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Mapping Soil Properties for Europe – Spatial Representation of Soil Database Attributes

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List of Acronyms

Acronym	Description
AOI	Area of interest
BD	Bulk density
CA	Cellular automata
CLC2000	Corine Land Cover data 2000
CORINE	Coordination of information on the environment programme
EEA	European Environment Agency
EFSA	European Food Safety Authority
ESDB	European Soil Database
ETRS89-LAEA	European Terrestrial Reference System 89, Lambert Azimuthal Equal Area projection
GCS	Geographic co-ordinate system
GLC2000	Global Land Cover 2000 database
EU27	European Union of 27 Member States
FOCUS	Forum for the Co-ordination of pesticide fate models and their use
GIS	Geographic information system
GISCO	Geographic Information System of the European Commission
GLC2000	Global Land Cover 2000
HWSD	Harmonized World Soil Database
JRC	European Commission Joint Research Centre
MCE	Multi-criteria evaluation
MOLA	Multi-object land allocation
NUTS	Nomenclature des Units Territoriales Statistiques
OC	Organic carbon
SGDBE	Soil Geographic Database of Eurasia
SMU	Soil mapping unit
SOC	Soil organic carbon
SOTER	Soil and Terrain Database
STU	Soil typological unit
TAWC	Total available water content
VS	Volume of Stones
WGS 1984	World Geodetic System of 1984

1 INTRODUCTION

The most detailed and comprehensive set of data for soil properties with pan-European coverage is given by the *European Soil Database* (ESDB; European Commission Joint Research Centre, 2003). The ESDB is distributed through the European Soil Portal of the *European Commission Joint Research Centre*[1] (JRC). Since its publication ESDB data have been used in numerous projects. The structure of the database (1:n link of spatial to attribute database) and the scale of the data types (frequently nominal or ordinal) make it difficult to represent all information of the database to spatial layers. A practical solution to address the complexity of the database structure was to transfer the *spatial mapping units* (SMUs) to a raster format and to map only the properties of the dominant *soil typological unit* (STU; van Liedekerke *et al*., 2006)[2]. An attempt to allow representing a soil property from all STUs pertaining to an SMU in a single raster layer was made by mapping the STUs to geographic positions (Hiederer, 2013). Mapping STUs is an option of resolving issues related to the database structure for the spatial representation of soil properties. To change the scale type or extend the range of these soil properties additional information coming from other databases need to be employed.

A soil property database with a very similar structure to the ESDB is the *Harmonized World Soil Database* (HWSD; FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). For the area covered by the ESDB the properties are also closely linked. The HWSD, in all versions, uses data from the ESDB V2.0 for the delineation of the mapping units in the HWSD, which are directly taken from the *Soil Geographic Database of Eurasia* (SGDBE). The attribute data are in part based on the STU table of the ESDB.

Where the spatial layer of the HWSD is provided by the ESDB the geometry of the spatial layer of the HWSD should therefore match the corresponding data in the ESDB. For attribute data characterising soil properties the HWSD differs considerably from the ESDB. The ESDB contains information on the characteristics of the STU other than those strictly related to soil, such as elevation, slope and land use. Parameters typifying the soil are mainly found as qualitative data on nominal or ordinal scale. The range of parameters is broadened by using *Pedo-Transfer Rules* (PTRs) to derive estimates of additional parameter. For the HWSD the information related to the site characteristics of an STU has not been transferred from the ESDB. However, the range of parameters typifying a soil unit has been augmented by incorporating data form other sources, such as the *Soil and Terrain Database* (SOTER)[3].

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[1] Available from: http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDBv2/index.htm
[2] Home page:
http://eusoils.jrc.ec.europa.eu/ESDB_Archive/ESDB_data_1k_raster_intro/ESDB_1k_raster_data_intro.html
[3] Home page: http://www.isric.org/projects/soil-and-terrain-database-soter-programme

The information available form the ESDB tends to be more suited to characterise the site of a soil unit, including morphological conditions, while the information of the HWSD provides more detailed information on soil properties. With a common spatial layer the attribute information form both databases can be combined. This can be achieved by either transferring attributes to the spatial layer from each database and processing the data by spatial overlay functions of a *Geographic Information System* (GIS) or by processing the attributes using a database management system and then linking the output to a spatial reference layer. Both approaches have their limitations: Using the spatial overlay functionality to combine and process data from different databases requires complete correspondence of the geometry of the mapping units; processing attribute data asks for equivalence of parameters which are available in both databases.

The information on specific soil characteristics offered by the ESDB and the HWSD may be combined to produce estimates of soil properties, which are not readily available from the databases. In the absence of mapped STUs such derived soil properties largely rely on using only the soil information available for the dominant STU of a mapping unit. Aggregating the information for a specific soil property from all STUs linked to a single representative value for a mapping unit by a weighted average is limited to parameters available on ratio or interval scale. Even where the data type of a soil property allows computing a mean value the method of aggregating the STU values for a mapping unit is limited to those mapping units where the linked STUs are of comparable characteristics. In cases where the characteristics of the STUs linked to a mapping unit are not comparable, for example when areas of soil are combined with non-soil areas, an aggregated value may still be computed but meaningless. When derived soil properties use non-linear functions to combine parameters a linear aggregation of STU values, such as using a proportional distribution based on the share of the STUs within a mapping unit, leads to different results from first producing the derived soil property for each STU and then aggregating the derived property values. Another aspect of statistically aggregating data for a mapping unit is the lack of information on the position of an STU within the area covered by the mapping unit. This may be of consequence where the derived property depends on the position in the landscape or where the value of the property depends on the properties of the neighbouring areas. To provide a measure of the effect of using the information of all STUs linked to a mapping unit to produce a derived soil property instead of only the information given for the dominant STU the soil available water content was estimated using different processing options.

2 BASIC LAYERS

The spatial frame of the raster data is set to cover all 27 Member States of the European Union and covers acceding countries, candidate countries, such as Iceland and Turkey, and potential candidate countries. The spatial layers are projected according to the *European Terrestrial Reference System 89, Lambert Azimuthal Equal Area* (ETRS89-LAEA) projection (Annoni, *et al*., 2001). The resolution of the grid is 1,000 m. The spatial frame properties are presented in Figure 1.

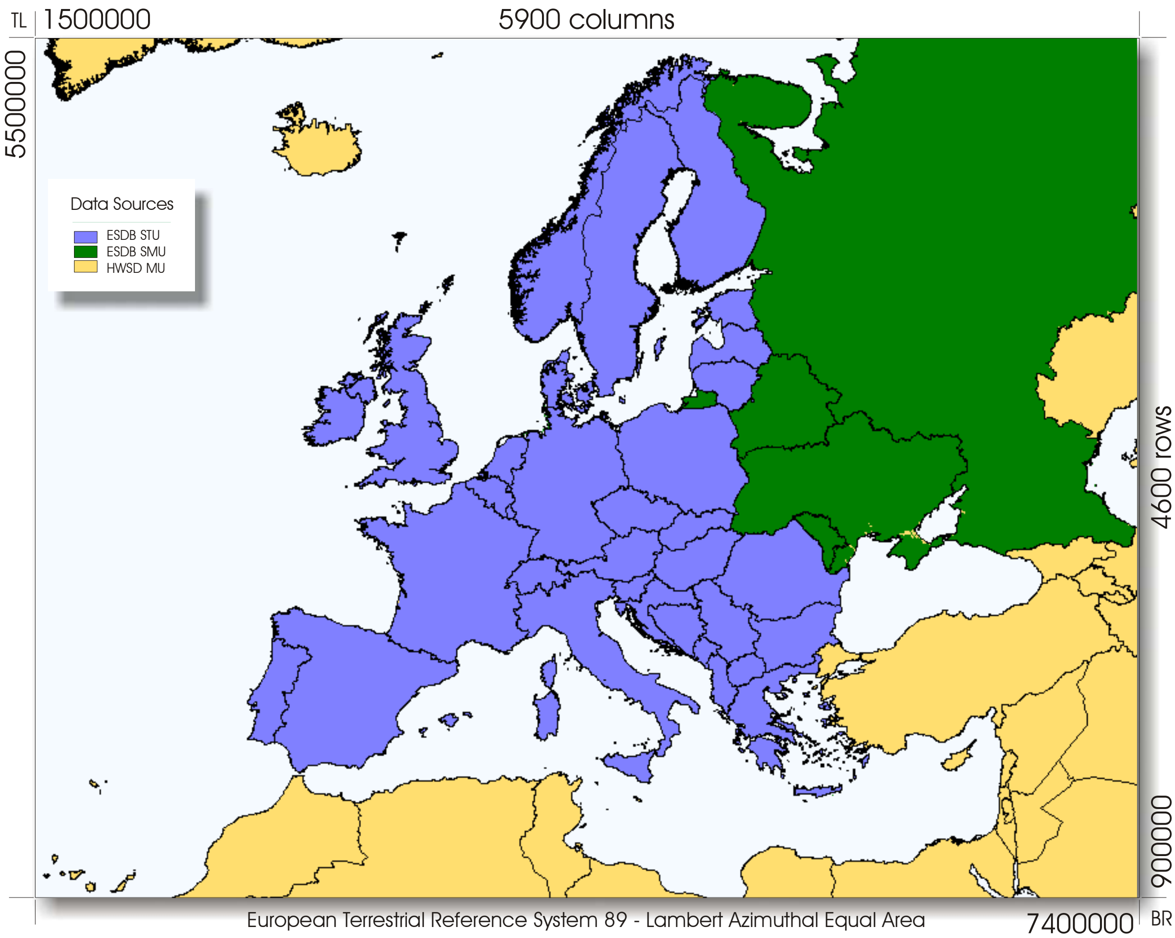


Figure 1: Spatial Frame Properties of Soil Attribute Layers

The spatial frame thus covers 5,900 columns by 4,600 rows. The area covered and the layer geometry is thus compatible with the Corine Land Cover data from the *European Environment Agency* (EEA; EEA, 2010) and the EFSA V.1.1 data from the *European Food Safety Authority* (EFSA; Hiederer, 2012).

Country borders and the land / sea boundary originate from the Eurostat *Geographic Information System of the European Commission* (GISCO) [4] reference data for administrative boundaries GISCO.CNTR_RG_01M_2010 (Eurostat GISCO, 2012) The land / sea boundary was generated from the layer by merging all country areas. For the area covered the result is equivalent to using the layer GISCO.COAS_PL_01M_2010. The scale of the 1:1,000,000 was considered adequate for use with the ESDB data. The boundaries integrate with the GISCO *Nomenclature des Units Territoriales Statistiques* (NUTS) boundaries [5] and allow extracting and combining information for administrative units.

For processing the data a larger area is used, from which the attribute layers are extracted. This avoids generating artefacts at the limits of the frame, for example when filling-in areas without data.

The attribute data are assigned to three layers of spatial units. The layers are:

- ***ESDB STU***
  Mapped STUs of the ESDB
- ***ESDB SMU***
  SMU layer of ESDB, using dominant STU data
- ***HWSD MU***
  MU layer of HWSD, using dominant SU data

Soil properties are assigned to these layers in the order given. The mapped STU layer is given priority to using dominant STUs and the ESDB is given priority to the HWSD, where appropriate.

[4] Home page: http://epp.eurostat.ec.europa.eu/portal/page/portal/gisco_Geographical_information_maps/introduction
[5] Home page: http://epp.eurostat.ec.europa.eu/portal/page/portal/nuts_nomenclature/introduction

3 GEOMETRY OF SPATIAL UNITS

With respect to the general structure of the HWSD and the ESDB bear some similarities. Both use a single spatial layer of mapping units and one or several tables containing the attributes of the mapping units. The relationship between the map units and the attribute data is 1:n, i.e. more than one attribute may be linked to a spatial unit.

Fundamentally different is the data format of the spatial layers: the HWSD uses a raster format while the ESDB presents the spatial mapping units in vector format.

3.1 HWSD MU Raster Layer

The spatial data of the HWSD consists of a single raster layer in a generic binary format (*Band Interleaved by Line* (BIL)). The grid resolution of the raster layer is 30 arc second, which corresponds to approx. 1 km at the Equator. The layer consists of 43,200 columns by 21,600 rows. The nominal coverage of the layer is global (Longitude: -180 to +180 deg; Latitude: -90 to +90 deg). When converting the BIL data to another format the settings for the minimum and maximum values depend on the GIS package used.

- The OpenEV viewer (OpenEV 1.8, © 2000 Vexcel Canada Inc., www.vexcel.com, using FWTools 2.4.7, http://FWTools.MapTools.org) sets the minimum longitude to -180.089999 deg.
- For Idrisi the meta-data are given in Table 1, Annex 3 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

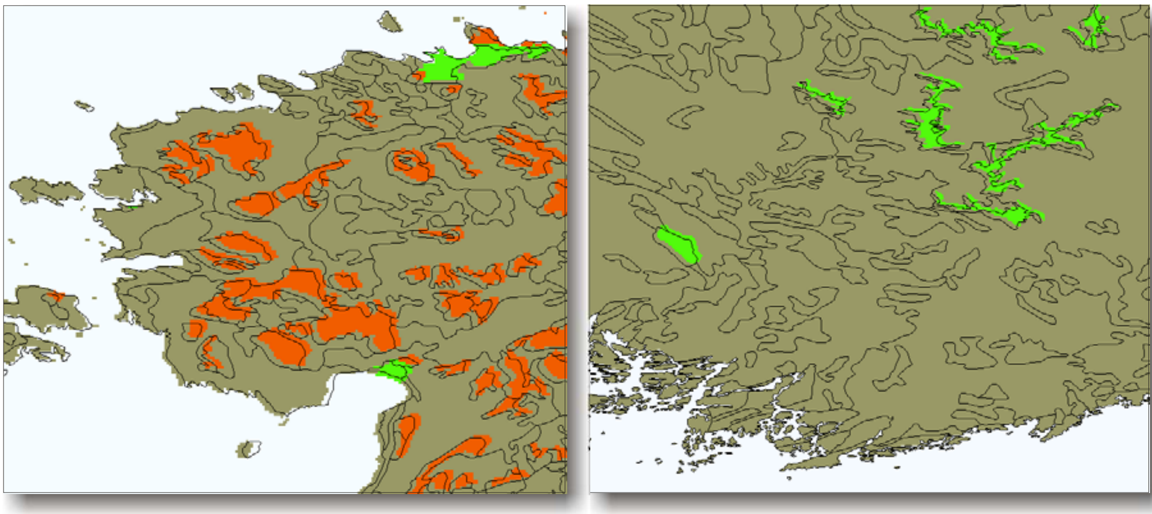
The spatial layer uses *geographic co-ordinate system* (GCS), i.e. no projection, but the datum is not specified. The data were processed applying the *World Geodetic System of 1984* (WGS 1984).

