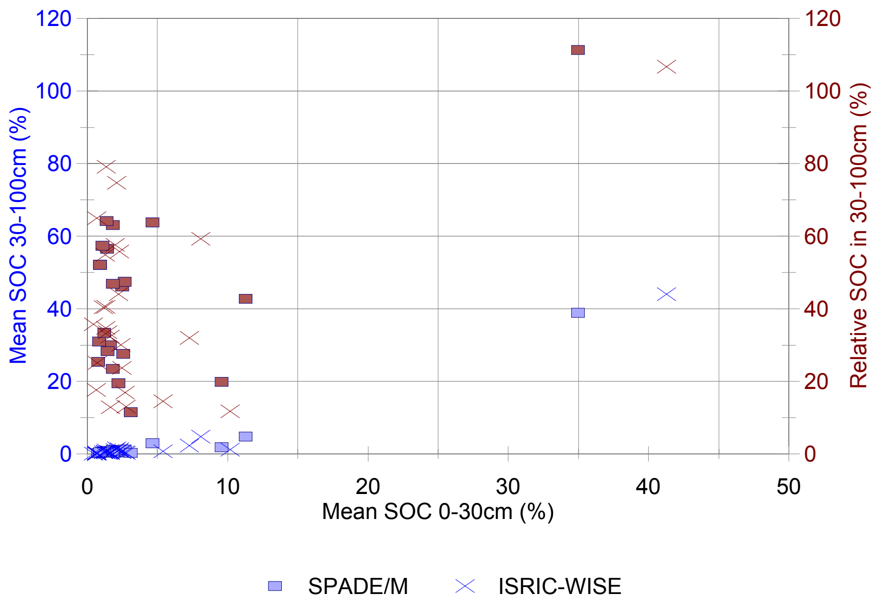


Figure 66: Relationship between Soil Organic Carbon Content in the 0-30 cm Topsoil Layer and the 30-100 cm Subsoil Layer for SPADE/M and ISRIC-WISE Major Soil Types

- ***Profile Sampling by Layers of Fixed Depth***

  The relationship between the mean SOC content in the topsoil and subsoil of profiles from Forest Focus Level I and Level II data are presented in Figure 67.

  Data from the ISRIC-WISE database for profiles under forest are added to the graph for reasons of facilitating comparability of the results. The Forest Focus data show distinctly lower values for the subsoil SOC content relative to the topsoil SOC content than the ISRIC-WISE profiles, which use the same soil classification scheme. This circumstance is attributed to the ambiguity with which the organic layer is sampled and recorded in the Forest Focus Soil Condition survey. The method of reporting the characteristics of organic layers was found to be a major shortcoming to the use of the data: For mineral soils the height of the organic layer severely restricted a description of the OC content with depth while organic soils are described by too few layers. The number of informative profiles was further reduced by limiting the sampling to the upper 20 to 30 cm. This restriction in the survey data almost completely excluded Level I from the analysis. A method of estimating the height of the organic layer by using a function relating SOC to bulk density was applied and tested. This method allowed computing rates of change of SOC content with depth, although some uncertainty remains with respect to the sampling method of the organic layer.