3.2 ESDB SGDBE Vector SMU Layer

The spatial layer of the ESDB is part of the SGDBE. It contains the SMUs as a vector file in Shape format. The data are presented in a GCS with WGS 1984 as datum.

3.3 Comparison of Spatial Layer Geometry

According to the documentation of the HWSD all spatial mapping units were available in vector format. To generate the raster layer these vector data were rasterized and merged to the global layer. When overlaying the vector layer of the ESDB with the HWSD raster layer some geographic changes in the geometry of the spatial units were observed. While the coastlines generally match there are shifts of about 2 pixels in latitude direction in some areas for inland features. The best matches are found for countries in the centre of the *area of interest* (AOI), such as Germany, Switzerland and Italy. Differences in the geometry increase with distance from this region. It appears that the coastline was adjusted to the extent of the spatial layer of the SGDBE, but not the inland features. Regions where also the geometry of the ESDB was problematic are the features in Estonia, Latvia and Lithuania. In particular for Estonia a shift of about 3 columns between the spatial layers of the HWSD and the SGDBE exists for the coastline and the inland features. For Finland the coastline matches, but inland features show a shift of several columns in longitudinal direction. The situation is presented for sub-areas of Estonia and Finland in Figure 2.



a) coastal and inland feature shift *b) inland feature shift*

Figure 2: Geographic shift in spatial layer of Mapping Units between HWSD and ESDB

As a consequence of these differences between the two data sets in the geometry of the spatial layers it seems advisable to avoid generating spatial data of soil attributes from mixing the two representations of the soil mapping units. For the purpose of generating a single spatial layer of mapping units from the SDGBE and the HWSD the HWSD was re-sampled to match SGDBE. For areas outside the coverage of the SGDBE the ground control points were set using the *Global Land Cover 2000* Database (GLC2000)[6] of the JRC. The geometrically adjusted HWSD was generated from the projected layer using a 2nd order polynomial and nearest neighbour re-sampling.

3.4 Linking Spatial Mapping Units of ESDB and HWSD

The spatial units of the ESDB can be linked to the mapping units of the HWSD by the field [MU_SOURCE_1.HWSD_DATA]. Attributes can be linked on the field [MU_SOURCE_2.HWSD_DATA]. When linking a field of the ESDB table containing the code for the spatial unit (e.g. [SMU.SMU_SGDBE]) to the field in the HWSD containing a reference to the code ([MU_SOURCE1.HWSD_DATA]) the data type of the fields providing the join may have to be adjusted to correspond to the same type. To cater for the codes of some spatial units outside the AOI the data type of the field MU_SOURCE1 is alpha-numeric, while the data type of the field SMU is numeric.

The coding of spatial units covering areas devoid of soil of the HWSD differs from the ESDB. A list of the codes is given in Table 1.

Table 1: Coding of Areas Devoid of Soil in the ESDB and the HWSD

ESDB		HWSD		Label
SMU	FAO85_FU	MU_ GLOBAL	SU	
Code	*Symbol*	*Code*	*Symbol (Code)*	
-2	-	7000	NI (34)	No data
1	111	7001	UR (32)	Urban, mining, etc.
2	222	-	-	Soil disturbed by man
3*	333	7003	WR (31)	Water body
4	444	-	-	Marsh
5*	555	7005	GG (35)	Glaciers
**	666	**	RK (29)	Rock Outcrop
	-	**	DS (30)	Sand Dunes
	-	**	ST (33)	Salt Flats
	-	**	IS (36)	Island

* *plus other SMUs*
** *no spatial unit code matching symbol*

[6] Available from: http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php

The codes of distinct spatial units of the ESDB for non-soil areas are found in the HWSD mainly by adding a value of 7000. Delineated areas without specific data (value -2 in SGDBE4_0) is translated into code "*7000*" in the HWSD. There is no symbol for "*Soils disturbed by man*" of the ESDB in the HWSD. Therefore, areas with codes "*7001*" and "*7002*" are described by the same symbol ("*Urban, mining, etc.*"). Spatial units of the ESDB for "*Water bodies*" and "*Glaciers*" can be linked to corresponding units in the HWSD.

Inconsistent with the coding of non-soil areas are "*Rock outcrops*". Such areas are generally not distinct but occur in a mixture with other surface types. In the table HWSD_DATA the spatial unit of the ESDB with code "4" is linked to the mapping unit with the code "*7004*". However, the mapping unit is linked to a *Histosol* (*HSf*), probably because the ESDB code specified marsh for the areas, which is not a category in the HWSD. Other non-soil areas of the HWSD have no direct correspondence in the ESDB.

The situation of linking non-soil areas of the ESDB with those of the HWSD for the AOI is made more complex by the invalid assignment of some areas in the ESDB.

- **Austria**
  Mixed areas of "*Rock outcrops*" and "*Glaciers*" also cover lakes.
- **Sweden**
  Lakes in Sweden are specified as "*No data*", the same as some islands.
- **Switzerland**
  There is confusion between areas of "*Urban, mining, etc.*" and "*Water bodies*" and *Histosols* (class "*Marsh*" in ESDB).

The invalid assignments of areas to codes of the ESDB have been carried through to the HWSD. Corrections of the codes are made to the spatial layer rather than the attribute tables.

The differences may be of limited practical consequence, because the areas concerned do not refer to developed soils, except for assigning *Histosols* to urban areas in Switzerland, such as Basel. Urban areas cover soils and may not be considered as completely sealed areas. For this reason the spatial units containing soil are extended to cover also urban areas.

Other than the consistent representation of non-soil areas within the soil databases is the corresponding occurrence of these areas with land use and cover data from other sources when integrating spatial layers for thematic analyses. The land use and cover data considered here is the *Corine Land Cover data 2000* (CLC2000)[7] of the *European Environment Agency* (EEA) for EU27 and the *Global Land Cover 2000* Database (GLC2000)[8] of the JRC for the pan-European cover.

CLC2000 classes relating to non-soil areas of the ESDB are presented in Table 2.

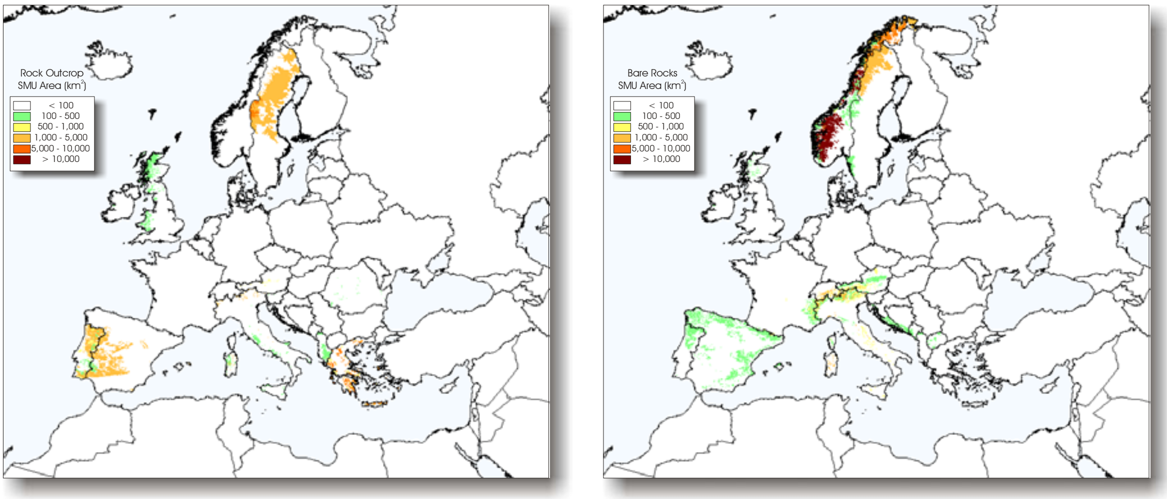
[7] European Environment Agency, Kongens Nytorv 6, 1050, Copenhagen K, Denmark.
Home page: eea.enquiries@eea.europa.eu
[8] Available from: http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php

Table 2: Relating non-soil areas of Corine 2000 Land Cover Classification to ESDB Classes

Corine Level 3		SGDBE FAO85	
Code	*Label*	*Code*	*Label*
332	Bare Rocks	666	Rock outcrops
335	Glaciers and perpetual snow	555	Glacier
411	Inland marshes	444	Marsh
421	Salt marshes	444	Marsh
511	Water courses	333	Water body
512	Water bodies	333	Water body

For all artificial surfaces and areas with soil disturbed by man no relation is established, because for these areas a soil is approximated. Areas of glaciers, marshes and water bodies are generally defined in the SGDBE as SMUs with a single STU. Thus these areas form one more or less compact but generally connected unit. This is not the case for areas of "Rock outcrops". In the SGDBE rock outcrops are defined by an FAO85 code and STUs, but not as an SMU. To provide some measure of geographic location of the areas the location of rock outcrops is estimated by the allocation procedure (Hiederer, 2013). Land cover information from CLC2000 is used to guide the allocation procedure, but the demands for area are specified by the SGDBE, not the land cover data.

For the area common to both data sets the total part covered by the class "*Rock outcrops*" is 37,958 km^2 and 46,560 km^2 by the class "*Bare rocks*". While the area of "*Bare rocks*" in CLC2000 is approx. 23% larger than the area of "*Rock outcrops*" in the SGDBE, the area where both occur within an SMU is 4,557 km^2. Where the proportion of rock outcrops for an SMU differs significantly between the data sets the geographic locations are spatially dispersed with a low correlation of the positions between the data sets. The areas of the class "*Rock outcrops*" in the SGDBE and the areas of the class "*Bare rocks*" of CLC2000 is presented in Figure 3.



a) SGDBE "Rock outcrops" *b) CLC2000 "Bare rocks"*

Figure 3: Areas of SGDBE class "Rock Outcrops" and CLC2000 class "Bare Rocks" in SMU

The graph shows a lack of spatial correlation of the classes between the two data sets. For the regions with areas of either class > 5,000 km^2 (Portugal, Spain, Greece, Norway and Sweden) some spatial correlation was found only for Portugal. Reasons for the variations differ. For SMUs in Norway the bare areas in CLC2000 are specified as *Lithosols* without information on depth, in Portugal and Spain areas of "*Rock outcrops*" seem to have been classified also as "*Sparsely vegetated areas*" in CLC2000.

The differences in the spatial distribution of areas without soil between the ESDB and the land use and cover data evaluated in this survey cause some areas with vegetation cover to be located on non-soil areas. As a consequence, no soil property data are available for those areas.

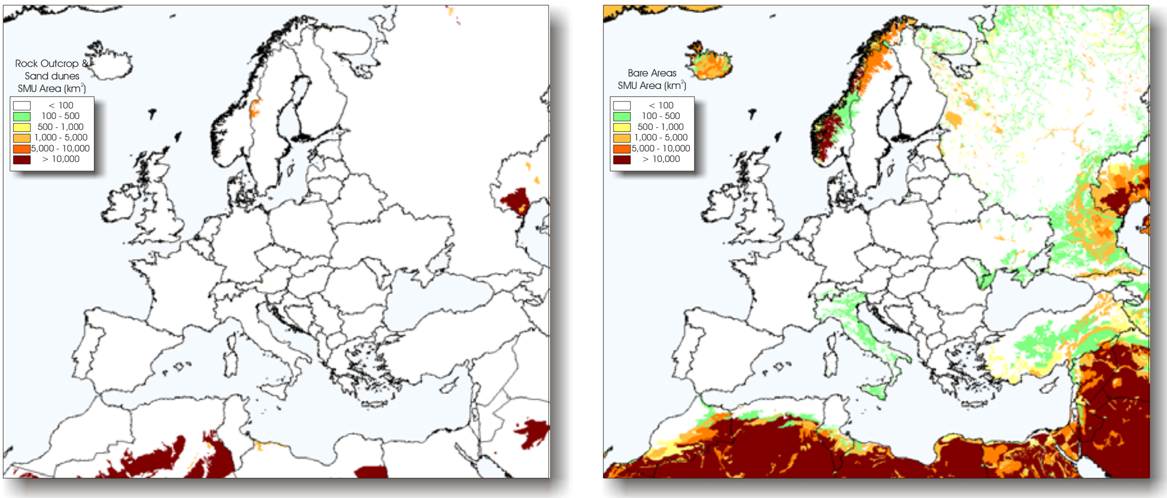
A more complex situation of the presence of non-soil areas exists between the HWSD and GLC2000. The correspondence between the respective classification systems is given in Table 3.

Table 3: Relating non-soil areas of Global Land Cover 2000 to HWSD Classes

	GLC2000 Classes		HWSD Symbol
Code	*Label*	*Code*	*Label*
19	Bare areas	RK	Rock outcrops
19	*Bare areas*	DS	Sand dunes
19	*Bare areas*	ST	Salt flats
20	Water bodies	WR	Water bodies
21	Snow and ice	GG	Glacier

In the HWSD "*Water bodies*" are linked to a single typological unit, as are areas specified as "*Glacier*", with the exception of MU 9667, where it amounts to 50% of the mapping unit. For "*Bare areas*" of the GLC2000 more than one class is likely to correspond in the HWSD ("*Rock outcrops*", "*Sand dunes*" and "*Salt flats*"). Areas of "*Salt flats*" are represented in the HWSD as a single mapping unit. Areas of "*Rock outcrops*" and "*Sand dunes*" generally share the mapping unit with other land cover or soil types. Therefore, their geographic position is uncertain and it may be presumed that they are spatially dispersed within the mapping unit.

The distribution of the areas in the HWSD where the dominant MU consists of "*Rock outcrops*" or "*Sand dunes*" and "*Bare areas*" of the GLC2000 is presented in Figure 4.



a) Dominant HWSD "Rock outcrops" and "Sand dunes"

b) GLC2000 "Bare areas"

Figure 4: Areas of dominant HWSD classes "Rock Outcrops" and "Sand dunes" and GLC2000 class "Bare Areas" in MU

The limited occurrence of classes "*Rock outcrops*" and "*Sand dunes*" in the HWSD is a result of mapping only the dominant symbol class of an MU. For the area covered 21 MUs have "*Rock outcrops*" as the dominant land cover and 12 have "*Sand dune*s". The share of these land cover types exceeds 50% of the MU area for 12 MUs. Therefore, when using the dominant typological unit of the HWSD in combination with GL2000 data soil properties may frequently be associated with bare areas of the land cover data set, but not vegetation with non-soil areas.

4 SOIL PROPERTIES IN ESDB AND HWSD

Attribute data of the ESDB and the HWSD are linked on the combined key composed of the SMU and STU fields. For the *area of interest* (AOI) 5,522 records in the ESDB are thus defined. All records can be linked to a corresponding record in the HWSD_DATA table.

4.1 Data Completeness

While the links between the data sets are complete, the spatial units shows areas of missing soil data and the records in the typological database on soil data contains items of missing information.

4.1.1 FAO 85 Soil Type

The parameter with the highest degree of completeness in the ESDB is the FAO 85 soil type ([FAO85FU.STU_SGDBE]). This is also the most prominent field for the conditions set for the PTRs. The corresponding field in the HWSD is [SU_SYM85.HWSD_DATA].

Of the 5,522 records 57 relate to areas not covered by soil in the ESDB (marsh: 1; glacier: 3; rock outcrops: 53). The non-soil surface cover classes of the HWSD (*Human disturbed soil* (HD), *Urban, mining, etc.* (UR), *Marsh* (MA), *Water bodies* (WR) and Not surveyed (NS)) have no correspondence in the ESDB. The label "*No Data*" has the code *NI* in the dictionary table of the HWSD D_SYMBOL85), but in the field codes *NI* and *ND* are found. While the code *NI* does not link to any entries in the ESDB for the AOI, the code *ND* is linked to two codes of the ESDB (*Dc*: 8 instances; *Io*: 1 instance). For differences concerning non-soil areas there is one case affecting a single STU where a non-soil cover of the ESDB (Code: 444, *Marsh*) has an entry of "*Od*" (*Dystric Histosol*) in the HWSD.

For soil typological units with soil cover the entries recorded in the HWSD should match those of the ESDB. Yet, when comparing the data for the FAO 85 soil types seven combinations showing different soil types were found. A list of the combination with the number of STUs affected is presented in Table 4.

Table 4: Different FAO 85 Soil Types Between HWSD and ESDB for Area of Interest

HWSD *SU_SYM85.HWSD_DATA*	ESDB *FAO85FU.STU_SGDBE*	STUs Affected *No.*
Be	R	1
I	Io	6
Jc	Dc	1
ND	Dc	8
ND	Io	1
PS	p	5
U	Uo	1

The seven combinations of differences in soil type affect 23 STUs. For three combinations (12 STUs) the difference in soil type may be considered minor. The code "*Dc*" in the field [FAO85FU] of the ESDB STU table is not defined as an FAO 85 code. In 8 out of 9 cases the soil type in the HWSD is "*ND*" (not defined). To be consistent, all entries of the soil type "*Dc*" in the ESDB should be marked as "*no data*" in the HWSD.

The correspondence of the five instances of "*PS*" in the HWSD to "*p*" in the ESDB refers to *Plaggensol*. This correspondence is complete for the AOI. There thus remain three instances (*Be* – *R*, *Jc* – *Dc* and *ND* – *Io*) where the change in soil type may be of consequence and could not be explained.

4.1.2 Areas Devoid of Soil

The STUs of the ESDB and the MUs of the HWSD specify areas devoid of soil for discrete or complex spatial units. A comparison between the nominal codes used for the spatial units and the typological data in the ESDB and the HWSD is given in Table 1.

When integrating the soil attribute layers with other spatial layers of thematic data, such as land use and cover, the extent of the non-soil areas should agree. Common land use and cover layers are

- CORINE Land Cover 2000 (CLC2000)[9] data from the EEA;
- Global Land Cover 2000 database (GLC2000)[10] , European Commission, Joint Research Centre, 2003 (Fritz, *et al*., 2003).

The area of the mapped STUs is largely covered by the CLC2000 data. The data set provides the most detailed and comprehensive analysis of land cover

[9] Download page: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-raster-2
[10] Home page: http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php

/ use for the area. Most areas were updated in 2006, at the time of writing data for Greece were not included. However, areas devoid of soil are not expected to change between the years and the status of 2000 would appear to be suitable. A land cover / use layer with a spatial resolution of 1,000m was generated from the 250m CLC2000 data at Version 16 (04/2012). The data were re-sampled using a majority filter rather than sampling every n^{th} pixel. The result shows the dominant land use / cover for 16 grid cells. It is thus biased against land use / cover types with relatively rare and scattered occurrence, but should be apt to be combined with data from the soil databases.

The global product GLC2000 V.1.1 data is used where no CLC2000 data are available. A comparison of the legend items for areas considered devoid of soil is presented in Table 5.

Table 5: Coding of Areas Devoid of Soil in the ESDB, HWSD, CLC2000 and GLC2000 Legends

ESDB	**HWSD**		**Corine**		**GLC2000**	
FAO85_FU	**SU**		**Level 3**		**Global**	
Symbol	***Symbol***	**Label**	***Code***	**Label**	***Code***	**Label**
333	WR	Water body	511	Water courses	20	Water bodies
			512	Water bodies		
			513	Coastal lagoons		
			514	Estuaries		
444	-	Marsh	411	Inland marshes		
555	GG	Glaciers	335	Glaciers and perpetual snow	21	Snow and ice
666	RK	Rock Outcrop	332	Bare rocks	(19)	Bare areas
	DS	Sand Dunes	331	Beaches, dunes, sands		
	ST	Salt Flats	422	Salines		
	IS	Island	-			

Level 3 of the Corine legend mostly corresponds to a legend of the soil databases. For water bodies the CLC legend is more detailed, but individual categories are within the definition of the soil category. The global legend of the GLC 2000 is more general than the other legends. There is no separate category for inland marshes and the category "*Bare areas*" is less distinct than in the soil or the CLC legend.

Combining the categories for non-soil areas of the land use / cover legends with those of the ESDB or the HWSD is not as straight forward as it may seem. An obstacle posed by the soil data is the lack of identifying distinct areas of "*Rock outcrops*". Except for one SMU in the AOI the surface category is only found mixed with other, mainly soil, categories. Areas specified as glaciers in Switzerland contain large portions of rock in CLC2000. The areas of mixed cover of glacier and bare rock in Austria mainly cover glaciers (and lake areas in the unadjusted data). As a consequence, the procedure for mapping STUs also maps areas classified as "*Rock outcrops*". Otherwise the resulting layer would contain only the one SMU with the category as a sole link. Obstacles posed by the land use / cover data mainly concern the GLC 2000 legend. For the CLC legend detailed categories of water bodies can be merged and the categories "*Beaches, dunes, sands*" and "*Salines*" are only specified in the HWSD. The global legend for GLC 2000 uses a very broad category "*Bare areas*". The category should cover "*Sand Dunes*" and "*Salt Flats*" in the HWSD. There is some confusion of "*Sand Dunes*" in the HWSD and "*Sparse Herbaceous or Sparse Shrub Cover*" in the GLC2000 for areas north of the Caspian Sea.

4.1.3 Areas Devoid of Soil Data

Beside areas devoid of soil there are also regions in the spatial layer where soils can be expected to be present but where corresponding links to with STUs with soil properties in the typological database are missing. The spatial units concerned are almost exclusively covered by urban land cover. To cover such areas with soil property data a simple procedure was introduced (Hiederer, 2013). The procedure is based on an anisotropic friction of soil properties where the friction is given by the direction and magnitude of the local slope angle.

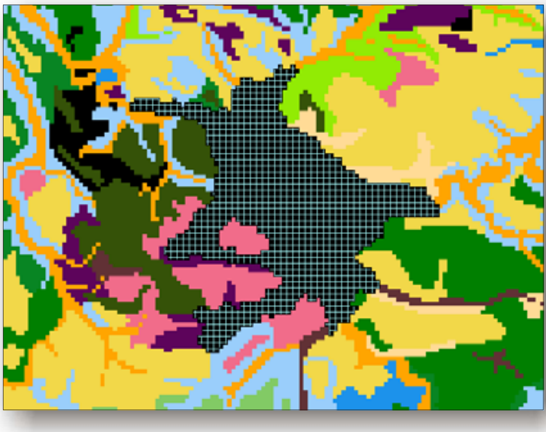
For larger areas a different and more elaborative method is applied, which consists of combining a Markov chain analysis for land transitions with a *multi-criteria evaluation* (MCE) and subjecting the transition probabilities and area demands to a procedure which combines *cellular automata* (CA) with *multi-objective land allocation* (MOLA). The method uses the properties of all spatial units with soil data neighbouring the area with missing data, not only the local neighbours, and the association of spatial units with topographic variables by combining .

The transition probability matrix of the Markov chain analysis uses the distribution of the spatial units neighbouring the area of missing data within a distance of 3 pixels. From the probability matrix demands for area in the zone of missing data are calculated for each spatial unit. The transition suitability of a spatial unit is estimated from the association of each unit with elevation, slope and distance to the flow network within a distance of 20 pixels from the missing data area. To estimate the suitability of an area for a spatial unit fuzzy membership functions are defined, J-shaped symmetrical for elevation and slope and asymmetric for the distance-to-flow network parameter. For elevation the central control point of the function is given by the mean and the mode, whereas the function for the slope factor uses the mean for both control points. The outer control points are set at one standard deviation form the inner control points. For the distance-to-flow network factor the mean and one standard deviation are used to define the control points.

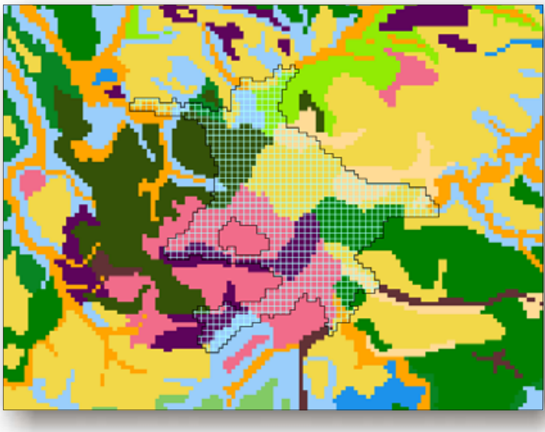
The membership functions for the factors are combined into a suitability map using MCE with a weighted linear combination for factors. The weight for the elevation factor is set to 0.40 and to 0.30 for the slope and distance-to-flow network factors. The allotment of spatial units follows the CA / MOLA procedure, which maximised the overall suitability of an object in cases of conflicts for demands for an area. The proportion of the spatial units within the buffer area may not be the same as the proportion of spatial units in the zone of missing data. Therefore, the area demands should not be based on the proportion of spatial units in the buffer area. An initial estimate of the proportion of spatial units in the zone of missing data is obtained from a minimum distance classification with a normalized distance and using the neighbouring area as training sites. For subsequent runs the area demands are derived from the Markov transition probability matrix obtained from comparing the allocations of spatial units made during previous runs.

The method can be implemented with a single demand for areas for the total zone of missing data or by advancing from the borders of existing spatial units to the centre of the zone with missing data. The first option is simpler to implement while the second option resets the demands for area with every step.

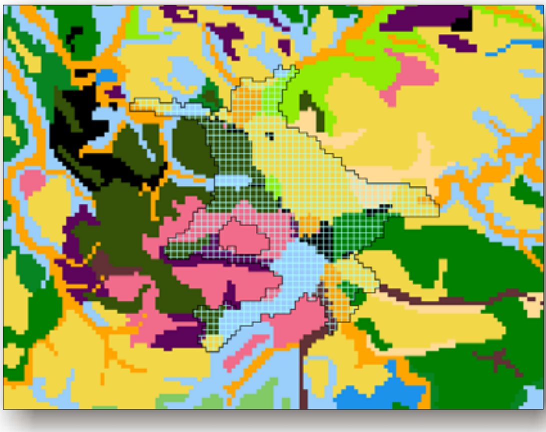
A comparison of the results obtained for Paris is given in Figure 5.



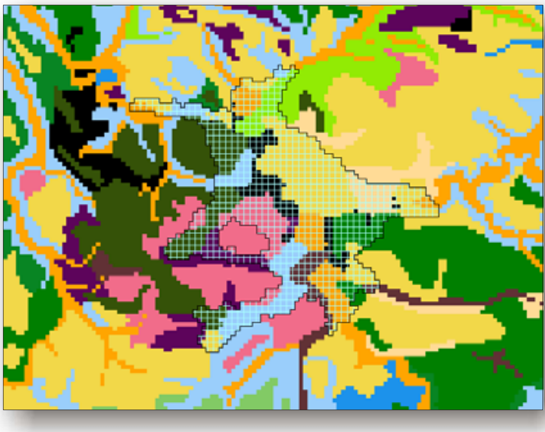
Area with missing data (Paris)



Fill by anisotropic friction over slope



Fill by single cellular automata run



Fill by multiple cellular automata runs

Figure 5: Methods of filling areas with missing soil data (Paris)

The area filled in with spatial unit codes covers 1,845 km^2 (shown on the maps as area with a raster). When using an anisotropic friction surface the area is filled by the main spatial units neighbouring the area with missing data. Allotting spatial units by a single run of the cellular automata / MOLA procedure show that some spatial units follow the topographic factors into the area of missing data. This tendency is more pronounced when applying the allocation procedure as a succession of multiple steps.

Another area to which the method was applied is London. The results if the methods used to fill in the area with soil unit codes are presented in Figure 6.