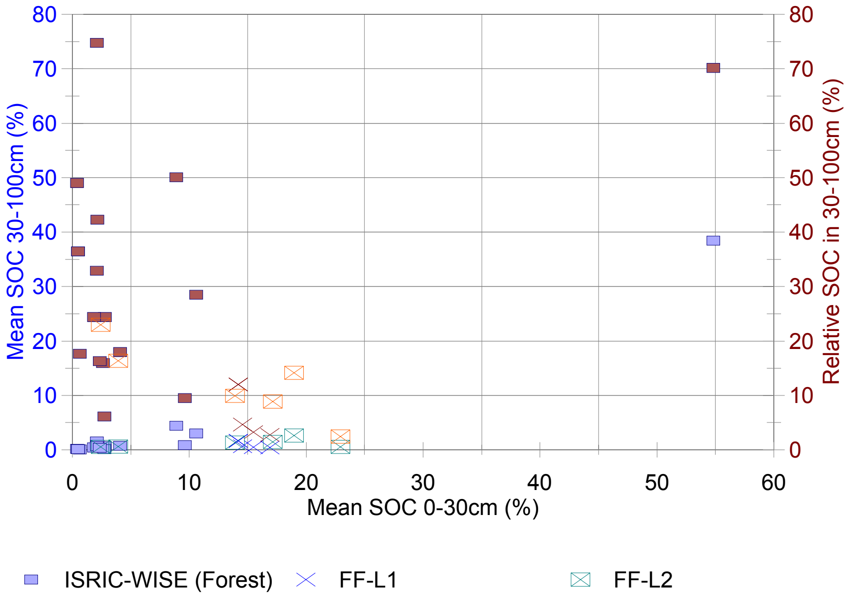


Figure 67: Relationship between Soil Organic Carbon Content in the 0-30 cm Topsoil Layer and the 30-100 cm Subsoil Layer for Forest Focus Level I and Level II and ISRIC-WISE Forest Profiles by Major FAO90 Soil Types

- ## Mineral vs. Organic Soil

The analysis of the distribution of the SOC content within a profile showed that the subsoil SOC content is unrelated to the topsoil SOC content for profiles with a change from mineral to organic soil. For profiles of either mineral or organic soils the change in SOC content with depth could be modelled by a function with a logarithmic transformation of the depth or the SOC content parameter. When transforming only the depth parameter a relationship between the coefficient describing the change in SOC content with depth and the SOC content in the upper 30 cm of the soil profile was found. A transformation of both depth and SOC content was found to describe the change in SOC content with depth of individual profiles with as much consistency as the transformation of the single factor, but the resulting function parameters were found to be unrelated to the topsoil SOC content.

While the rate of change of OC content with depth could be described by a linear function using a logarithmic transformation of depth the direction of the change was found to depend on the SOC content. In mineral soils the SOC content generally decreases with depth, whereas in organic soils it increases with depth. The actual rate of change was found to differ significantly with land use / cover.

- ## Influence of Land Use / Cover

  Distinct associations between the changes in SOC content with depth by land use were obscured by the prevalence of some land uses to occur on specific soil types. The pedological horizon data (SPADE/M and ISRIC-WISE) suggest that the coefficient of the change on SOC content with depth is largely determined by variations in the topsoil rather than the subsoil SOC content, where less variability in SOC content seems to exist. For mineral soils on arable land the coefficient characterizing the decreasing SOC content is lower than for soils under forest or grassland.

  - ***Arable Land***

    Under arable land the subsoil SOC content is approx. 70% of the topsoil SOC content for mineral soils.

  - ***Forest***

    For soils under forest a tendency for a more rapid decrease in SOC content from the topsoil to the subsoil was found, an effect which is mainly due to an organic upper layer. On average the subsoil SOC content under forest is approx. 25-30% of the topsoil SOC content.

  - ***Grassland***

    The general change in SOC content with depth under grassland is comparable to the one found for soils under forest, but with a larger variability in the topsoil SOC content between the SPADE/M and the ISRIC-WISE data than for soils under forest.

  - ***Shrub***

    For soils under shrub and other land uses the subsoil SOC content is on average 33% of the topsoil SOC content for mineral soils.

- ## Depth of Soil Stratum

  An influence of soil depth on the coefficient of the change in SOC content with depth has been observed when the profile SOC content was aggregated. The trend of a decrease in the rate of change of SOC content with deeper soils is rather the consequence of a decrease in the variability of the SOC content for deeper soils than an indicator of a relationship of the coefficient of the change in SOC content with depth with the subsoil SOC content for individual profiles.

- **Clay Content in Subsoil**

  The impact of the subsoil clay content on the coefficient describing the rate of change in SOC content with depth in aggregated data is a result of a decrease in the variability of the coefficient with clay content. When evaluating individual samples a strong decrease in the variability of the subsoil SOC content was found when the coefficient of change in clay content with depth increases. The SOC content seems to increase with clay content in the subsoil on soils where the clay content decreases with depth, but no relationship was found for soils where the clay content increase with depth.