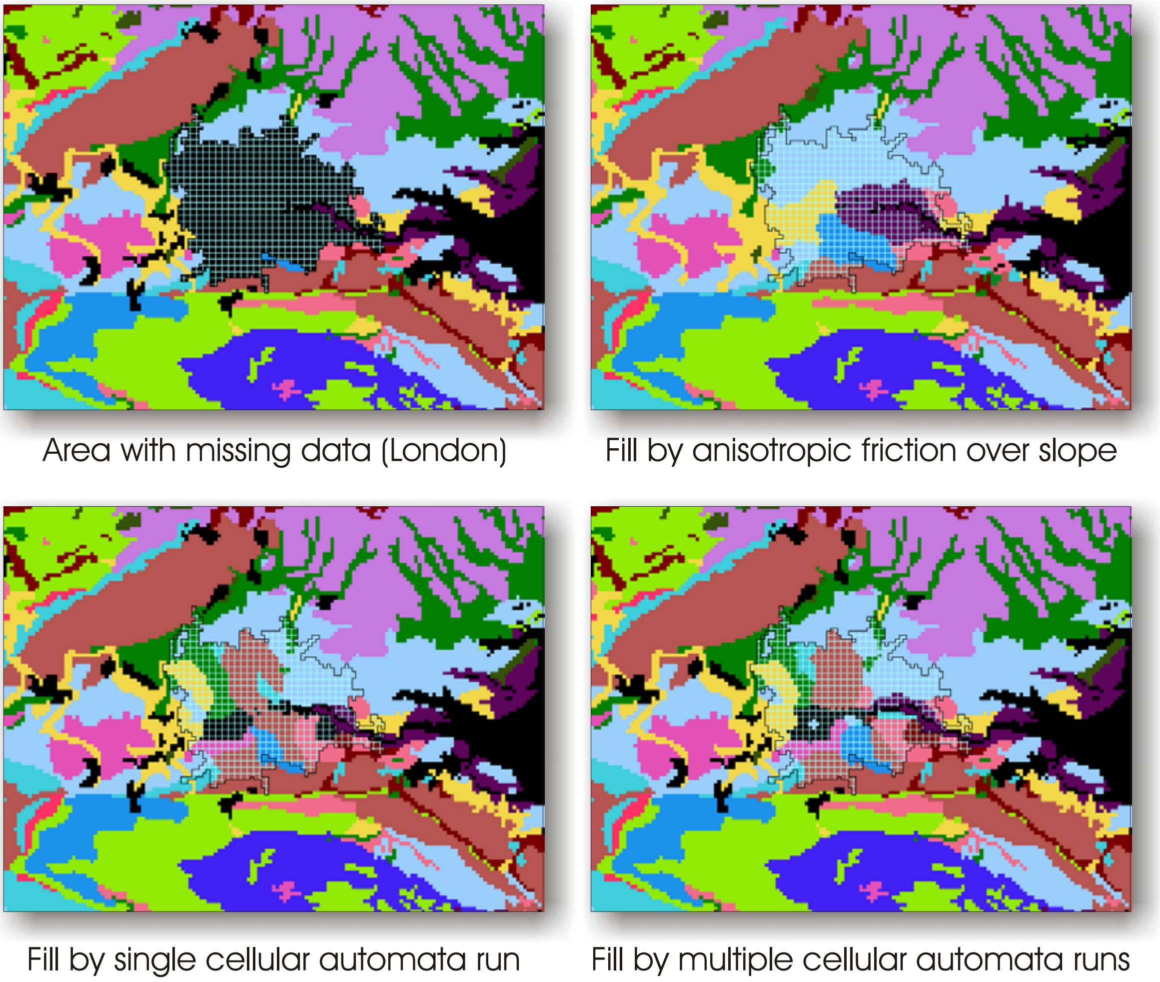


Figure 6: Methods of filling areas with missing soil data (London)

The area with missing soil data covers 1,658 km^2 (shown on the maps as area with a raster). The method of using a CA / MOLA procedure extends spatial units further into the area of missing data than when using an anisotropic friction surface. As for Paris the allocation of spatial units for London obtained from the multiple runs tends to be more detailed than the distribution of spatial units when filling the area with a single run.

The procedure was found to be quite sensitive to all aspects of setting parameters. Small changes to the weights of the multi-criteria evaluation significantly change the allocation of spatial units as do the number of iterations set for the cellular automata. This may be the consequence of the indistinct suitability for several spatial units when using topographic features as signatures in these areas of low variability. Furthermore, the number of training sites is often small (< 30 pixels) for spatial units that follow the river in a narrow band.

4.2 Restrictions to Attribute Mapping from Merging Typological Data

Soil properties recorded on ratio or interval scales would notionally allow merging the information to a single value. This method could be applied to at least partially overcome the 1:n link between the mapping and typological units of the soil databases. A single value could be found by a weighted average from the share of the typological units linked to a mapping unit, e.g. for soil depth, or include soil density as a weighting factor, e.g. for texture and organic carbon.

In order to allow merging the soil properties from various typological units the values should allow forming a meaningful average. Whether an average property is also a meaningful value depends to some degree on the intended application. For example, the average soil organic carbon content for a mapping unit can be mapped to show the spatial distribution of the property, but not to re-classify the data to identify areas of organic soils, if the mapping unit contains a mixture of mineral and organic soils. Similarly, areas of non-soil and soil may behave differently from areas with a homogenous cover of the mean soil property, such as texture.

For peat the ESDB contains 274 SMUs with links to typological units classified as *peat* in the PTRDB (264 are *Histosol*). Consisting solely of peat are 19 SMUs (all *Histosols* in FAO 85). For the remainder the percentage of peat ranges from 1 to 95%. For 66 SMUs peat is given as the dominant soil type. Forming the dominant soil type is not synonymous for peat having a share of 50% or more in the area of an SMU. The share of organic soils in the SMUs where it is dominant ranges from 29% to 100%. The share exceeds 50% of the area for 70% of the SMUs.

The total area of peat covered by the STU map is 306,393 km^2. The area of the SMUs where peat is the dominant soil type is 112,209 km^2. Because to total area of an SMU is assigned to the dominant soil type the area of peat as the dominant soil type is 203,907 km^2, which is about one third less than the total area of peat. When calculating the area-weighted mean organic carbon content for the topsoil the area of organic soils is 244,866 km^2 for a threshold of 12% OC content, 175,548 km^2 for 18% and 160,664 km^2 for a threshold of 20% OC content. As a consequence of the under-representation of peat areas when using the dominant soil type estimates of SOC density, and subsequently stocks, can be expected to be affected by the difference in peat areas.

A different conceptual problem poses the mix of soil and bare areas in an SMU. The area of rock outcrops in the AOI is 37,958 km^2 for all typological units (52 SMUs) and 8,834 km^2 where the land cover type is dominant (4 SMUs). For the organic carbon content the average could be the weighted mean computed over the total area of the SMU, e.g. when estimating SOC stocks. However, this approach would not be applicable for computing an average soil texture. An average soil texture from an area-weighted mean is only valid for areas with texture.

A consequence, having soil property values on a ratio or interval scale solves only part of the complexity posed by the 1:n link of the spatial to the typological units in the ESDB and the HWSD. To allow computing average soil property values at least areas of non-soil and peat should be spatially separated from areas of mineral soils.

4.3 Generating Soil Property Layers

From the modified and combined typological databases of the ESDB and the HWSD key soil properties are processed and transferred to spatial layers. As spatial coverage the completed STU map is merged with a map of the filled-in dominant SMU for the regions covered by the ESDB and the dominant MU of the HWSD for regions outside the ESDB.

4.3.1 Depth

The ESDB contains several parameters referring to depth:

- Depth class of an obstacle to roots ([ROO.STU_SGDBE])

  The parameter contains numeric depth codes for a layer thickness of 20cm up to 80cm. An exception is class 5, which covers "*Obstacle to roots between 0 and 80 cm depth*". This class could contain the layers defined in classes 2, 3, 4 and 6.

- Presence of an impermeable layer within the soil profile ([IL.STU_SGDBE])

  The depth of an impermeable layer in the soil profile is recorded in 4 classes (<40cm, 40cm – 80cm, 80cm – 150cm, >150cm). There is no ambiguity in the classification, as for the ROO parameter.

- Depth to rock ([DR.STU_PTRB])

  Depth to rock is defined by PTR 411. The rule generates as output four alpha-numeric codes of the parameter, estimating depth layers with a thickness of 40cm (<40cm, 40cm – 80cm, 80cm – 120cm, >120cm).

Depth in the HWSD is recorded by three parameters:

- Depth class of an obstacle to roots ([ROOTS.HWSD_DATA])
  Same definition as for [ROO.STU_SGDBE].

- Presence of an impermeable layer within the soil profile ([IL.HWSD_DATA])
  Same definition as for [IL.STU_SGDBE].

- Reference Depth ([REF_DEPTH])
  The parameter contains three classes of depth (<10cm, 10cm – 30cm, 30cm – 100cm).

A comparison of the depth limits defined for the various parameters related to depth is presented in Figure 7.

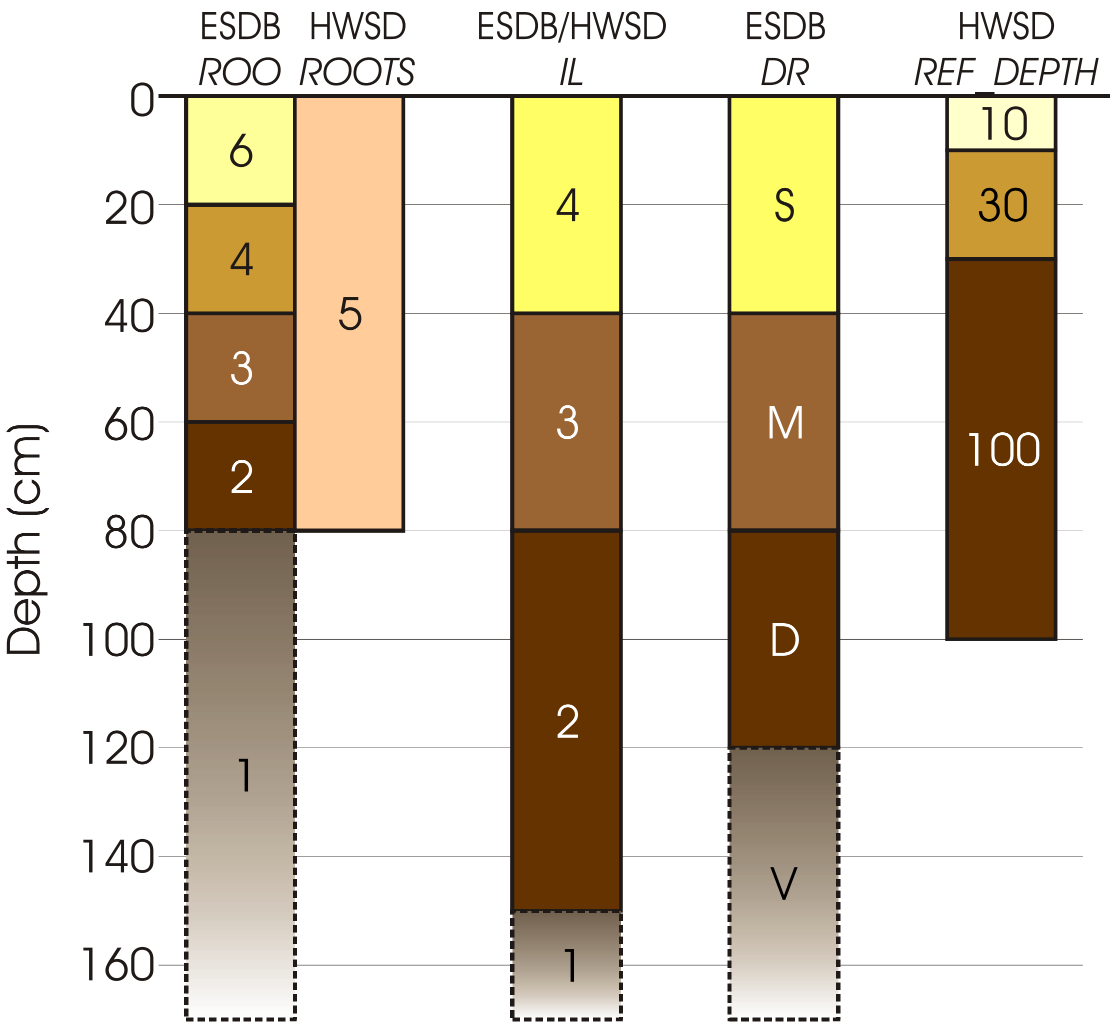


Figure 7: Class Limits for parameters related to depth in the ESDB and the HWSD

The graph shows some correspondence of class limits for the ESDB depth parameters at 40cm and 80cm. For depths below 80cm the class definitions are not compatible. The class limits of the HWSD depth parameter do not match any of the limits of the ESDB depth parameters. This situation very much restricts comparing depth classes between the two databases and, as a consequence, merging depth data where such information is missing n one of the databases.

Entries in the fields [ROO.STU_SGDBE] should be identical to those of the corresponding field [ROOTS.HWSD_DATA]. This is the case, but for 595 STUs in the AOI a value is given in the ESDB while the HWSD contains a blank entry in the field. The count includes comparing entries where [ROO.STU_SGDBE] = 0.

Data in the field [IL.STU_SGDBE] can be expected to equal the entries in [IL.HWSD_DATA]. No corresponding entry in the HWSD exists for the same 595 STUs as for [ROO.STU_SGDBE].

Although no direct links between the fields [DR.STU_PTRB] and [REF_DEPTH.HWSD_DATA] can be established some relationships can be specified, but only in the direction of linking the HWSD to the ESDB:

- REF_DEPTH 10 is fully included in DR-S
- REF_DEPTH 30 is fully included in DR-S

These relationships allow only a very limited comparability of the parameters depth classes for the topsoil (0 - 30cm), and almost complete ambiguity for deeper soils. The first condition for the topsoil depth is respected for all 307 STUs. For the 287 STUs with [REF_DEPTH] = 30 a medium depth is set in the field [DR.STU_PTRB]. In all cases soils of type *Rendzina* are concerned (*E*: 23; *Ec*: 8; *Eh*: 1; *Eo*: 34). For these soil types the reference depth is not set exclusively related to a medium [DR] depth class, but to a shallow soil for 130 STUs.

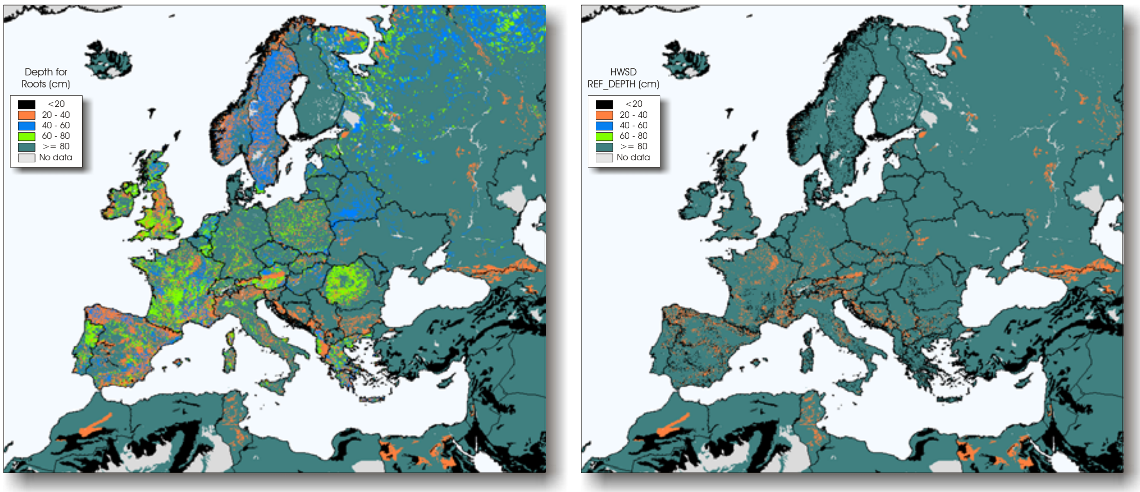
The limits of the depth classes of the field [REF_DEPTH.HWSD_DATA] correspond to other specifications for the topsoil (OC_TOP, IPCC) and seem to be better suited for use than those of the ESDB. An added advantage is that the field does not contain blank entries.

The depth parameter considered depends on the subsequent use of the data. For applications related to plant growth the depth available to roots may be consider. Root growth may be limited by rock, an impermeable layer or other strata in the soil. Therefore, it can be expected to not exceed the depth to rock. In practice the depth to rock may not be the depth to a solid layer of underlying rock, but also to rocky material, such as boulders, which leads to variations in measurements (Chapman *et al*., 2013). From the available data a layer of the depth available to roots was estimated using a hierarchical procedure, depending on the availability of data:

1. ROO.STU_SGDBE
2. IL.STU_SGBDE
3. REF_DEPTH.HWSD_DATA

Depth information from the HWSD was preferred to the data of the field DR.STU_PTR because the PTR on which the data are based defines a shallow soil for all Histosols. In the AOI the depth values from the HWSD were thus used for 208 STUs, for which the ESDB STU database does not contain data for ROO or IL.

The depth value was set the mean value of the range limits. The resulting layer of soil depth available to roots and a comparison to the reference depth of the HWSD are presented in Figure 8.



a) Depth available to roots *b) HWSD Reference Depth*

Figure 8: Depth available to roots within 0-100cm and HWSD Reference Depth

The map shows a depth of <100cm available to roots for significant parts of Spain, the UK, Norway and Romania. In the UK and Norway a depth < 80cm is indicated as a general condition. This is to some degree the result of setting the depth value to the arithmetic mean of the range limits and the logic for displaying depth in the graph. For example, class 2 of the ROO data the limit is defined as "*Obstacle to roots between 60 and 80 cm depth*". The depth value is set to 70cm and the area is assigned to the class "60 – 80" cm in the graph. Using the maximum as the depth value (80cm) would result in the area being shown as belonging to the class "≥ *80cm*".

4.3.2 Texture

The ESDB STU table provides information on soil texture using a classification scheme. The definitions are presented in Table 6.

Table 6: ESDB Classification Scheme for Soil Texture

Code	Label
1	Coarse (18% < clay and > 65% sand)
2	Medium (18% < clay < 35% and >= 15% sand, or 18% < clay and 15% < sand < 65%)
3	Medium fine (< 35% clay and < 15% sand)
4	Fine (35% < clay < 60%)
5	Very fine (clay > 60 %)
9	No mineral texture (Peat soils)
0	No information

Texture is given separately for the surface (_SRF) and the sub-surface (_SUB) layers. A further distinction is made into a dominant (_DOM) and a secondary (_SEC) fraction. No information is provided on the proportion of dominant or sub-dominant fractions within an STU.

In the HWSD texture is recorded in several fields. A reduced classification of the ESDB is recorded in the TEXTURE fields, as given in Table 7.

Table 7: HWSD FAO Classification Scheme for Texture

Code	Label
1	Coarse
2	Medium
3	Fine
0	None

The HWSD class for "*Medium*" texture combined ESDB classes for "*Medium*" and "*Medium fine*" texture. "*Fine*" texture in the HWSD is presented in the ESDB as "*Fine*" or "*Very fine*" texture. Not represented in the scheme are organic soils.

Consequently, for the soils with texture the classes of the ESDB could be translated into those of the HWSD. The entries for the filed [T_TEXTURE.HWSD_DATA] in the HWSD seems to originate from the filed [TEXTSRFDOM.STU_SGDEB] of the ESDB without taking into account the information on the secondary texture. Between the tables correspondence of entries was found for 5.036 instances. In 22 instances no correspondence was found. The cases are listed in Table 8.

Table 8: Instances of different soil texture from re-classified ESDB field [TEXTSRFDOM] to HWSD field [T_TEXTURE]

ESDB		HWSD	Instances
FAO85FU	*TEXTSRFDOM*	*T_TEXTURE*	*No.*
Q	1	2	1
Qc	1	2	2
Ql	1	2	3
Dg	2	1	6
Dgs	2	1	2
La	2	3	2
Oe	2	1	1
Oe	2	3	1
Rx	2	1	2
Od	3	1	1
V	3	1	1

An explanation for the different soil texture classes for these cases is not evident from the data or the documentation.

The fields [T_USDA_TEX_ CLASS] and [T_USDA_TEX_ CLASS] contain data on soil texture for topsoil and subsoil according to the USDA classification scheme. The scheme distinguishes 13 classes of soil texture, while no specific code is defined or present in the HWDS for organic soils.

Ratio (interval) data on soil texture in percentage of relative proportion is given in the HWSD for sand, silt and clay for the topsoil and subsoil layer. From the documentation it is not immediately evident from which database these values were derived or how they were determined.

Re-classifying the HWSD texture percentages for the dominant soil typological unit to soil classes of the ESDB shows general agreement (1,222 instances), but also some differences (286 instances). Of these, 11 instances are related to classifying organic soils, mostly (10 instances) where an organic soil of the ESDB has been attributed texture in the HWSD. In 253 instances a soil texture class "*Medium fine*" of the ESDB is given percentage values in the HWSD, which correspond to a soil texture class of "*Medium*". Although it may be argued how to translate the relational operators specified in the definition of the texture classes of the ESDB to conditions without ambiguity or gaps in the range of values, the differences in classes are not the consequence of the position of greater equal or less equal operators. The differences could also not be attributed to a specific soil type, since 64 entries in the field [FAO85FU.STU_SGDBE] are affected, but not exclusively.

The SMUs affected by a difference in ESDB texture class and the texture fractions of the HWSD are presented in Figure 9.

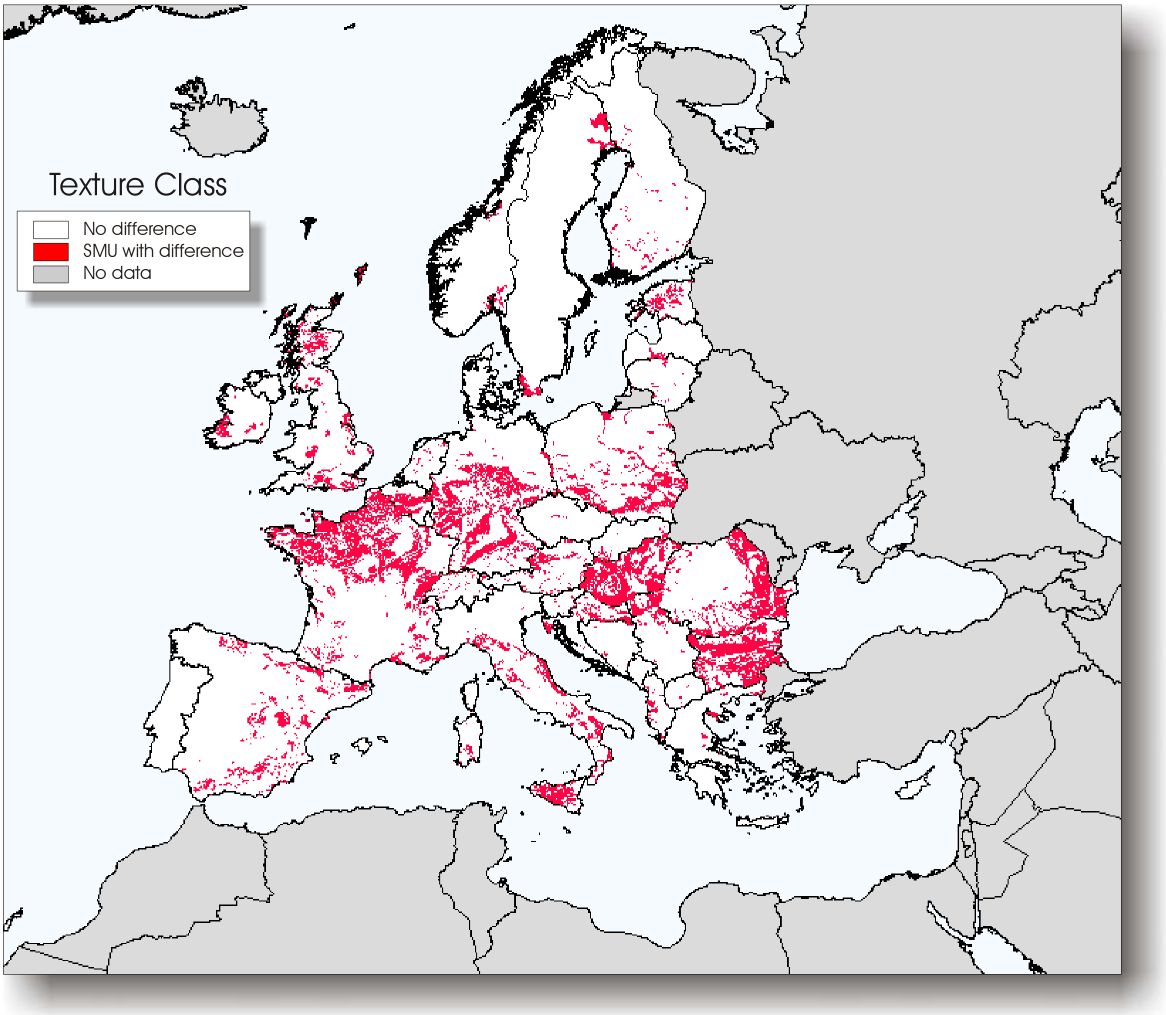


Figure 9: Difference in ESDB topsoil texture and classified texture fractions of HWSD for dominant STU

There is no discernable geographic preference for the occurrence of the differences in texture data. If the differences in soil texture classes and percentages of texture fractions found for the dominant soil typological units are representative for the complete set of data texture fractions belonging to class "*Medium*" would be given in the HWSD where a "*Medium fine*" texture class is given in the ESDB in 20% of all instances of soil typological units in the spatial layer.

While technically the continuous texture values of the HWSD can be assigned to STUs the resulting layers may lead to conditions of inconsistencies with other soil properties other than for the soil texture classification.

A particular situation is presented for organic soils in the ESDB without texture, for which values of texture are found in the HWSD. There are 288 instances of such soils in the SMUs of the ESDB in the AOI. For these instances a texture is given in the HWSD, for texture classes as well as texture fractions, affecting 287 SMUs. In the PTR database of the ESDB 284 STUs are defined as "*Peat*" in the AOI. As a consequence, in case organic soils are to be represented without texture, priority should be given the ESDB data. Excluding STUs designated as "*Peat*" in the ESDB a value for topsoil texture fractions sand, silt and clay of the HWSD can be assigned to 4,816 STUs of the ESDB and for 4,222 STUs for the subsoil texture.

The attribute layers of soil texture clay, sand and silt for the topsoil and the subsoil with no texture for areas with organic soils are presented in Figure 10.

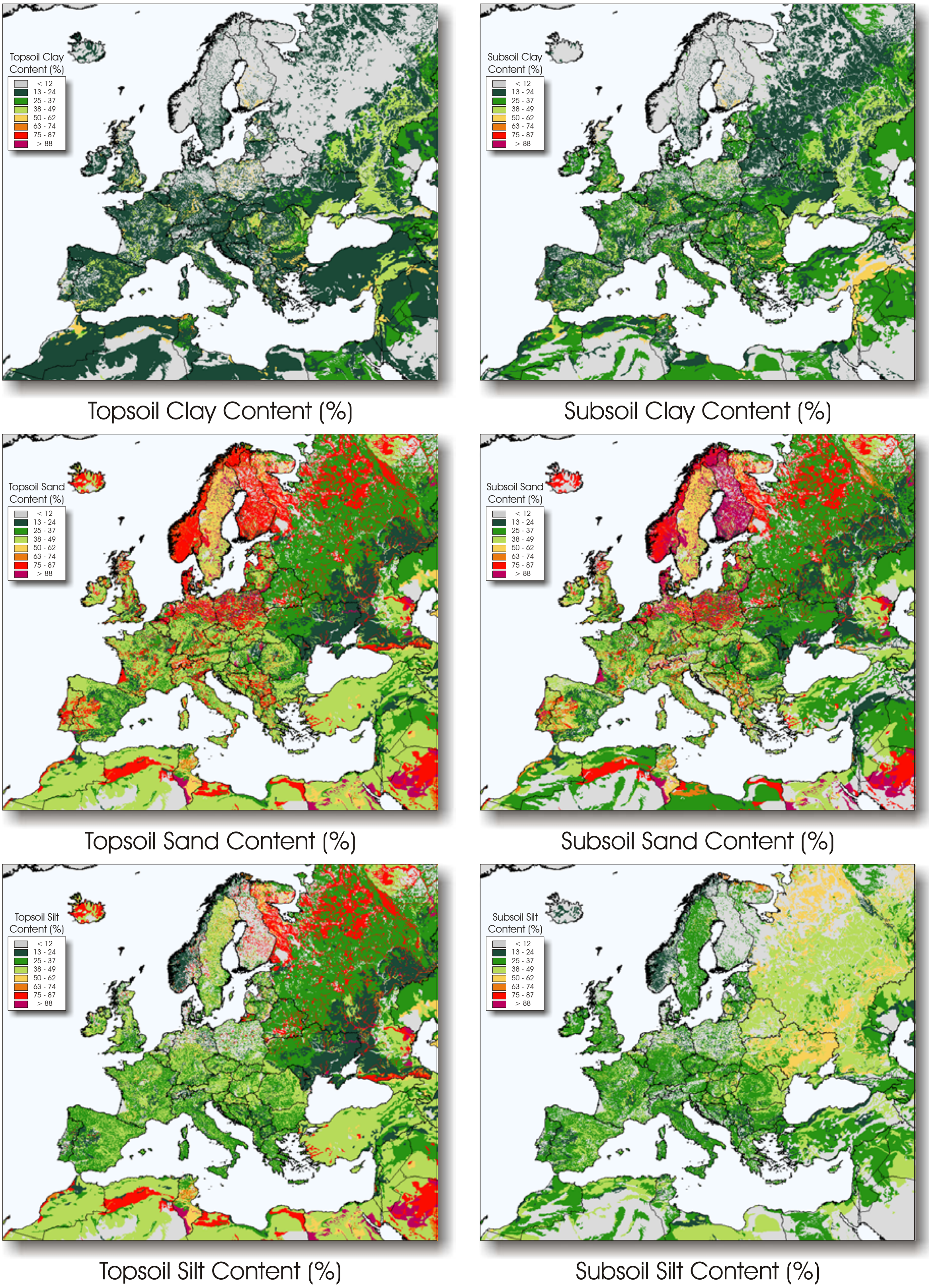


Figure 10: Topsoil and subsoil texture for mineral soils

The graphs show texture for the topsoil and the subsoil layer based on the HWSD, but there are differences in the depth parameter values between the HWSD and the ESDB. Two situations may occur:

a) A subsoil layer exits in the HWSD for an STU where the depth available to roots only covers the topsoil layer.
b) The depth available to roots extends below 30cm, but the HWSD indicates no subsoil layer.