The study found that the subsoil SOC content could be estimated from the topsoil SOC content by a function with a logarithmic transformation for the depth parameter. The applicability of such a function depends on

1. identifying soils with an abrupt change between mineral and organic horizons,
2. separating mineral from organic soils and
3. the availability of suitable land use / cover data.

Soils with abrupt changes in SOC content can be identified by the FAO class in the SGDBE. In the absence of a relationship of the SOC content between the mineral and organic horizons within a soil profile generalized values obtained from soils with a gradual change could be used. The depth at which the change in soil type occurs should be available to adjust the SOC content to the fixed depth of the topsoil and subsoil layers. For mineral soils with a more gradual change in SOC content with depth the subsoil SOC content in the 30-100 cm layer is approx. 27% of the topsoil SOC content under forest, 70% for arable land, 60% for grassland and 65% for all other areas. These values are only guides and have to be adjusted by the actual depth of the soil stratum. For organic soils and peat the SOC content generally increases with depth. The topsoil SOC content is loosely correlated with the subsoil SOC content but as a general rule the subsoil tends towards a SOC content of >30% on any organic soil.

No discernible relationship was found between the topsoil SOC content and the depth of the soil segment to an impermeable layer or rock for any land cover / use type. Such a relationship could be assumed based on a different water regime in deeper soils. However, investigating the relationship further requires analysing the data also by soil type, for which an insufficient number of samples was available in the data sets. Similarly, a widely applicable relationship between the clay content in the subsoil and SOC content could not be ascertained. The relationship seems to be affected by the change in clay content with depth. For the task of estimating the subsoil SOC content from the topsoil the depth of the soil stratum and the clay content the study did not uncover a serviceable function.

The study found few soils and pedological horizons with SOC content ranging between 6-20%. It was considered unlikely that the procedure for sampling soil data was biased against positioning sites on these soils in all databases and found more likely that the SOC content tends to be wither below 6% or above 18%. This lack of a transitional phase raises the question how SOC content reacts to changes in environmental conditions. A main factor determining SOC content is the soil water content, which was not taken into account in this study. Under the assumption of a steady-state between SOC content and environmental conditions, as used by IPCC (2003), the lack the absence of a transitional phase could indicate rather rapid changes in SOC content once a critical condition has been reached.

To improve the understanding of the interdependence between land use / cover, soil type and their combined effect on the distribution of SOC content with depth more data from samples data needs to be evaluated. In the assessment of the results changes in environmental conditions will have to be taken into account when data are analyzed which were collected at different dates.

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Abstract

While the major portion of organic carbon in the soil is concentrated in the upper 30 cm soil profile data show that significant quantities of OC can also be found at lower depths even in mineral soils. The subsoil layer of 30-100 cm layer is estimated to contain as much organic carbon as the topsoil layer (Batjes, 1996; FAO, 2001; Jobbagy & Jackson, 2000).

For the topsoil layer soil organic carbon content has previously been estimated at pan-European scale for the topsoil layer (Jones *et al*., 2005). In this study the possibility of advancing the existing methodology to allow estimating organic carbon in the subsoil layer to 100 cm was therefore investigated. Rather then developing a pedo-transfer rule for subsoil organic carbon content it was investigated whether the rule-based system could be substituted by a function linking the subsoil organic carbon content to the portion found in the topsoil. In the analysis the foremost factors influencing the change of organic carbon within a profile have been evaluated. To develop the function and the influence of the factors influencing the distribution of organic carbon within the profiles data from several databases were subjected to a statistical analysis.

The findings indicate that the organic carbon content of the subsoil layer varies to a much lesser degree that of the topsoil layer. The evaluation of the influence of land cover suggests that under forest the subsoil stratum amounts to approx. 25% of the topsoil value while for arable land the decline of organic carbon content with depth is shallower with approx. 55%, with soils under grassland and shrub land ranging in between. A marked difference in the distribution of organic carbon between the topsoil and the subsoil layer from profiles with mineral soils to those form organic soils was observed. For organic soils the organic carbon content generally increases with depth, in particular under arable land.

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