In the first case the subsoil texture could be discounted. For the second case a simple solution is to apply the topsoil texture to the subsoil layer. These practices were applied to the subsoil texture layers.

4.3.3 Bulk Density

The ESDB contains data on bulk density in form of topsoil and subsoil packing density (PD) estimated by PTR 431 and 432. The PTR defined PD as one of three classes: *low*, *medium* and *high*. The qualitative and indistinct output of the PTRs suggests looking for alternative sources of data on bulk density.

The HWSD contains two parameters for bulk density:

- Reference Bulk Density (T_REF_BULK_DENSITY, S_REF_BULK_DENSITY)
- Bulk Density (T_BULK_DENSITY, S_BULK_DENSITY)

The values for the reference bulk density in the HWSD are derived from sand and clay fraction using a calculator[11]. Restrictions to using the calculator are discussed in Hiederer & Köchy (2011). The main aspect in using the calculator is that it is applicable only within a limited range of proportions of soil texture fractions and not at all for organic soils. In Version 1.2 of the HWSD data on bulk density derived from SOTWIS database were introduced (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

Bulk density based on SOTWIS contains two values for organic soils:

- 0.10 $g\ cm^{-3}$ and
- 0.28 $g\ cm^{-3}$

These values are more realistic than those provided as reference bulk density.

The two values of bulk density of the HWSD were compared to the estimates provided by the PTF for global soil data (Hiederer & Köchy, 2011). The average bulk density (no area-weighting applied) for FAO 85 soil types was computed for the STUs in the AOI. The relationships are graphically presented in Figure 11.

[11] Available from: http://pedosphere.ca/resources/bulkdensity/triangle_us.cfm

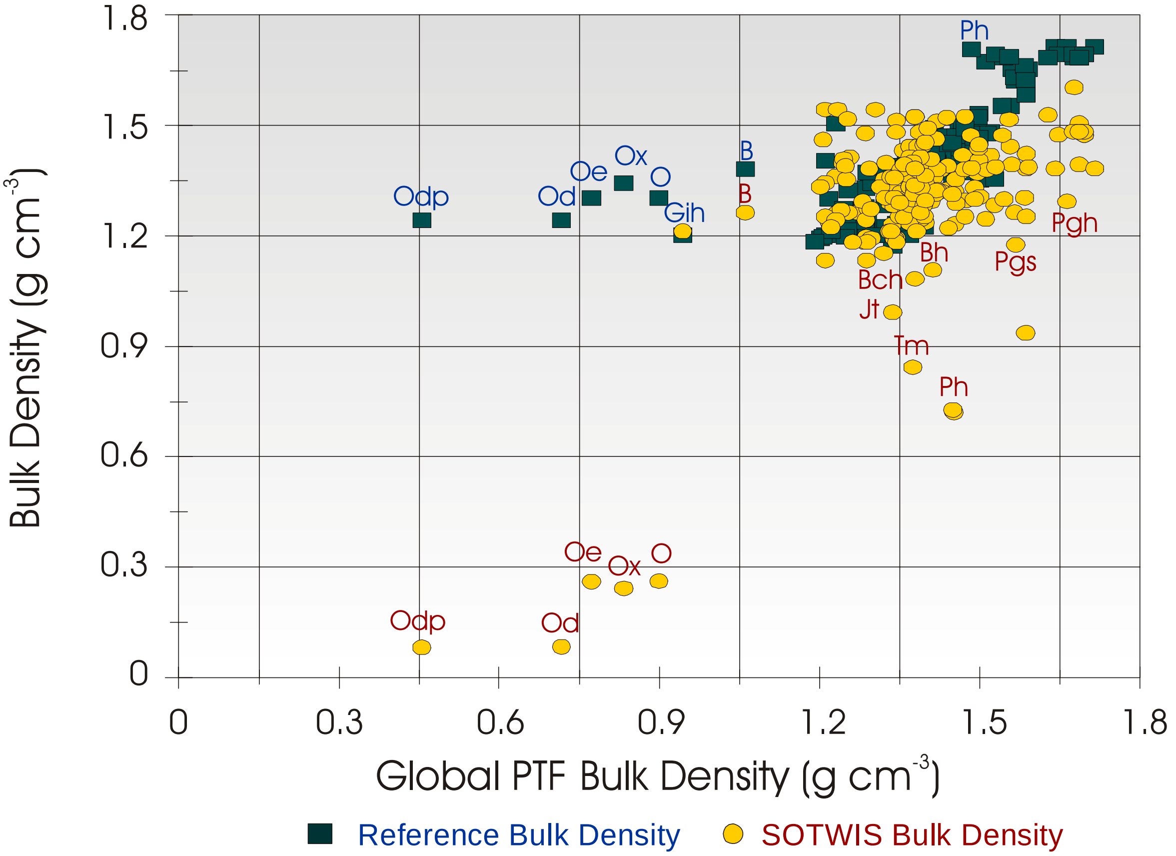
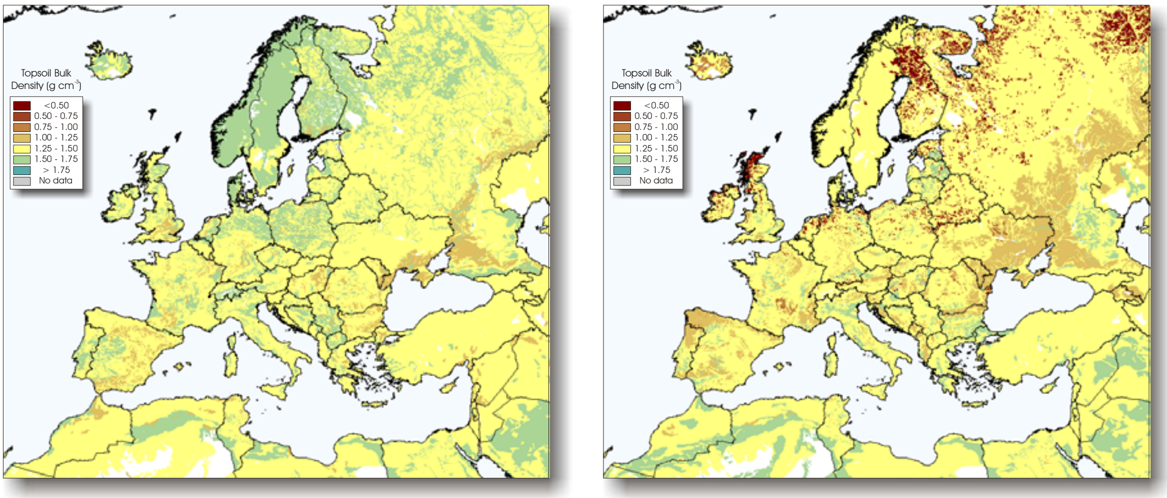


Figure 11: Comparison of Topsoil Bulk Density from global PTF with HWSD reference and SOTWIS-derived values

The distribution of bulk densities shows the marked difference in bulk density of organic soils between the global PTF estimates and the SOTWIS-derived data with those provided as reference bulk density. The data of the topsoil ([T_REF_BULK_DENSITY]) and subsoil ([T_REF_BULK_DENSITY]) reference bulk density should not be used for organic soils. For mineral soils the global PTF estimates are close to those provided by as reference bulk density, i.e. provided by the bulk density calculator, although different functions and parameters are used. The SOTWIS-derived values differ more notably from the other estimates of bulk density. They are also limited in the maximum bulk density.

Based on the average bulk density by FAO 85 soil type the relationship between the values from the three parameters were compared using a linear regression, limiting the analysis to mineral soil types. For the comparison of PTF values vs. reference bulk density the regression coefficient was 1.04 with a coefficient of correlation (r^2) of 0.82. Comparing either bulk density parameter to the SOTWIS values for the same range showed low correlation with a coefficient < 0.25 and an r^2 <0.07.

The distribution of bulk density for the topsoil layer according to the data derived from the reference data (field [T_REF_BULK_DENSITY.HWSD_DATA]) and the SOTWIS-derived data (field [T_BULK_DENSITY.HWSD_DATA]) in the HWSD is presented in Figure 12.



a) Reference Bulk Density (g cm^{-3}) *SOTWIS-derived Bulk Density (g cm^{-3})*

Figure 12: Reference and SOTWIS-derived Topsoil Bulk Density (g cm^{-3}) in the HWSD

An alternative to bulk density derived from the SOTWIS database is the use of a PTF. At the most basic PTFs use OC content as the sole variable to estimate bulk density, but may be gross simplifications (Hollis, *et al*., 2012; Kaur *et al*., 2002). When covering the whole range of bulk densities on continental scale a simple reciprocal or logarithmic function of OC content was found to model the parameter better than simple exponential functions (Hiederer & Köchy, 2011).

For estimating bulk density from OC content alone the parameters of PTFs were derived from generalized data form a variety of field survey data (BioSoil, SPADE/M, HYPRES, ISRIC-WISE V3; Hiederer, 2011). The data pairs used are:

OC (%)	0.10	0.58	1.17	1.75	6.00	30.0	40.0	58.0
BD (*g cm^{-3}*)	1.80	1.42	1.32	1.25	0.80	0.23	0.20	0.10

A linear function with a logarithmic transformation of OC content may be used when limiting the estimation of bulk density for OC content > 0.1%. The general function is formulated as:

$$\rho_b = 1.2736 - 0.2838 \bullet \ln(OC)$$

where

ρ_b dry bulk density (*g cm^{-3}*)
OC soil organic carbon content (%)

When not restricting the range of values of OC content a reciprocal function may be used to estimate dry bulk density ρ_b with the parameters set as:

$$\rho_b = \left[0.1289 + 0.5786 \bullet OC\right]^{-1}$$

The reciprocal function gives higher estimates of bulk density than the logarithmic function for OC contents between 0.3% to 5.0% and lower values for other values. For an OC content of 1.75% (3.0 % Organic Matter) the reciprocal function gives a bulk density of 1.24 g cm^{-3}, compared to 1.11 g cm^{-3} obtained from the logarithmic function. The average bulk density for OC contents from 1% - 2% (0.58% - 1.17% organic matter) in the HWSD is 1.40 g cm^{-3} and 1.31 g cm^{-3} for the range 1.17%-1.75% OC content (2.0% - 3.0% organic matter).

For the two values of OC content in the HWSD (33.63% and 39.60%) the estimates for bulk density for the reciprocal function are 0.20 g cm^{-3} (0.28 g cm^{-3} for logarithmic function) and 0.18 g cm^{-3} (0.23 g cm^{-3} for logarithmic function). These estimates are within the range of the two values (0.10 g cm^{-3} and 0.28 g cm^{-3}) given for bulk density derived from SOTWIS in the HWSD. However, in the HWSD the lower bulk density is given for the lower OC content (167 cases of BD: 0.1 g cm^{-3}, OC: 33.63%) and the higher value for the higher OC content (119 cases of BD: 0.28 g cm^{-3}, OC: 39.40%). The effect of the data pairs found in the database and a combination more in line with the general relationship between OC content and BD on SOC density (mass of OC per unit volume) is less consequential than the difference in the values. This is due to the compensating effect of the parameters of BD and SOC when computing density. For 1 m^{-3} of organic material the density of organic carbon in the soil using the existing combination of the properties and an alternative combination is presented in Table 9.

Table 9: Existing and Alternative Combination of SOC Content and Bulk Density in HWSD

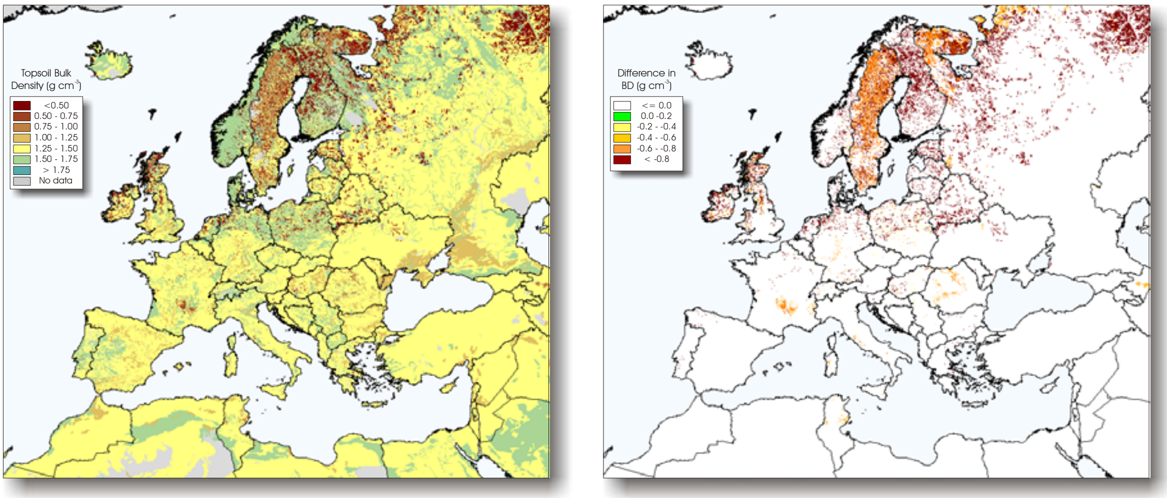
Parameter	HWSD *Existing Combination*		HWSD *Alternative Combination*	
OC Content (%)	33.63	39.40	33.63	39.40
Bulk Density (*g cm^{-3}*)	0.10	0.28	0.28	0.10
SOC Density *(kg C m^{-3}*)	33.63	110.32	94.16	39.4
Combined SOC Density *(kg C m^{-3}*)	143.95		133.64	

As the worked example demonstrates the effect of associating different bulk density values with OC content on the overall SOC density is compensated for to some degree when combining the density to estimate total SOC stocks for an area.

For most of the range of OC content in mineral soil the estimates of the bulk density differ little between a logarithmic and a reciprocal function. As defined neither PTF should be used for values of OC < 1.0%. For mineral soils with an OC content <5% a reciprocal PTF gives values closer to the HWSD values derived from SOTWIS. For this range and area the values are also closer to those obtained from using the quadratic PTF from Manrique & Jones (1991), as recommended as one of the functions by Kaur, *et al*. (2002) for estimating bulk density from OC content alone. It is, however, recommended to include soil texture as a parameter in the PTF for a more robust estimation.

For a wide range of mineral soils the bulk density can be estimated using texture information following the function described by Saxton, *et al*., 1986[12]. The function was used in the HWSD to derive the reference bulk density estimates. For soils high in organic carbon (here > 3.0 %) the function is not valid and the logarithmic PTF was used to estimate bulk density for those soils.

The resulting map of bulk density of the topsoil and the difference to the reference bulk density of the HWSD is presented in Figure 13.



a) Topsoil Bulk Density (g cm^{-3}) *b) Difference to HWSD (g cm^{-3})*

Figure 13: Estimated bulk density in the topsoil and difference to the HWSD

From the comparison of data with soil organic carbon values and the variability of values the use of the global PTF to estimate bulk density was found preferable to either bulk density values provided in the HWSD. This is not a statement related to the accuracy of the estimates, but on the comparability of the output from two models using other soil parameters as input variables.

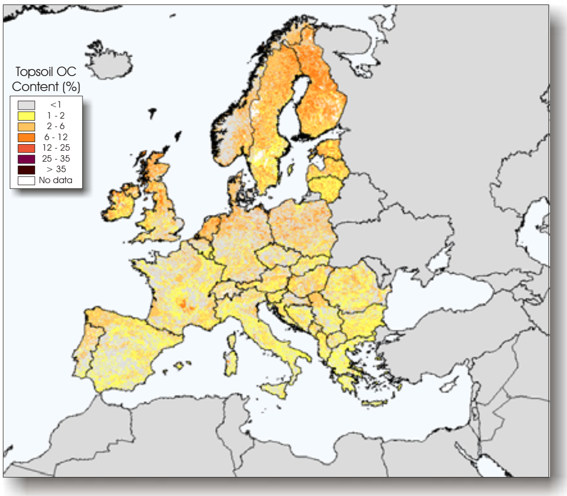
When using modelled data for bulk density, which includes soil organic carbon as a variable to estimate the parameter, the bulk density estimates have to be adjusted to the organic carbon data. This consideration is applicable for

[12] Calculator available at: http://www.pedosphere.com/resources/bulkdensity/index.html

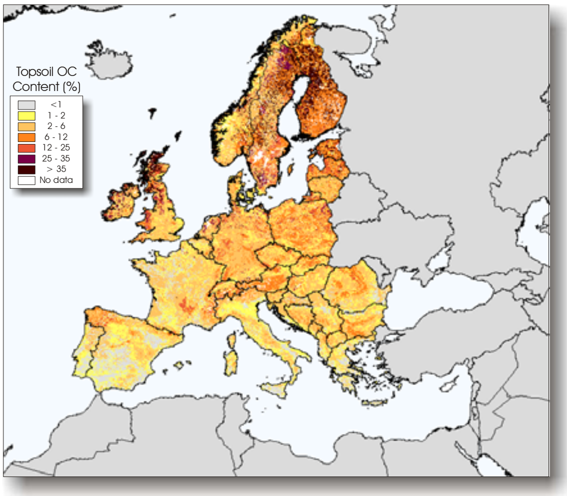
example when using the global PTF, but not for the reference bulk density of the HWSD, which is based only on the sand and clay texture fractions.

4.3.4 Soil Organic Carbon

The ESDB contains organic carbon (OC) content for the topsoil in the PTRDB. PTR 21 outputs topsoil OC content as four classes. Mineral soils high in OC content and organic soils are found in a single class with OC content > 6%. The resulting map of OC content from the PTR is presented in Figure 14.



a) PTR 21 original



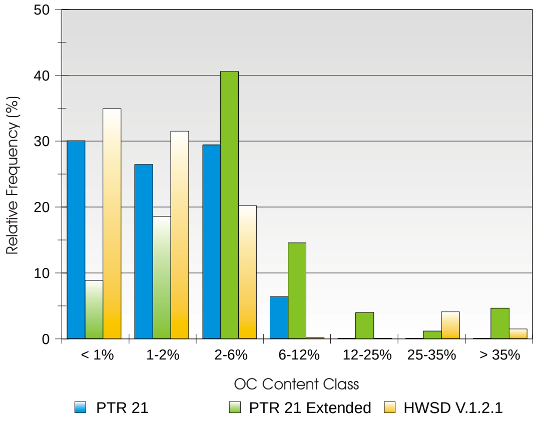
b)PTR 21 modified for OCTOP

Figure 14: Topsoil organic carbon content from ESDB PTR 21

With the limitation in the range of OC content to a maximum of 6% the map only covers the distribution in mineral soils. The conditions of PTR 21 were modified to generate the European Topsoil Organic Carbon layer (Jones, *et al.*, 2003).

The HWSD provides OC content for the topsoil and subsoil layers (T_OC, S_OC) as continuous values. Although the values are given on a ratio scale, in the AOI the database contains six distinctive values > 6% OC content: 6.74% (10 cases), 7.75% (2 cases), 33.63% (167 cases), 35.27% (1 case) and 39.40% (119 cases). There are thus only two distinct values of OC content for organic soils. This should be considered when using the OC content to estimate bulk density by a PTF, which includes OC content as a variable. The value of bulk density for organic soils in the HWSD should be higher than the value used for the bulk density of organic material with an OC content of approx. 58%.

For the OCTOP values of PTR21 of the ESDB, the extended PTR and the T_OC of the HWSD the distribution of OC content across the classes is presented in Figure 15.



OC Range %	PTR21 %	PTR21 Extended %	HWSD V.1.2.1 %
< 1	32.5	9.6	37.8
1 - 2	28.7	20.1	34.1
2 – 6	31.9	43.9	21.9
6 – 12	7.0	15.7	0.1
12 – 25	0.0	4.3	0.0
25 – 35	0.0	1.3	4.4
> 35	0.0	5.0	1.6

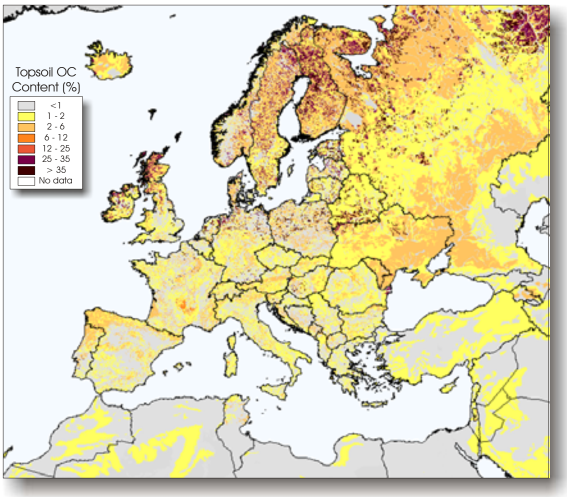
Figure 15: Relative frequency of topsoil organic carbon content by class for ESDB PTR21, PTR21 Extended and HWSD

The graph shows a resemblance of the frequency of OC content for the two classes < 2% between the PTR21 and the HWSD. The OCTOP map shows a prevalence of values in the range of 2 – 6 % OC content (43.9%), which is approx. twice as often as the values appear in the HWSD.

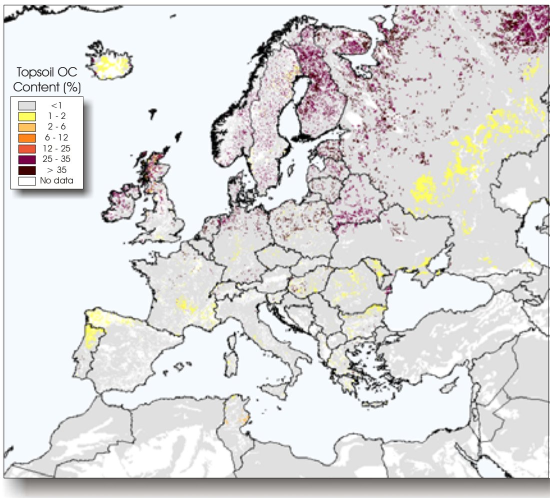
The absence of any noteworthy occurrence of values in the range of 6 – 25% OC content in the HWSD is caused by the absence of such entries within this range in the database. In the AOI the database contains two distinct values within the range: 6.74% (10 cases) and 7.75% (2 cases). There are no values between 7.75% and 33.63%.

The partial coverage of the OCTOP map of the area frame and the restriction to the topsoil limit the use of the layer for an extended pan-European layer. Important differences with the HWSD very much hamper merging the two data sets. As a consequence the OC layers for the topsoil and subsoil are taken from the HWSD.

The distribution of OC content in the topsoil and subsoil is presented in Figure 16.



a) amended HWSD topsoil OC content



b) amended HWSD subsoil OC content

Figure 16: Topsoil and subsoil organic carbon content from HWSD V. 1.2.1

For the topsoil OC content the graph shows a distribution similar to the OCTOP map, with noteworthy differences in the magnitude. The amount of subsoil OC content shows a distinct division into low-value mineral soils, with OC content mainly < 1%, and organic soils with OC contents close to those found in the topsoil. In case the presence of a subsoil is given by the depth layer, but not found in the HWSD the corresponding subsoil OC content is estimated as 65% of the topsoil value. The value can be used as a general rule for mineral soils under most land cover types and for forest when the organic material overlaying a mineral soil is not included (Hiederer, 2009). For the areas concerned the value was proportionally adjusted to the depth of the soil available for roots for a subsoil layer ranging from 30cm to 100cm[13].

4.3.5 Coarse Fragments

In the ESDB coarse fragments in the soil are estimated by PTR 412 as the "*Volume of Stones*" (VS). The PTR does not distinguish between topsoil and subsoil VS. The rule output is an estimates of VS in terms of four classes (0%, 10%, 15% or 20%). The conditions of the PTR lead to an output of class "0" for 3,416 STUs.

In the HWSD the amount of coarse fragments is recorded in the fields for gravel, separately for the topsoil and the subsoil layer. For the AOI all typological units with soil show the presence of gravel, ranging from 1% to 48% for the topsoil and from 1% to 33% for the subsoil.

To compare the data on VS of the ESDB and the gravel of the HWSD the average content of the parameter by FAO85 soil type was computed. The average was weighted by the reference depth of the HWSD for both

[13] After: OC_SUB = (-0.005 * DEPTH_SUB + 1.0) * OC_TOP

parameters, but not for the area. A graphical presentation of the mean FAO 85 VS with the mean gravel content in the topsoil and subsoil is presented in Figure 17.

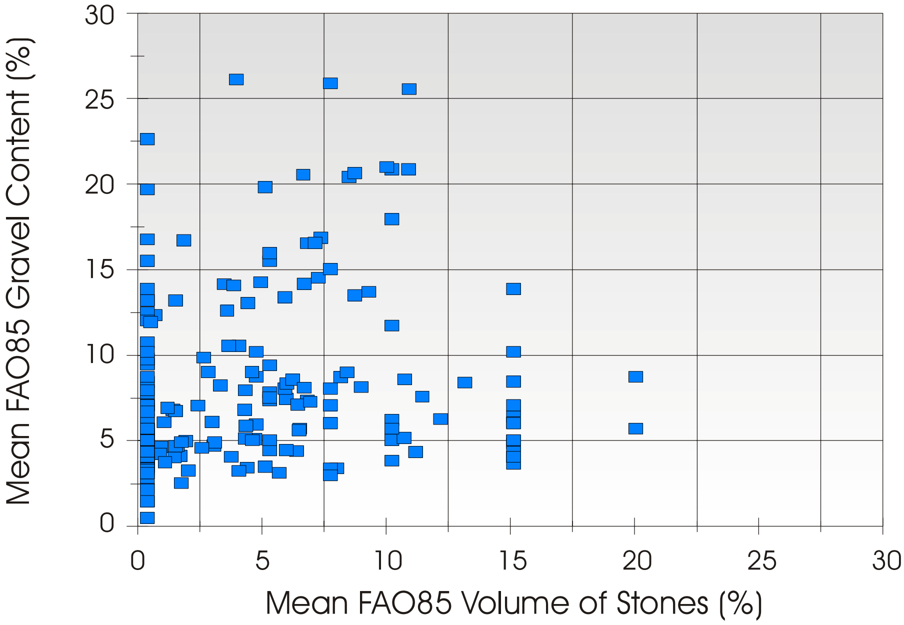
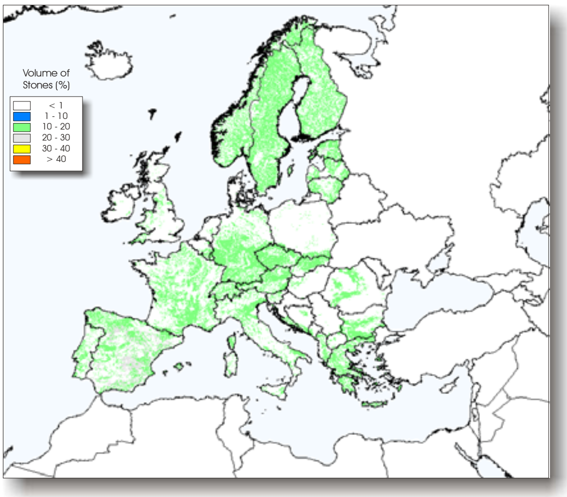


Figure 17: Mean volume of stones and gravel content in combined topsoil and subsoil layers

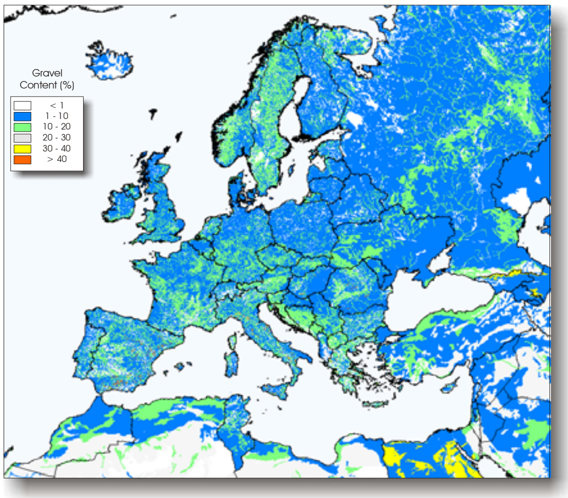
The graph shows a concentration of 89 soil types with a VS of zero and the limit in VS of 20%, which is reached for two soil types (*Verti-Calcic Kastanozem* (*Kkv*) and *Luvic Xerosol* (*Xl*)). For the mean gravel content the values span a range of 1% to 26.4%. From the graph a relationship between the ESDB VS parameter and the gravel content of the HWSD for FAO85 soil types is not apparent.

The differences in the parameter values affect the total volume of coarse fragments in the AOI. For areas with soil the total volume to a max. depth of 100 cm is 4,396 km^3 (using HWSD reference depth). The volume of stones in the AOI is 248.8 (79.6 km^3 in the topsoil, 169.2 km^3 in the subsoil). This amounts to a mean VS of 5.7%. The mean volume of gravel in the AOI is 393.9 km^3 (79.6 km^3 in the topsoil, 169.2 km^3 in the subsoil), which corresponds to an average gravel content of 9.0%.

The spatial distribution of the VS of the ESDB PTRDB and the gravel content of the HWSD is presented in Figure 18.



a) ESDB PTRDB Volume of Stones



b) HWSD Gravel Content

Figure 18: Spatial distribution of Volume of Stones (PTRDB of ESDB) and topsoil Gravel Content (HWSD)

The graphs demonstrate the limited range of values for the VS parameter. The PTR distinguishes only four values: 0%, 10%, 15% and 20%. The lack of differentiation of soils with a VS < 10% is obvious when comparing the spatial distribution of VS with gravel content of the HWSD. However, for the area with common coverage there is less spatial variation between the data than the graphs suggest. There are no values in the range 30 – <40% for gravel content and 0.5% of the common area are classified as having a gravel content of 40% or more. Of the area assigned to the range of 10-20% for VS 42% is assigned to the same range for gravel content and 47% to a content of < 10%. There are distinct variations in spatial distribution of the differences. For areas such as the Carpathian Mountains, France, Germany, the Czech Republic, Greece, Bulgaria or Sweden the spatial distribution of VS and gravel content is closely related. Notable differences are found for Poland, Norway and the Dinarides.

This difference in the volume of coarse fragments in the soil directly affects any calculations, which only cover the fine soil fractions. Examples are SOC density or the quantity of available water. For the area covered by the STU map SOC stocks in the topsoil increase by 0.6% when using the STU data instead of the dominant typological unit, mainly due to the larger are of peat in the STU map. Including data on coarse fragments from the HWSD reduces topsoil SOC stocks by 9% for either data. Applying a constant soil depth of 30cm instead of the data on depth increases topsoil SOC stocks by 1.7% for the STU map and 2.7% when computing SOC stocks from the dominant typological unit.

Since these differences are prevalent in some areas more than others this spatial variability of the difference would also have an influence on to soil properties calculated from the data used to represent the volume of coarse fragments.

4.4 Integration of STU Attribute Layers

While the layers of mapped attributes of the ESDB may be of use on their own by presenting all typological data in a single layer their real usefulness is the combination of several soil properties or integrating soil properties with other thematic data to derive new information, which characterize the environment. One such application of combining only soil property data is calculating *total available water content* (TAWC; Reynolds, *et al*., 2000). The TAWC computed here is a volumetric parameter describing the water content between field capacity and permanent wilting point (Richards & Wadleigh, 1952; FAO, 1998). It is a function of available water content, presence of coarse fragments and depth given by:

$$TAWC = \left(\theta_{fc} - \theta_{pwp}\right) \bullet \left(1 - \frac{CF}{100}\right) \bullet d$$

where

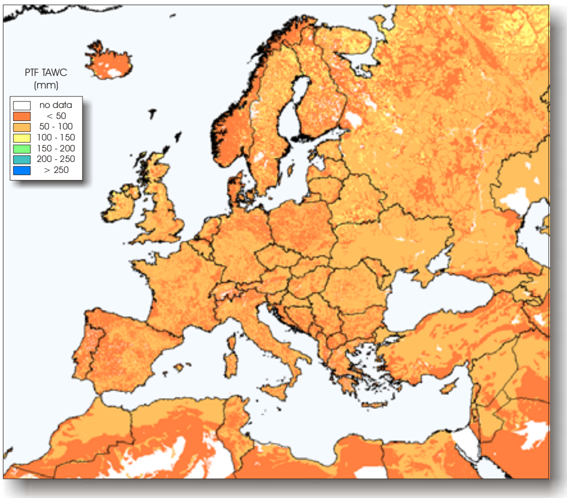
θ_{fc}	field capacity ($cm^3\ cm^{-3}$)
θ_{pwp}	permanent wilting point ($cm^3\ cm^{-3}$)
CF	coarse fragments (%)
d	depth of layer (mm)

Water content at field capacity and permanent wilting point were determined following the equation from van Genuchten, 1980 to estimate the soil water retention curve. The parameters of the equation are provided by the *pedo-transfer function* (PTF) for volumetric soil water content computed from the soil water retention curve as given by Wösten, *et al*., 1999. The PTF uses soil texture, organic carbon content and bulk density to determine the parameters of the soil water retention curve based on soil profile data from sites across Europe. For areas outside Europe other PTFs may be found more applicable (Wösten, *et al*., 2013).

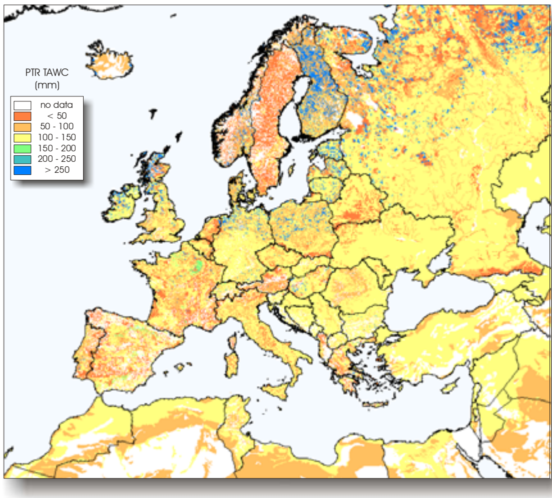
In the absence of ratio or interval values for the parameters of the PTF Wösten, *et al*., 1999 also provided values for five texture classes plus one for organic soils for the topsoil and the subsoil. These values for the parameters could be used to construct a *pedo-tranfer rule* (PTR) to estimate water content from classified data, such as the ESDB. In the absence of a map of STUs the soil parameters from the ESDB or the HWSD are generally mapped to the dominant SMU.

An alternative procedure for the parameters of the HWSD would be to compute mean values for the parameters, since the database contains the parameters on a ratio or interval scale. The mean values would need to be weighted by area and soil depth. The procedure runs into difficulties when the SMU contains a mixture of mineral and organic soils and when the linked typological units include non-soil areas. Organic soils may not have values for texture and non-soil areas have no parameter data other than area. It is therefore not evident how to compute a meaningful value for example for the mean depth in an SMU where soil and non-soil areas are mixed. When a mask for non-soil areas is applied one may want to compute the soil depth only for the area with soil data. When such a mask is not applied the mean depth would be computed for the total area of the SMU. Similarly, computing mean values for soil texture does not provide valid results when mineral and organic soils occur in an SMU. As a consequence, even with the availability of the parameter values on ratio or interval scale the PTF is applied only to the dominant SMU, unless STUs are mapped.

The TAWC for the topsoil and subsoil when applying the HYPRES PTF the ratio and interval scale values for the mapped STUs are presented in Figure 19.



a) Topsoil TAWC



b) Subsoil TAWC

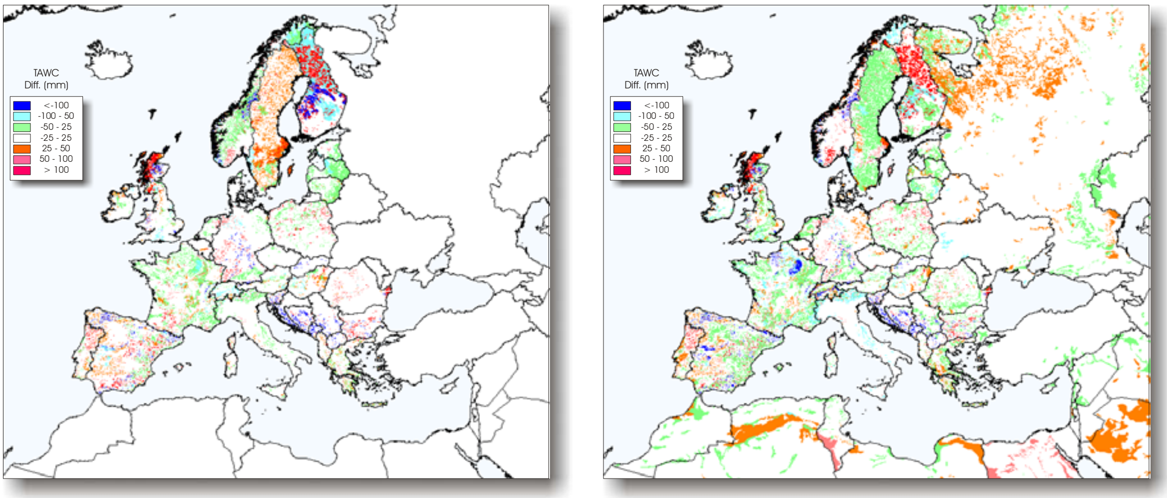
Figure 19: Total Available Water Content for topsoil and subsoil from HYPRES PTF applied to Mapped STUs

For the TAWC the pressure head for the water content at field capacity was set to -100cm and to -15,000cm at permanent wilting point. For the topsoil TAWC the soil depth is given by the depth of the soil to a maximum of 30cm, for the subsoil the depth is given from 30cm to a maximum depth of 100cm, therefore the depth ranges from 0 to 70cm.

To offer some insight into the effect of using the soil characteristics of all STUs instead of only the data from the dominant STU the TWAC were compared with other processing options:

- PTF applied to soil characteristics of dominant STU of an SMU
- PTR applied to soil characteristics of dominant STU of an SMU

Differences in the TAWC between the processing options and the results obtained from the mapped STU properties are based on the arithmetic mean TAWC for an SMUs and the combined topsoil and subsoil. For the comparison the TAWC from the topsoil was combined with the subsoil to a single layer. The differences of the processing options to the PTF applied to the STU map are given in Figure 20.



a) TAWC Difference Dominant STU, PTF *b) TAWC Difference Dominant STU, PTR*

Figure 20: Difference in TAWC between PTF applied to STU map and dominant STU and PTR applied to dominant STU

For areas outside the STU map the TAWC is calculated from soil characteristics of the dominant STU, hence there is no difference between the TAWC when applying the PTF (Figure 20 a)). Limited differences are found for example for Italy, Check Republic, Slovakia, Hungary and Slovakia, while differences are more common in countries such as Spain and France. Prominent differences in the TAWC between applying the PTF to all STUs and only the dominant STU are found in areas where organic soils are present. TAWC values are higher for the dominant STU than all STUs in Scotland, Sweden and the northern half of Finland. Lower TAWC values are found for the southern half of Finland and along the Adriatic coast.

Differences in the TAWC between applying the HYPRES PTR to the dominant STU and the PTF to the STU map are shown in (Figure 20 b)). For Scotland and the northern half of Finland the PTR results in higher values than the PTF, but for Sweden the TAWC is higher for the PTF applied to the mapped STUs. For areas outside the STU map the differences of using the PTR concern mapping units with organic soils in Russia and some large mapping units in arid areas of Northern Africa and Saudi Arabia.

From the comparison it would appear that the differences in TAWC between processing options are more affected by using all STU data than from applying either the PTF or the PTF to only the dominant STU.

5 SUMMARY

For mapping soil properties with pan-European coverage the combination of the spatial layer of typological units derived from the ESDB with soil attribute data from the HWSD has been found possible and advantageous. The ESDB provides additional information in the attribute database, which allows the spatial allocation of soil typological units. For larger areas with soil, but missing data on soil properties, a method was developed to estimate the spatial position of typological units within these areas. The method combines fuzzy logic for defining land suitability with a multi-criteria evaluation and an allocation of typological units by cellular automata and a multi-object land allocation procedure. The method was tested for the urban areas of London and Paris. The results obtained were found to be highly dependable on the parameter settings and a priori information on the proportion of typological units within the area of missing data.

For mapping soil properties the attribute values of the ESDB are very much restricted by the use of ranges or classes. For the area of common coverage the HWSD contains data on major soil properties on a ratio or interval scale. This allows the use of PTFs instead of PTRs. As a consequence, soil properties found in the database can be combined by a mathematical model to derive supplementary soil property data on a ratio or interval scale. Such derived soil property data on a continuous scale should help to better tune environmental models that use spatial soil data and provide a more detailed output.

The study has also shown that combining soil data from different sources, but also with other thematic data, for example for an integrated analysis, is not without difficulties. Problematic to processing data coming from different sources were in particular areas without soil, such as bare rock or glaciers. This dissimilarity in the spatial distribution of areas without soil can lead to inconsistencies in the analysis of land use and land use change. For the derived soil property data the use of all typological units was found to lead to greater variations than changing from a PTR to PTF applied only to the soil properties of the dominant typological unit. Although the spatial allocation of STUs facilitate processing it is still recommended to aggregate the final results of processing STUs to SMUs.

Acknowledgements

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Abstract
The European Soil Database (ESDB) of the European Commission Joint Research Centre provides the most detailed and comprehensive set of data for soil properties with pan-European coverage. However, using the ESDB soil properties in combination with spatial applications is hampered by the structure of the database for soil typological attributes. In this study a layer of mapped typological units was used to resolve issues related to the database structure for the spatial representation of soil properties and to map key soil properties to standardized spatial layers.
The information available form the ESDB tends to be more suited to characterise the site of a soil unit, including morphological conditions. The range of soil property data was extended by the Harmonized World Soil Database (HWSD), which provides more detailed information on soil properties. Combining data from both databases was achieved by processing the attributes in a database management system and then linking the output to a spatial reference layer and by transferring attributes to the spatial layer from each database and processing the data by spatial overlay functions of a Geographic Information System (GIS).
The information offered by the ESDB and the HWSD was combined with the spatial reference layer of typological units to derive other soil properties, which are not readily available from the databases. To provide a measure of the effect of using the information of all STUs instead of only the information given for the dominant STU the soil available water content was estimated using different processing options.

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